Low Cost Grid Electrification Technologies

A Handbook for Electrification Practitioners

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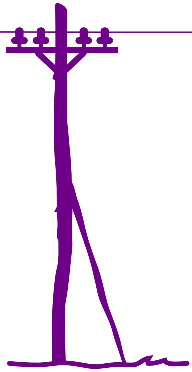
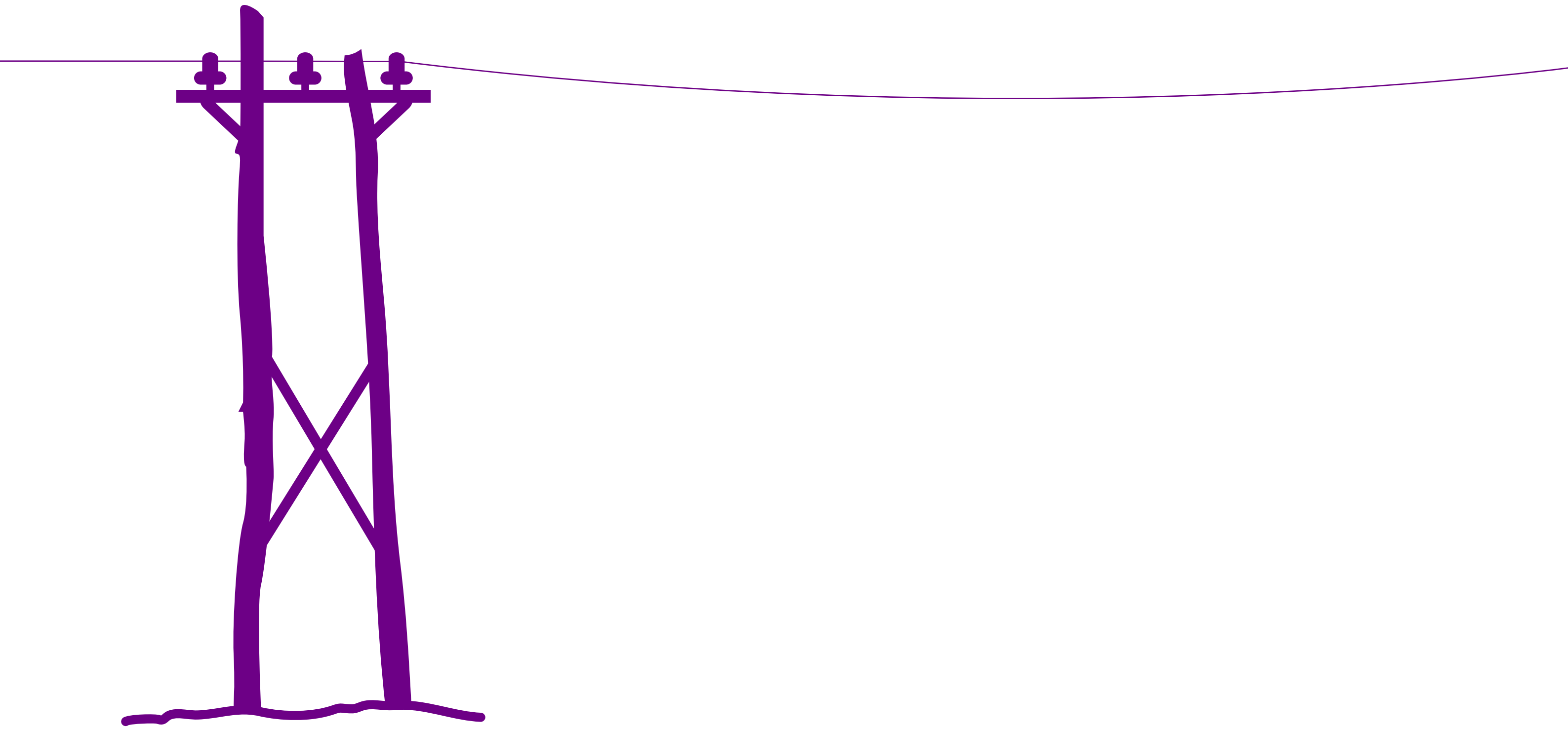
THE AFRICA ELECTRIFICATION INITIATIVE





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About this handbook
This handbook is a joint product by the EU Energy Initiative Partnership Dialogue Facility (EUEI PDF) and the World Bank's Africa Electrification Initiative (AEI). It has been developed in association with two workshops conducted in Arusha, Tanzania (September 2013) and Cotonou, Benin (March 2014) to disseminate knowledge on low cost grid electrification technologies for rural areas*. The workshops were conducted in cooperation with the Rural Energy Agency Tanzania, Société Béninoise d'Energie Electrique (SBEE), Agence béninoise d'électricité rurale et de maitrise d'énergie (ABERME), and the Club of African agencies and structures in charge of rural electrification (Club-ER).

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*) The workshops results are available online at http://euei-pdf.org/dialogue-events/aei-workshop-on-low-cost-on-grid-electrification-technologies and http://euei-pdf.org/fr/activites-de-dialogue/atelier-sur-les-technologies-d-electrification-a-faible-cout-par-extension-de-

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Executive Summary

Why focus on low cost technologies?
Universal energy access has become an international development priority, as highlighted in the United Nations 'Sustainable Energy for All' initiative. Despite significant investments made during the past decades, rural access rates in sub-Saharan Africa remain below 10 % in most countries. A major factor that has hampered the effectiveness of past investments has been the extension of the practices used in urban areas – and the associated high costs – to an entirely different scenario present in the rural areas.

This handbook and the associated practitioners' workshops arranged in Arusha (September 2013) and Cotonou (March 2014) have been intended to assist rural electrification practitioners in sub-Saharan Africa to adopt more appropriate technologies applicable to the loading conditions in rural areas. The application of low cost electrification technologies has led to major success stories in many countries such as Tunisia, South Africa, Brazil, the Philippines, Indonesia and Bangladesh.

Selection of an appropriate technology
This handbook covers the following technologies suitable for providing electricity supply to low load density rural areas:

Single phase reticulation: In this technique, the backbone line is designed to carry the overall load using three phase technology while single phase laterals serve each dispersed load area. This allows the cost of the laterals to be reduced from the three phase option and also allows further reduction by use of conductors of a minimal cross sectional area. As single phase (phase-neutral) laterals require a neutral conductor, the backbone line needs to be of four wire construction. To make this practicable, countries such as Tunisia have converted the older three phase three wire technology to a four wire system by extending a neutral wire from the grid substation along existing feeders.

Alternatively, phase-phase laterals, which do not require a neutral wire, can be used instead of phase-neutral single phase. This doubles the load carrying capacity at a minimal cost increase and also allows three phase loads to be served[1]. Single phase (phase-neutral and phase-phase) laterals are most suitable for application when the load density does not allow the lower cost Medium Voltage (MV) distribution options described below. The system is combined with the use of single phase transformers, extensive MV coverage and minimal Low Voltage (LV) networking.

1) Using a special technology (open star – open delta connection)

Single Wire Earth Return (SWER) system: SWER systems have been successfully used in many countries, particularly where the load densities are considerably low. It offers the lowest cost technology for rural electrification with grid extension when the loads are at a minimum. It can be carried out with and without an isolating transformer. Isolating transformers are essential on systems employing neutral grounding reactors at the MV supply substations, unless the grounding reactance is sufficiently small.

Isolating transformers will also enable the use of sensitive earth fault protection schemes on the feeders emanating from the supply substation. In view of the earth potential rise (EPR) experienced in a SWER network it is important to ensure that the earthing system is appropriately designed, constructed and maintained. SWER is best applied when the load density is sufficiently small and expected load growth rates are not high enough to need an upgrade of the system in a few years.

Shield Wire Systems (SWS): These systems are characterized by the use of the shield wire of transmission lines to transport MV power along the transmission route. A single shield wire can provide a single phase MV system and two shield wires can be used to obtain a three phase system using the earth return as the third phase. With the use of two shield wires, a phase-phase MV system can also be designed without using an earth return. SWS offer an ideal solution to reach remote areas where access through a transmission line is readily available.

In addition to the technology options listed above, the costs of distribution networks can be further reduced by adapting appropriate **construction and design practices** to the rural setup, such as optimized line spans, appropriate pole top configurations and conductor sizes.

Low cost transmission expansion

For many unserved rural areas in sub-Saharan Africa, it is technically not possible to provide the needed supply by extending MV networks, due to the large distances involved. Often it would also not be cost effective to extend the transmission system and build grid substations using traditional standards. However, various low cost options are available to enable grid extensions to reach such locations at the required technical standards and at acceptable cost.

Options to pursue include: wooden or concrete pole configurations for transmission line extensions, direct tapping of existing transmission lines, and grid substation designs with minimal hardware and structures. Another key aspect is that reliability levels needed should not be confused with system voltage. In fact, the reliability of a low cost transmission extension will be greater than the alternative of MV extensions over long distances. Hence, serious consideration should be given wherever possible for low cost transmission extension to feed areas not feasible by MV extensions.

Maximizing connections
All too often lines are built, but household connections either take a long time to materialize or even remain unrealized over extended periods. This is mainly due to the high service connection charge levied on consumers, the requirement to pay the full costs upfront, restrictions imposed on housing types, and logistical difficulties faced by rural consumers.

The situation can be improved by (i) use of appropriate gauge conductors for service connections; (ii) arrangements for payment of the service connection charge over an extended period with instalments along with the monthly bills; (iii) community involvement, consumer mobilisation and education in all aspects of the electrification program; (iv) offering a 'group connections' programme to reduce the cost and eliminate difficulties in securing the services on an individual basis; and (v) developing norms and guidelines to enable service connections to be given to semi-permanent and temporary houses.

Rural electrification planning
Systematic distribution planning is a key success factor of any electrification programme. The process includes the collection and analysis of consumption data, information on unelectrified areas, migration to a GIS platform where possible, and carrying out network analyses to determine the most appropriate technology to be used for network development.

The financial health of all associated organizations needs to be ensured, by developing clear and transparent schemes for funding – including subsidy mechanisms where feasible and application of appropriate tariffs.

1. Introduction

Why focus on low cost technologies?

Rural areas in sub-Saharan Africa suffer the lowest electrification rates in the world with as much as 85 % of the rural population living without access to electricity. According to the International Energy Agency's "Africa Energy Outlook 2014"[2], more than 620 million people in sub-Saharan Africa remain without access to electricity. Under the report's 'New Policies Scenario', the number of people without access to electricity in sub-Saharan Africa is projected to reach 635 million in 2030, as the rate of population growth outpaces the rate of electrification. With current efforts, the goal to achieve universal access by 2030 – as targeted by the Sustainable Energy for All initiative – will hence not be achieved in this scenario. Around 90 % of the sub-Saharan population without access to electricity is expected to live in rural areas by 2040, accounting for two-thirds of the global population without access.

These figures indicate that a major turnaround of the current methodologies used in sub-Saharan Africa for rural electrification is needed. It is now widely recognized that a key factor leading to the high cost solutions hitherto practiced, is due to the use of standards developed for urban areas – which have a much higher loading density. Rural areas are characterized by sparse populations resulting in low load densities, and remoteness from existing transmission and distribution facilities.

2) IEA (2014). Africa Energy Outlook. Available online at http://www.iea.org/publications/freepublications/publication/africa-energy-outlook.html

Furthermore, rural loads do not require the high reliability standards needed in urban settings where the economic costs of power outages is considerably higher. Thus the technologies to be applied for rural areas need to be tailored to its own characteristics, rather than the replication of the methodologies used in urban areas. If this concept is realized it will be easier to find appropriate solutions to addressing the low access rates in sub-Saharan Africa.

Objectives of this handbook

The main objective of this handbook is to provide a knowledge base of available low-cost technology options for grid-based rural electrification, together with associated network planning guidelines, to increase access to electricity in sub-Saharan Africa. It addresses specific technical issues associated with each low cost technology and provides simplified planning techniques and methodologies for computing the line end voltages and power losses to ensure compliance with the required technical standards.

While optimising existing technologies, including cable section, pole height and pole type can reduce the costs of electrification schemes to some extent, the selection of alternative technologies in distribution and transmission can bring substantial cost savings in the longer term. Hence the focus of this handbook is on presenting alternative distribution and transmission technologies that have been tried and tested successfully in sub-Saharan Africa and elsewhere.

Target audience

The handbook is primarily meant for use by power sector practitioners at utilities responsible for planning rural electrification networks, particularly in sub-Saharan Africa. It will enable practitioners to develop appropriate cost effective solutions that would meet the required technical standards.

The handbook can furthermore support staff of rural electrification agencies, government departments and organizations with preparing projects and assigning funds for rural electrification, in particular, to determine whether the assigned funds are put to efficient and economic usage. It will similarly be useful for staff of international development institutions that evaluate power sector expansion projects in the rural sector and provide funds for their implementation.

Structure of this handbook

This handbook covers descriptions of distribution and transmission technologies that have been tried and tested successfully in several countries as cost-effective solutions to challenges faced in rural electrification. It summarizes methodologies which can be used for technical design and the selection of appropriate technologies. The Handbook also covers the important issue of maximizing service connections in completed rural electrification schemes and provides brief references to other crosscutting issues related to the subject.

Chapter 2 provides a description of the various low cost technologies used in distribution system reticulation. The technologies presented consist of (i) the use of predominantly single phase lines (phase-neutral and phase-phase) MV networks as opposed to the traditional three phase systems, (ii) Single Wire Earth Return (SWER) systems, and (iii) the use of Shield Wire of transmission lines (SWS). This chapter also addresses how three phase loads can be accommodated in such developments.

Chapter 3 addresses the issue of how cost-effective transmission system extensions can be carried out in rural areas, including potential cost savings in transmission lines and substation design.

Chapter 4 addresses the important associated issue of maximizing service connections in completed rural electrification schemes. This aspect is considered to be of particular relevance due to the fact that many rural electrification schemes in sub-Saharan Africa remain poorly utilized, with low connection rates even after many years post-completion.

Chapter 5 discusses the area of distribution network planning. The methodologies and techniques described can be used to select the appropriate technology to serve rural areas.

The appendix provides the basic technical data related to a network planning exercise. It also describes a simple spreadsheet-based methodology for computing the voltage drop and losses of a distributor which can be used when more sophisticated software is not available.

Off-grid vs. on-grid electrification

In planning rural electrification development, an important consideration is the decision between the overall technology options of:

- Grid-based electrification;
- Mini-grids; and
- Stand-alone solutions such as Solar Home Systems.

The appropriateness of each of these options for a particular area will depend on a number of factors: proximity to grid supply, availability of local generation resources, load density, expected development of motive power and other industrial applications etc. The growing demand to serve the rural populations can be met from a variety of resources, both grid and off-grid.

In some areas, where the load densities are extremely low and motive power is not needed, Solar Home Systems will be the appropriate solution. For larger communities and in areas where renewable energy sources such as hydro and wind power are available, renewable or hybrid mini-grids may be the optimal choice for electrification.

In areas with larger electricity demands and close distance to the grid however, the technology of choice would be extensions from the national grid. **Grid-based** alternatives have the singular advantage of being able to meet additional loads, particularly linked to industrial, irrigation and agricultural demands, which normally develop over time.

It should always be borne in mind that these options are complementary to each other and should not be treated as competing alternatives. In many cases the first stage of electrification of an area is provided by a low power resource, e.g. Solar Home Systems. As demand for electrical power grows, the need may arise for an upgrade to a system that can provide more power.

Further Reading

EUEI PDF, ARE & REN21 (2014). The Mini-grid Policy Toolkit. Policy and Business Frameworks for Successful Mini-grid Roll-outs. Available online at http://euei-pdf.org/thematic-studies/mini-grid-policy-toolkit

ARE & AEEP (2014). Best Practices for Clean Energy Access in Africa. A compilation of 20 case studies and business cases on access to off-grid energy services. Available online at http://www.ruralelec.org/fileadmin/DATA/Documents/06_Publications/ARE-Best-Practice-Africa-2014_final.pdf

S. Szabó et al. (2013). Sustainable energy planning: Leapfrogging the energy poverty gap in Africa. Renewable and Sustainable Energy Reviews 28 (2013), 500–509. http://iet.jrc.ec.europa.eu/remea/sustainable-energy-planning-leapfrogging-energy-poverty-gap-africa

Urban vs. rural electrification

When a grid based development is considered to supply a particular area, a further consideration is whether to use standards appropriate for urban or rural areas.

In urban areas, both the economic and nuisance value of power outages is high. Alternative stand-by generation plants with high capital and operating costs are employed in many establishments, such as commercial buildings, industry and office complexes. The costs of such alternative or stand-by supplies can be minimized with higher reliability of the grid supply. Even where such alternative stand-by arrangements are not used, the enhanced willingness to pay for lower outages in urban areas justifies designs at higher reliability levels. Increased reliability requirements in urban areas should thus be met with suitable network designs, which enable greater switching flexibility by providing a number of alternative supply options. This also requires enhanced conductor sizes to meet higher load carrying capabilities when network changes are made.

For **rural networks**, such stringent conditions do not need to be adhered to, enabling simpler network designs at lower cost. Rural networks have significantly lower load densities than in urban areas (usually measured in kW[3] per unit area or kW per km of line). The lower loads on the distributors enable the designer to choose from a greater array of options, thus allowing lower cost technologies to be used. Compared to urban areas, requirements for reliability of supply are also usually lower in rural areas; as well as the willingness to pay for increased reliability of supply. Taking into account these considerations, substantial costs savings can be achieved by applying standards appropriate for rural areas – enabling increased electricity access rates with the same budget.

Significant advances have already been made in developing and applying alternative **low cost technologies for rural electrification** in several countries. Success stories as the examples listed in the textbox below can be used as models for upcoming rural electrification programmes. The use of appropriate technologies described in this handbook will enable more networks to be constructed, resulting in maximum electrification rates from the funds available.

3) Load density is usually measured in terms of power (kW) and not energy (kWh) as it is peak power demand that is more relevant for network planning

Low Cost Rural Electrification – Success Stories

- **USA:** In the 1930s, the US embarked on a targeted program to increase electricity coverage to rural farmsteads and townships using low cost technologies in both network design and construction techniques.
- **New Zealand and Australia:** About the same time in New Zealand the innovative Single Wire Earth Return (SWER) technology was invented to serve the far-flung low density areas in the countryside. This technology was thereafter used extensively in Australia.
- **The Philippines:** A major effort was commenced in the 1970s to provide rural access by a system of rural electric cooperatives following the single phase reticulation model developed in the US.
- **Bangladesh:** A similar programme (to the Philippines) was developed in the 1980s. The PBSs (rural cooperatives) are well known for their high connection rates, efficiency of operation with low losses and good collections.
- **Tunisia:** When the country embarked on a massive rural electrification program in the 1970s, a major change was made from the existing three-wire three-phase MV network to a four wire system to enable single phase extensions.
- **South Africa:** ESCOM launched its program of "electricity for all" using similar low cost technologies in the 1990s.
- **Ghana:** The innovative Shield Wire System (SWS) was developed in the 1980s to provide electricity at lower costs to far-flung communities close to transmission lines.

2. Low Cost Electricity Distribution Technologies

The **historical development of power distribution systems** in sub-Saharan Africa was based on the European model, and introduced in the mid-20th century. This model was ideal for serving concentrated urban loads, which was the initial stage of electrification in these countries. Initially, supply networks received power from diesel generation plants and had limited geographic coverage. The distribution networks consisted of low voltage (LV) lines at 230/400 Volts and used thick gauge conductors to feed areas extending to a few kilometres. Thereafter, as the capacity of power plants increased, coverage was extended using Medium Voltage (MV) lines, usually at 11 kV and 33 kV. The supply transformers stations to feed the LV networks were of large capacity, ranging from about 50 to 500 kVA.

With further developments in large scale power resources, such as hydro power and thermal fuel-based steam plants, **national grids were established and transmission networks constructed** to bring power from the generation plants to the load centres. The design of the MV and LV lines, as well as transformer sizing, were maintained as before, creating a network with predominantly three phase supply. The LV network coverage area from an individual transformer was relatively large with long lines, using thick gauge conductors to meet the limits posed by voltage drops. Overall, such systems functioned well both technically and economically, for the high load densities of urban populations. With time however, there was a growing demand for servicing more peripheral townships and rural populations as well as rural agro-industrial loads.

Nowadays, in almost all sub-Saharan African countries many urban load centres are fairly adequately covered, while rural access is at a very low level – often in single digits. While various countries struggled to meet the new challenges of extending the grid system to cover new areas, the initial design philosophy of the MV and LV reticulation and sizing of transformers remained as before. In most developing countries, no systematic effort was made to ascertain the best network design that would meet the substantially different conditions in rural areas. This chapter will examine alternative approaches available to meet this challenge.

2.1 Single Phase Reticulation

In many sub-Saharan African countries, network expansion to rural areas was the direct application of the technology used for the urban loads. These consist of MV networks (usually 33 kV / 11 kV), large capacity transformers (50 kVA to 500 kVA), and long LV lines often extending to over 2 km in length. While single phase LV lines are only sometimes used for by-lanes, the main LV network is usually of three phase construction.

The use of single phase lines at MV can however result in substantial cost reductions, as applied in the USA and successfully adopted in several countries. The main features of such power systems include:

- three phase, four wire MV lines which serve as the system backbone,
- single phase to neutral MV laterals that extensively cover the supply area,
- single phase to neutral small capacity transformers to feed small clusters of consumers, and
- very limited or hardly any LV lines.

The main function of this system is to cover the supply area with an extensive network of single phase MV distributors bringing the MV power virtually to the doorstep of the consumer. These single phase lines are fed from the three phase backbone system which carries the combined loads of the distributors. The single phase transformers (see *figure 1*) are of low capacity from 5 kVA to 37.5 kVA and constructed with cylindrical steel sheets and thus

Figure 1 Single Phase Transformer used in Bangladesh

considerably cheaper to manufacture than the rectangular frame transformers used for three phase transformers. Single phase transformers are used both on the three phase and single phase lines.

When three phase supply is needed at a three phase line, three single phase transformers are symmetrically mounted on a single, often wooden, pole. The service connection is often directly from the transformer pole or within a couple of additional poles. Thus, there is a larger number of transformers along the MV line. There is no continuous LV coverage and gaps with no houses are left without any LV coverage. This practice substantially reduces the LV network; power is transferred to the LV system in small quantities close to the consumer. The ratings of the LV conductors are therefore much smaller.

As an alternative, **phase to phase configuration** can be applied for the MV laterals instead of phase to neutral. This way, the laterals in an 11 kV system are 11 kV (phase to phase) instead of 6.35 kV (phase to neutral); and in a 33 kV system 33 kV (phase to phase) instead of 19.1 kV (phase to neutral).

If a country's standard MV reticulation system from existing grid substations is a three wire network, the use of phase to phase laterals will obviate the need for a neutral wire to be strung from the grid substation. Phase to phase arrangements will also allow for a higher power transfer capability than the single phase laterals due to the increase of line voltage. It will however involve additional costs due to the need to insulate the return phase wire. Hence the decision of phase-phase vs. phase-neutral for laterals should be made on a case by case basis, in particular whether a 4 wire MV network can conveniently be made available.

Technical considerations

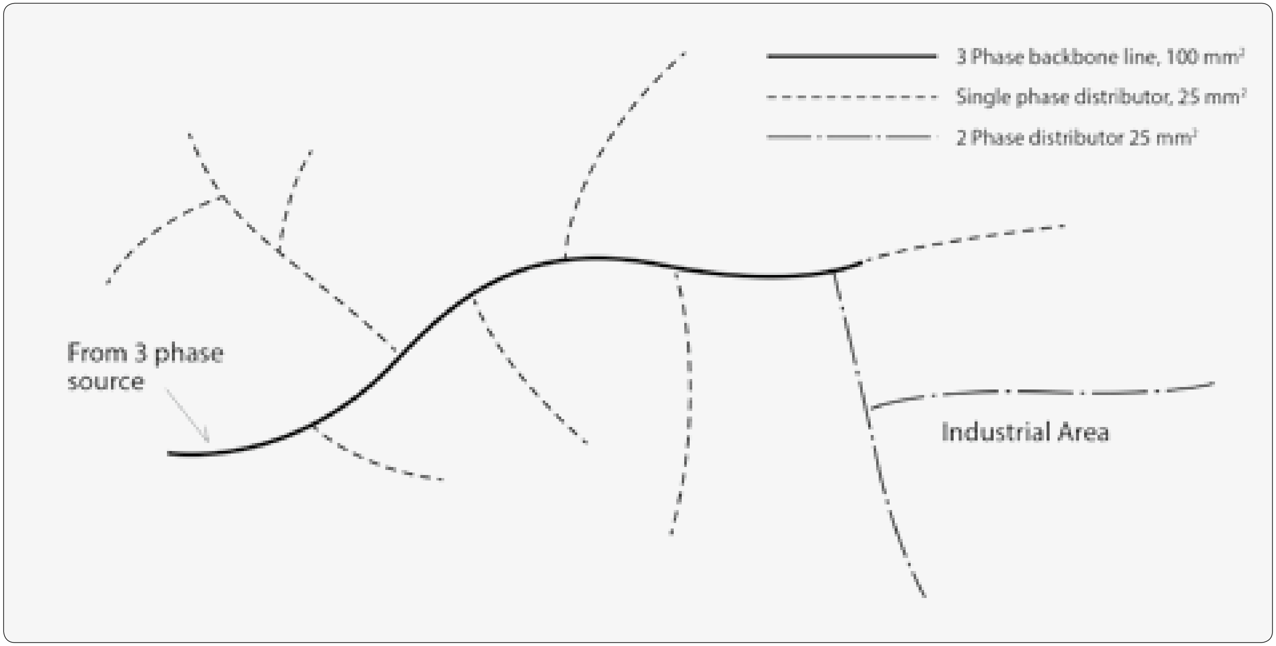
Single phase systems (phase-neutral and phase-phase) have been in wide usage around the world for many years and there are no major technical issues that need special attention. An important consideration however, is to ensure the balancing of the three phase backbone system. This can be done by ensuring that successive laterals are made from different phases giving also consideration to the number of consumers off each lateral. A good documentation of the consumer locations and the phase of supply will help to keep the main system well balanced and to minimize the neutral current to the main supply substation. The documentation is ideally done in a GIS based network data base. It may be noted that:

- For a given voltage drop and the same conductor sizes, a single phase (phase-neutral) line will carry one sixth of the power of a three phase line. A phase – phase line will carry half the power of a three phase line.
- If single phase (phase-neutral) laterals are used (instead of phase-phase laterals), the backbone system need to be a four wire three phase network with the neutral conductor strung all the way from the main grid substation.

The system also lends itself conveniently to network improvement to meet additional load development in a future year. Such improvements can be undertaken in the following ways:

- conversion of the single phase (phase-neutral) laterals to phase-phase or three phase – if necessary, combined with the change of conductor size to a higher gauge, and
- development of the backbone network and altering the feeding arrangements of the laterals with the aim of reducing the lengths of the lateral lines.

Figure 2 Example of a network with backbone line and lateral arrangement



Note: The industrial area is fed off a phase-phase line which allows three phase LV supply to be provided via open wye – open delta transformations.

Figure 3 Subsequent augmentation of the network to meet additional distribution loads

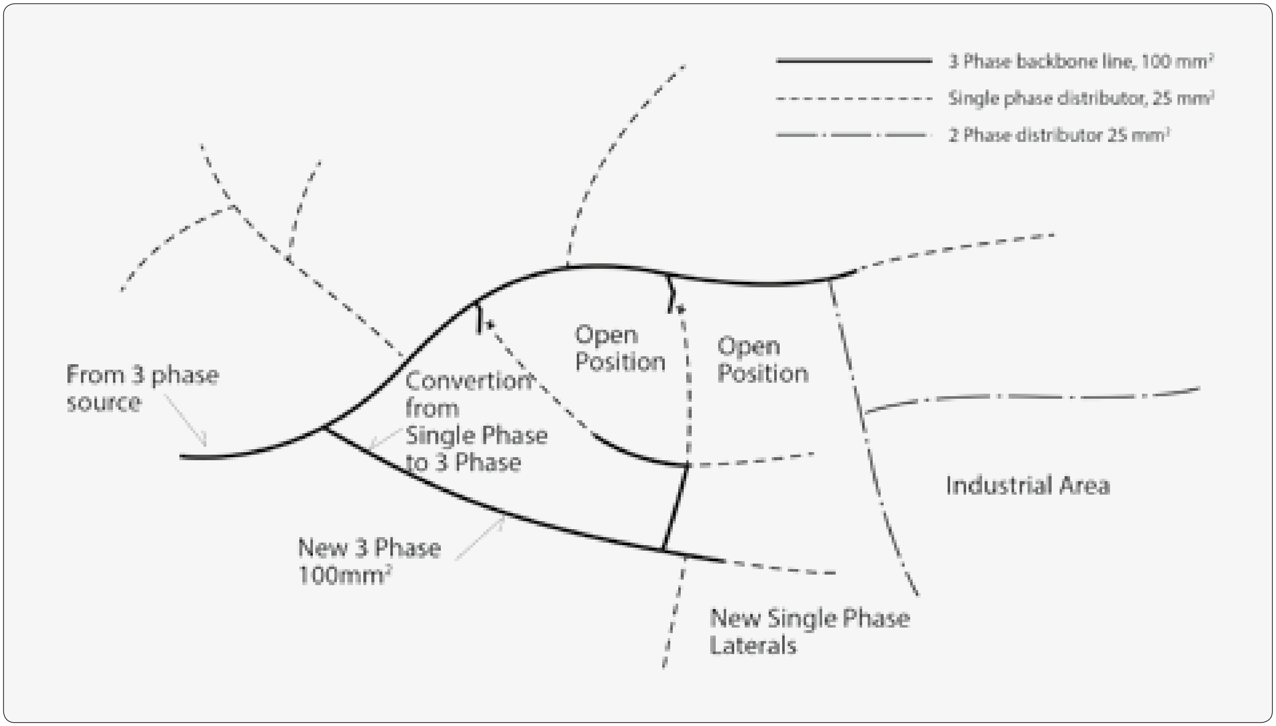


Figure 2 gives an example of a network with backbone line and lateral arrangement. In *Figure 3* additions are made to this network to meet additional loads. The strategy adopted is to convert a single phase portion to a three phase backbone line thereby changing the manner of feeding the laterals, thus enabling a greater power flow.

Access Improvement with Single Phase Reticulation

- **USA:** the rural electrification rate increased from 10 % in 1935 to 96.5 % in 25 years (1960) and to 98 % by 1964.
- **The Philippines:** after an initial set back in the early years a second phase carried out in the 1970s resulted in the addition of one million consumers in ten years.
- **Bangladesh:** A system of rural electricity cooperatives have been developed over the last 25 years and now serves over 50,000 villages providing supply to over 10 million consumers.
- **Tunisia:** the rural electrification rate increased from a mere 6 % in mid 1970s to 88 % by end of 2000 and near complete access as at present.
- **South Africa:** electricity increased from 35 % of households in 1990 to 84 % in 2011.

Advantages

The reduction in cost of using single phase[4] at MV compared to traditional three phase settings arises due to (i) the lower cost of MV reticulation and (ii) the elimination of the extensive LV line coverage: The cost of a four wire (three phase) LV line is of the same order as that of a three phase MV line. Depending on the terrain, unit costs of MV lines is sometimes even cheaper than an LV line due to the longer spans possible, resulting in lesser number of poles and pole top hardware (which is more costly for MV). When the loads are widely dispersed, the advantage of the single phase reticulation becomes more pronounced. In such locations the single phase laterals can conveniently be erected with small capacity single phase transformers supplying small clusters of consumers. The alternative of having a three phase arrangement will require the coverage area per transformer to be enhanced and the erection of more extensive LV lines.

Examples of the cost savings possible by the use of single phase reticulation for supply extensions on a network can be seen from the examples provided in the Appendix. In the MV case studies[5] S1 to S4, it is seen that cost savings of around 25 % can be achieved. In the case study S5, which involves both MV and LV lines, it is seen that the cost savings can increase up to 32 % when extending new networks to areas of lower loading densities.

4) Includes phase-neutral and phase-phase systems

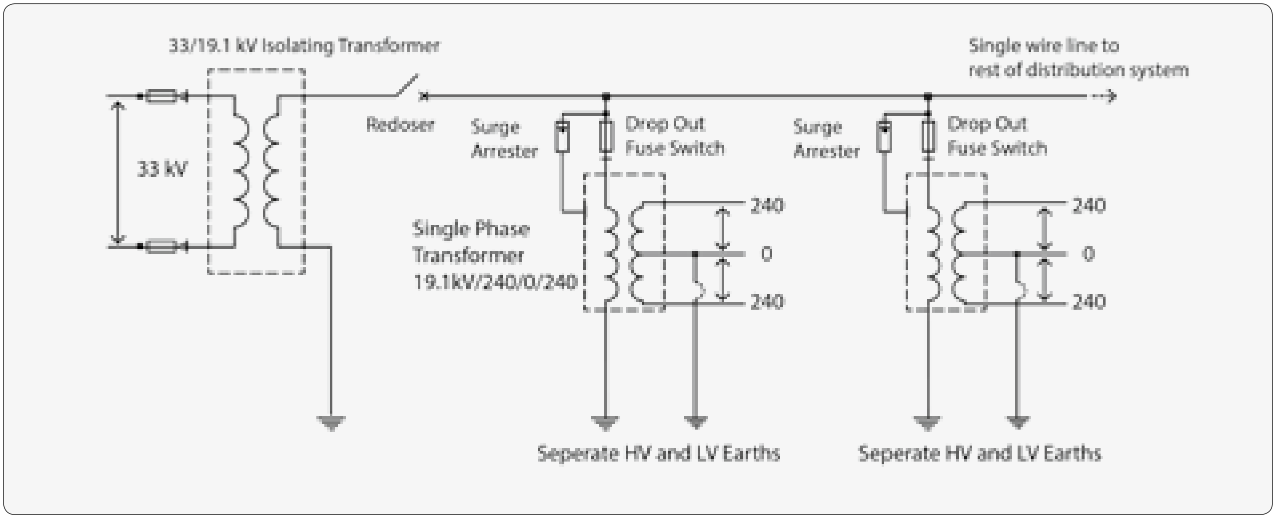
5) Carried out at the workshop in Arusha and Cotonou

2.2 Single Wire Earth Return (SWER)

The Single Wire Earth Return (SWER) system is basically a single phase distribution system at MV using the earth as the return conductor. There are two basic types of SWER systems in use: (i) using an isolating transformer at the tap-off from the main supply line (*Figure 4*), and (ii) tapped directly from the main supply line ("direct SWER", *Figure 5*).

The SWER system is usually combined with the North American practice of having a number of **dispersed single phase transformers** to feed small load clusters rather than having a centralized transformer with substantial LV lines. Thus the LV network is substantially reduced, similar to the case of single phase reticulation (see previous chapter). The single wire MV phase line, which is extended to the load sites, uses single phase distribution transformers in the order of 5 kVA, 10 kVA, 15 kVA and sometimes up to 37.5 kVA. The voltage used depends on the supply voltage available and the requirements of the system to carry the expected load.

Figure 4 SWER System with isolating transformer



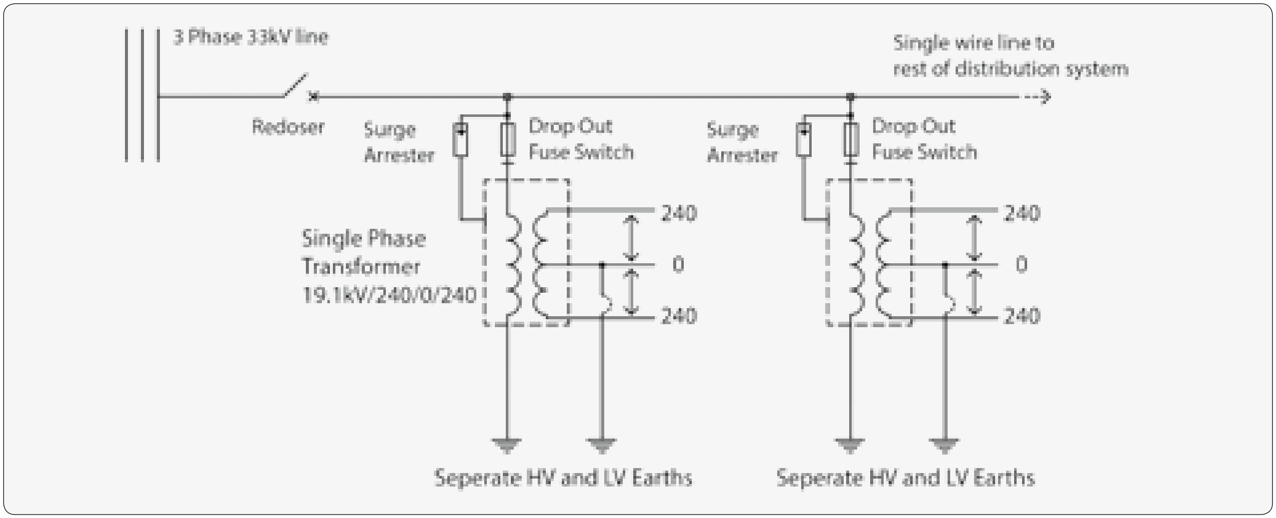
Note: The distribution transformers are indicated as bi-voltage +/- 240 V. However, the single phase LV transformers, 19.1 kV/240 V can also be used instead.

When an **isolating transformer** is used, it is possible to select a different voltage for the SWER network from that of the main system: If supply voltage available is either 11 kV or 22 kV, the isolating transformer is often used to uprate the SWER system to 19.1 kV or even 33 kV. Such uprating of the voltage has been successfully carried out in South Africa where substantial networks at 11 and 22 kV are in place. If no isolating transformer is used, the SWER network voltage is the same as the phase voltage of the supply system; namely 19.1 kV for a 33 kV system, 12.7 kV for a 22 kV system and 6.7 kV for an 11 kV system.

Technical considerations

Isolating transformer vs. direct SWER
The advantages of **using isolating transformers** are primarily associated with the ability to limit earth fault currents to the area of the SWER system: The earth return current will flow back to the earthed terminal of the isolating transformer and the rest of the network is unaffected. Any difficulties caused by the earth current will not be felt outside of the SWER supply area. Isolating transformers are essential on systems employing neutral grounding reactors at the HV/MV supply substations,

Figure 5 Direct SWER System



Note: The distribution transformers are indicated as bi-voltage +/- 240 V. However, the single phase LV transformers, 19.1 kV/240 V can also be used instead.

unless the grounding reactance is very small. They will also enable the use of sensitive earth fault protection schemes on the feeders emanating from the supply substation.

With **direct SWER**, the earth return current will flow to the earth electrode at the main HV/MV substation which is the source of the MV system for the SWER network as well as other three phase MV networks in the overall area. If many SWER systems are used and the loading of the different systems is appropriately balanced among the three phases, the return current can be substantially minimized as the phase displacement of the three phases will cancel out the resulting earth current. However, in practice this is difficult to achieve and a resultant feedback current will be experienced at the earth electrode of the main substation. Thus direct SWER cannot be practiced if sensitive earth fault protection is employed at the source substation as the normal load current flowing in the earth will trigger an outage. Direct SWER is therefore usually only used when the source substation has a solidly grounded neutral.
The use of an isolating transformer limits the load that can be served, as higher load currents require extremely low impedance of the earthing electrodes to maintain the step voltage to an acceptable level. Usually the maximum rating of isolating transformers are about 315 kVA although 480 kVA systems are also in practice. With direct SWER, there is no limitation of loads on any SWER feeder.

Another advantage of direct SWER is the reduced costs due to the omission of the isolating transformer. However, if the source substation is situated in an area of considerable telecommunication activity ground currents may cause interference, once again reiterating the need for careful balancing of various SWER lines from different phases.

Figure 6 SWER isolation transformer and take off line in New Zealand

Earthing System
During normal operation of the SWER line, a MV load current flows through the earth from each of the distribution transformers back to the isolating transformer (or the source transformer in a direct SWER). This will cause a 'continuous' **earth potential rise** (EPR) at each of the earthing systems. In the case of an earth fault on the SWER conductor, the fault current flows to the earth at the point of contact and returns to the earthing system of the isolating transformer. This will cause an 'intermittent' or 'fault duration' EPR. The corresponding human hazard voltage limits will be considerably higher than for the continuous EPR.

Due to the typical fault current being much smaller in SWER applications and their longer distances from the source substation, the values of earth fault current are much lower than in the normal line fault situations.
If the MV and LV earthing systems are common or interconnected, the EPR will also be transmitted to the consumer's earthing terminal and to exposed metal parts of connected appliances. Transfer of EPR hazards can also occur to telecommunications equipment in the vicinity of the isolation transformers, distribution transformers and consumer's premises particularly dependent on the electrical interconnection between the MV and LV earth systems. The main area of transferred EPR hazards to telecommunication equipment at the consumer's premises occur on any mains powered telecommunication equipment at these premises.

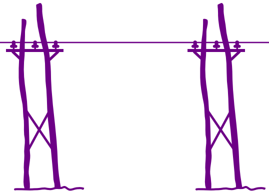


Table 1 Ground resistance required to maintain an EPR of 50 volts

	From a 33 kV system				From a 22 kV system			
Line voltage, kV	19.05	19.05	19.05	19.05	12.70	12.70	12.70	12.70
Transformer capacity, kVA	16	50	315	480	16	50	315	480
Full load current, Amps	0.84	2.62	16.53	25.19	1.26	3.94	24.80	37.79
Ground resistance, Ohms	59.54	19.05	3.02	1.98	39.69	12.70	2.02	1.32

In view of the above, the critical issue in a SWER system is to ensure that the earthing system is appropriately designed, constructed and maintained. Usually, permissible touch and step voltages are regulated in each country to ensure the safety of persons who may accidently connect with any part of the earth system. In the absence of any appropriate regulations, a safe value to maintain for the EPR (referred to in the literature also as the ‘potential to remote earth’) is 50 volts. Touch voltage refers to the voltage that can appear between any point of hand contact with uninsulated metal work and the ground surface; the step voltage refers to the surface voltage difference experienced by a person bridging a distance of 1 meter on earth.

Table 1 gives the minimum ground resistance needed to maintain an EPR of 50 volts at full load current.

It can be seen that achieving the required maximum grounding resistance will not be a problem for distribution transformers even if a capacity of 50 kVA is used, although the recommended ratings are much lower, of the order of 5 to 16 kVA. However, maintaining a low ground resistance will be an issue for the isolating transformers and due care should be taken to ensure compliance with the maximum values of earth resistance. When designing an earthing system it may also be kept in mind that seasonal changes can make a significant impact on soil resistivity. Furthermore, as there are diminishing returns to reducing the earthing resistance, it is preferable to lower the transformer capacities used instead.

Measures to maintain a good earthing system and to limit dangers caused by EPR include:

- **Conducting surfaces:** Minimize bare and inadequately insulated conducting surfaces at the isolating transformer station and at the distribution transformer stations. For this purpose, the use of wooden poles instead of steel or concrete poles will be advantageous.
- **Connections:** Use duplicate connections from the transformer earth terminal to the earthing electrode. The duplicate connections should use separate routes; a minimum of 3 meters is recommended between the two electrode systems.
- **Type of electrodes:** The appropriate types of electrodes depend on the soil conditions, such as specific resistance and acidity. Copper plated steel electrodes of about 16 mm in diameter are suitable for most locations. When soil acidity is high, copper clad steel, solid copper or stainless steel electrodes may be used. Galvanized electrodes and pipes should not be used in corrosive soil as electrolytic corrosion is accelerated due to the continuous current flow. The electrodes may be rods of about 5 meters or connectable rods of the same length.
- **Electrode system:** A usual electrode system may consist of three electrodes in an equilateral triangle spacing of about 5 meters. When the required ground resistance (see *Table 1* left) is not achieved, further electrodes need to be added at 5 meter spacing. The connection from the transformer to the electrodes shall be of sufficient gauge, well secured and insulated. The cross-section of the earth connections should be a minimum of 16 mm^2 stranded copper (25 mm^2 recommended). These should be PVC covered and provided with mechanical protection, such as by galvanized water pipe securely fastened to the pole to prevent theft or malicious damage. Connections between the electrode and earth conductor and any other jointing should be by compression jointing. Bolted clamp joints are not acceptable underground due to the continuous earth current producing electrolytic corrosion. The earth electrode/s used for the earth return currents may be used for other earthing or bonding connections; in particular the transformer tank and the surge diverter earth.
- **Aerial Earth Wires:** In poor soil conditions, aerial earth wires may be strung for some distance to find better resistivity soils and electrodes connected to the earth wire and installed at each pole or selected poles along this line, as in the case of multiple grounded four wire systems. Alternatively it may be necessary to change the location of the transformer to an area with better soil resistivity. If the earthing conditions are difficult within a village, a wire neutral can be strung in the village, with the neutral earthed in open areas outside.
- **Bore holes:** As a last resort in achieving low earth resistance values, deep bore holes can be drilled to reach constant moisture zones (of about six meters) and a mixture of Betonite and Gypsum filled around the electrodes.

- **Electrical separation** of the MV and LV earthing systems should be ensured. The larger the MV system earthing system, the greater should be the separation between the two systems.
- **Physical protection** of the earthing system is important particularly where there is easy public access. Vandalism and theft of copper wires has been a major problem in several countries; SWER systems are particularly susceptible to this danger. Copper clad aluminum and even galvanized steel wires instead of copper wires have been effectively used to guard against this problem. When using these alternatives it is important to ensure that the earthing resistance is sufficiently low enough to limit the EPR to acceptable values. Another interesting arrangement is to run the earthing conductor in an embedded conduit in the concrete poles used for the isolation and distribution transformers. It may also be necessary to fence off some areas particularly at the isolating transformers. Areas subjected to cultivation also need special protection to prevent exposure and damage to any buried conductors.

Protection

In a SWER system, dry ground conditions can result in high impedance earth faults, which are difficult to distinguish from the normal SWER current. Protection of a SWER system is thus generally restricted to overcurrent protection and should be such as to reduce to a practical minimum a conductor remaining live after breakage of a line. While standard drop out fuses (DDLOs) may suffice for short lines, longer lines should be protected with circuit breakers with auto reclose function. It is recommended to install drop out fuses on longer spur lines, too.

In very dry areas or where ground contact resistances are very high, circuit breakers with special ground current sensing relays can be used. However, these involve higher costs and should be used only if needed. The relay monitors for arcing patterns rather than fault current and thus can detect very low current faults of a few amps. As in any normal distribution system, surge arrestors are needed at the isolating transformer and at each distribution transformer for lightening protection.

Fault discrimination is better when higher voltages are used, thus favouring the 19.1 kV phase voltage of 33 kV systems in preference to the lower voltages. In addition, larger isolating transformers with lower impedance increase the fault level resulting in better fault identification. Sensitive earth fault protection should not be used, as SWER systems can generate return currents in excess of the usual set-off values.

Multiwire Systems

A number of variations can be used when a simple SWER system is unable to meet the expected loading conditions:

- The isolating substation may use **two isolation transformers** and supply two separate SWER lines. In this case the earth currents can be minimized by cross-connecting the primary windings of the transformers so that the earth-return currents are in phase opposition.
- A **centre tapped single phase isolating transformer** can be used to give 19.1–0–19.1 in a 33 kV system or 12.1–0–12.1 in a 22 kV system with the centre tap grounded. As in the previous case, the earth-return currents will be in phase opposition. The two phase wires can be used as a backbone SWER network and single wire direct tapped SWER lines can be taken as laterals; alternatively, each phase wires can go in different directions as single wire SWER lines.
- A **three phase SWER backbone system** can be provided by using a single delta-star transformer. As before the three lines can be used as a backbone to supply single wire SWER laterals or strung in different directions to feed separate areas. If the three SWER lines have identical currents and phase angles, the resultant earth return current at the isolating transformer will be zero.

When computing earth electrode resistance for limiting EPR, the faulted line condition should be considered where the earth-return currents will not balance each other.

Advantages

The main advantages of SWER systems may be summarized as follows:

- Substantial **cost savings** are realized from the use of only one MV wire to cover the supply area. Thus SWER systems have a substantially lower initial investment costs than that of other alternatives.
- The **design simplicity** results in less pole top hardware and no crossarms.
- Substantially **longer spans** can be used as the wind loading is much less than for three conductor or two conductor lines, and there is also no issue with respect to conductor clashing. In New Zealand, hilltop to hilltop spans of over 1 km have been used providing substantial cost savings. With an appropriately designed line route, the usual routing along road ways can be avoided resulting in a line length much lower than for a standard line.
- The ability to use longer spans also eases out **interference with vegetation.**
- Due to the simplicity of design the **construction** is also much easier and can be carried out by less skilled personnel in normal terrain.
- The **reliability of the network** is improved due to fewer components to breakdown. Field experience has in fact confirmed this in many countries and it is observed that the SWER systems have a record of less breakdowns and unplanned outages than standard systems.
- **Maintenance costs** are also substantially reduced due to the fewer components in the system.

A major line routing and design consideration to address in a SWER system is to **extend the design span lengths** instead of adhering to the norms practiced on normal lines. This can be achieved by use of conductors with high steel content and high stringing tensions to minimize the conductor sag. In fact in the early years SWER systems were constructed using galvanized steel wires. To limit problems caused by wind induced vibrations, armour rods and vibration dampers can be used. The longer spans can also be used effectively in route selection to substantially reduce the line length from that of a standard line to reach a particular village. With an appropriately designed line route and making use of the longer design spans, the usual routing along road ways can be avoided.

Upgradability

SWER lines can easily be upgraded when required by load growth in the area by judicious selection of pole height and strength and also pole spans to allow the insertion of intermediate poles. In this way, the network can be upgraded when needed to either phase-phase or three phase systems. In addition, the system as a whole can be upgraded by introducing new three phase backbone lines and reconnecting the existing SWER networks to the new lines as laterals of shorter sections. In the second alternative, the laterals may be conveniently retained as SWER lines if direct SWER is used.

With respect to the distribution transformers, it is recommended that the existing transformers be retained and additional transformers be installed rather than the change out of the transformers. This will increase the number of MV/LV transformations, reduce the need for long LV line lengths and improve the system loss and reliability functions of the network. If previous distribution laterals are converted to three phase, the simple addition of two more single phase transformers on the same pole can convert a single phase distribution point to a three phase supply, when such is needed.

Further Reading

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The SWER Success Story

The SWER system was invented and applied initially in New Zealand by Lloyd Mandeno in the 1930s. Within a few years SWER systems were used widely to provide economic extension of the power networks to sparsely populated regions in New Zealand and Australia. In both countries this system began to be widely used to supply the power needed in rural areas and finally reached a network of over 200,000 km, giving almost total coverage to the rural areas in these countries. Many of the supply areas were rural farms; apart from the general lighting demands of the communities it also supplied the needed power for water pumping, milling and other associated agro industrial applications. This technology provided the impetus for the rapid electrification of farmsteads and rural townships and was the mainstay that enabled the economic development of the electrified areas. The success in New Zealand and Australia led to its use in many other countries such as Canada, Brazil, Tunisia, and South Africa later on.

2.3 Shield Wire System (SWS)[6]

The Shield Wire System (SWS) of transporting MV power over long distances was developed many years ago by Professor Francesco Iliceto of Rome University. It is characterized by the use of the shield wire of transmission lines to transport Medium Voltage (MV) power along the transmission route to a convenient location and then extending the supply from there, by normal pole lines up to the supply area. For this purpose, the shield wire/s (which is normally grounded) need to be insulated up to the MV level. The SWS allows electricity to be made available at MV to communities located along HV transmission lines, with an installation cost that can be as low as 10–15 % of cost of independent MV lines on the same right-of-way.

If the **insulation of the shield wire** is carried out along with the transmission line construction, the costs are minimized, with practically only the cost of the additional MV insulators and arching horns being incurred for most of the line length. If the insulators are to be attached retroactively i.e. on existing transmission lines, the costs increase substantially as it would involve live line working on a transmission line, or alternatively requiring outages on the transmission line.

The **MV supply is derived** from the substation where the transmission line commences and is usually between 20 to 34.5 kV depending on the MV system used in the country. The SWS system utilizes the physical infrastructure of the high voltage (HV) transmission line and enables the transport of the MV power over long distances at minimal cost. It is particularly useful to supply power to many communities situated along or close to the transmission line. Distance of these communities from the closest HV/MV transformer station may be quite substantial (often exceeding 100 km) and the load demand considerably low, so that it is uneconomical to provide supply by normal means.

The **main features** of SWS are:

- Shield wire(s) insulated from the transmission line towers for MV operation (20–34.5 kV)
- Shield wire(s) energized from the HV/MV transformer at the main supply substation
- MV network extended along pole lines (when the line route moves away from the transmission line)
- MV/LV transformers installed to feed the supply area

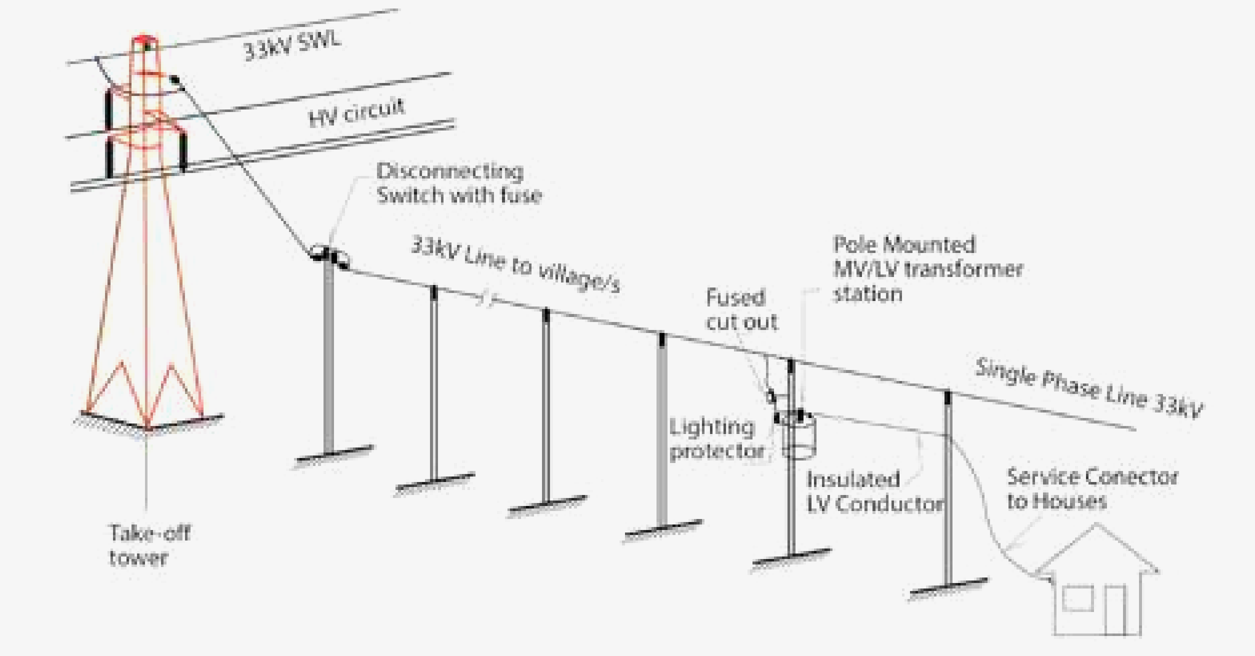
SWS can be used in the following **configurations:**

- with a single insulated shield wire with earth return providing a single phase MV;
- with two shield wires used providing a two wire single phase MV; or
- with two shield wires used with earth return providing the third phase.

6) This section is prepared using information in the presentation of Prof. Francisco Iliceto at the workshop held in Arusha on September 3rd–4th 2013. The presentation is available at http://euei-pdf.org/dialogue-events/aei-workshop-on-low-cost-on-grid-electrification-technologies

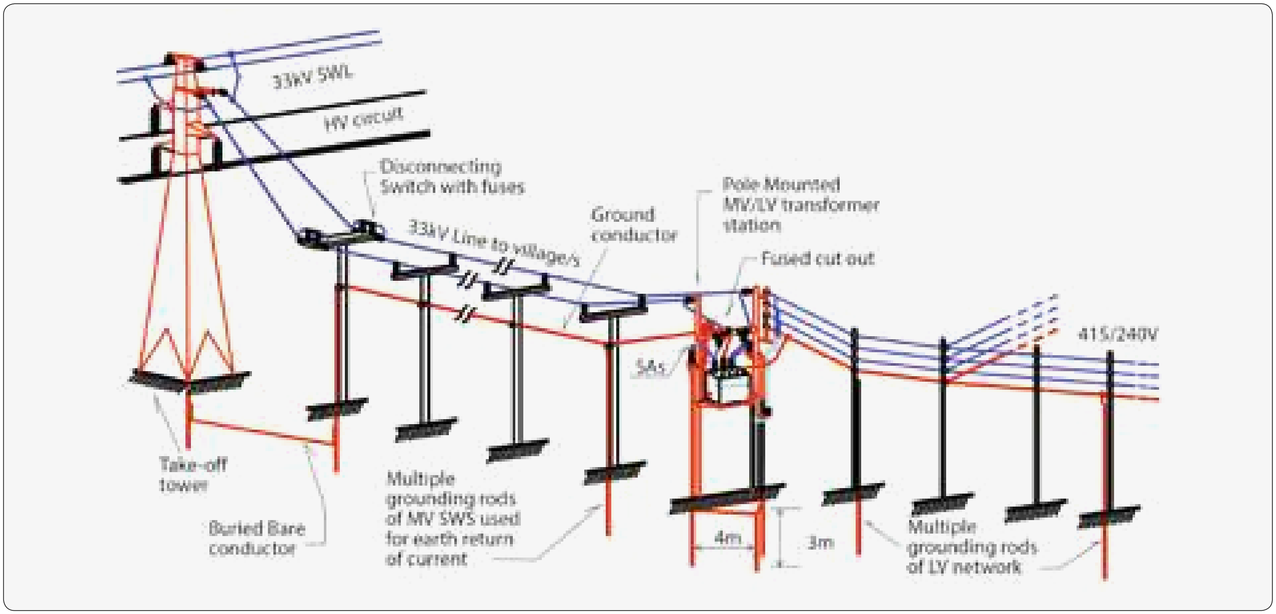
If the **HV line** is protected by one shield wire, only a single phase earth-return SWS can be realised. This arrangement is shown in *Figure 7*. If the HV line is protected by two shield wires, two alternative systems are possible; (i) a two wire single phase (which could be phase to phase system, thus realizing the benefit of the increased voltage) or (ii) a 3-phase MV line by using the earth return as the 3rd phase conductor. This arrangement is shown in *Figure 8*.

Figure 7 Shield Wire Scheme with one shield wire and single phase LV



Source: Sketch by Prof. Francesco Iliceto

Figure 8 Shield Wire Scheme with use of two shield wires and earth return providing three phase MV



Source: Sketch by Prof. Francesco Iliceto

Technical considerations

Supply from a Single Phase Shield Wire Line
If the HV/MV transformer station at the origin of the shield wire line (SWL) has a MV winding with the neutral solidly grounded, the SWL can be directly supplied from one terminal of the MV winding. This scheme is also applicable if the neutral is grounded via a grounding transformer of low homopolar reactance or via a reactor of low impedance.

If the neutral is high-impedance grounded, the single phase SWL is supplied via an interposing transformer. Similarly, an interposing transformer can be used to increase the voltage of the SWL when the grid substation transformer has a low rated voltage which will not suffice for the line length and load to be supplied.

Three phases SWS

In the case of three phase SWS, the phases are balanced by using a grounding resistor-reactor (R-L circuit) along with unsymmetrical power factor correction capacitors. The ohmic resistance of earth path is low, only 0.05 ohm/km at 50 Hz. The voltage drop in the R-L circuit adds to the low resistive voltage drop of the earth return circuit and the total voltage drop is made about equal to the drop in the shield wires. The unsymmetrical capacitors cancel out the voltage dissymmetry along the SWL, which are caused by the unsymmetrical induced voltages and leakage capacitive currents from the HV circuit. Capacitors also eliminate the risk of ferro-resonance over voltages.

The three phase SWL can be supplied by a dedicated tertiary winding of the HV/MV transformer. If a dedicated tertiary winding is not available, a MV/MV interposing transformer is used. It may be noted that a multiple earthing system is applied for achieving the low ground resistance required for the earth return of the current and for the safety of people. In the HV/MV substations supplying the SWS, the station ground mat is used for earth return of the current.

In the case of three phase MV, the voltage to ground of the two shield wire phases will be √3 (i.e.1.732) times higher than for a conventional three phase as the ground operates as the third phase. This requires an enhanced basic insulation level (BIL); thus a BIL of 200 kV is used instead of the usual 170 kV for 34.5 kV systems.

Distribution transformers

The MV/LV pole mounted distribution transformers supplied by the SWS and of the LV reticulation in the villages is practically the same as for the conventional MV/LV distribution.

Lightning performance of the HV line

The shield wire/s should continue to serve its main purpose of providing protection against lightning strikes on the transmission line. To enable the shield wire to perform this usual protective function in the event of a lightning strike, arching horns are placed at the ends of the MV insulators. It has been shown by technical analysis and confirmed by many years of operational experience that such a system does not change the lightning performance (flashover rate) of the HV line.

Long-distance SWL

With very long SWLs (100 km or over) use of reclosers at intermediate points should be considered (particularly in areas of high keraunic level).

Optical Ground Wire Systems and SWS

If an optical ground wire (OPGW) is applied in the HV line for telecommunications, SWS can be realized by insulating the standard OPGW for MV. The required accessories and fittings are available on the market. 34.5 kV SWLs with OPGW are in operation in Togo and Burkina Faso. It may be noted that part of the cross section of an OPGW must be of aluminium or aluminium alloy, in order to ensure low ohmic resistance for limiting overheating by short circuit currents that is detrimental to the fiber optics. An OPGW is thus, by its concept, suitable for use as a conductor of a SWL. Protection of SWLs using an OPGW must include fast dependable fault clearing.

Transient Faults
The large majority of transient faults of the SWLs are cleared by the automatic high-speed reclosure of the circuit breaker at the sending end, or are cleared in any case by the follow-up manual reclosure by the operators of the HV/MV substation, as usual for the transient faults of conventional MV lines.

Advantages

The SWS provides a convenient means of supplying loads at long distances from available MV networks but nearby to the transmission line and has the following distinct advantages:

Costs
The cost of the MV component is minimal, as conductors and supports are already included in the transmission development. The only additional cost of the MV line is the insulators (along with a minor increase for its installation costs). Cost analysis in a number of cases where electricity supply has been provided to villages along transmission line routes has shown that the investment for making electricity available at MV with the SWS to these communities is only 10–15 % of the cost of the conventional solution using long independent MV lines of the same rated voltage.

Voltage drop
The larger cross section of the shield wires – compared to MV lines on traditional supports – allows for reduced voltage drops and lower losses, thus enabling a larger flow of power than would be possible under traditional MV lines.

Environmental impact
The SWSs do not increase the impact on the environment of the HV line. An independent MV line – often requiring a different route – requires a new right-of-way with added environmental impacts.

Mountainous Terrain
A particular area in which SWS has a distinct advantage is in mountainous terrain. In such areas, the transmission line is erected using a more direct path often with spans from hill top to hill top, whereas traditional MV lines would need to be erected along curving roadways along mountain contours. The longer routes of the conventional MV lines add to the construction costs and increase the voltage drop and losses of the line. This advantage has been put to good use in Laos in a number of remote hilly regions.

Support of local communities
The system can also be conveniently used to supply village areas along the transmission route thereby gaining the support and cooperation of the villages in these areas. Often such cooperation is crucial in large hydropower development schemes, as the local communities feel that their resources are being utilized and expect to receive some of the benefits of these mega schemes. In the absence of such SWS arrangement, the long distances

involved in building alternative MV lines often makes it near impossible to serve the affected communities. Securing such cooperation will also prevent vandalism of tower components which also has been a major problem in developing countries.

Upgradability

After several years of SWS operation along a long HV line, the construction of a new HV/MV transformer station at an intermediate point of the HV line may be justified. This may even serve a largely increased load of a town initially supplied by SWS. In such a case, the initial SWLs can be split to shorter SWLs supplied from the original and new grid substations. This will enable a larger loading capability of the SWLs including supply to other towns along the SWL.

Furthermore, when a town served by SWS is converted to a conventional three phase supply, the pole lines used between the transmission line and the supply area, MV/LV transformers and the LV reticulation can continue to be operated with only minor changes on the MV supply equipment. Hence pre-electrification by a SWS will enhance and assist further upgrade when the overall supply system is upgraded.

Figure 9 SWS 161kV transmission line with two insulated shield wires in Sierra Leone

Experience with SWS

The SWS was **first implemented in Northern Ghana** in the 1980s to provide electricity supply to small communities which were in close proximity to the transmission line. Currently about 30 communities and over 10,000 consumers are served by SWS in Ghana. The towns to be served can be as far as 100 km or more from the supply substation. Many of these schemes have been in operation for over 15 years, thus proving its robustness and operational efficiency.

- **Ghana:** About 1000 km of 161 kV–50 Hz lines have been equipped with SWS.
- **Brazil:** Three phase 34.5 kV SWSs have been in operation since 1995 in a 230 kV–60 Hz line.
- **Laos:** Single phase SWSs are in operation since 1996 in 190 km of 115 kV–50 Hz lines. Three phase 34.5 kV SWSs are in operation since 2002–2003 in 335 km of 115 kV lines.
- **Sierra Leone:** A three phase 34.5 kV SWS is in operation since 2010 in the first 161 kV–50 Hz line built in the country.
- **Togo:** Three phase 34.5 kV SWSs are in operation in 265 km of 161 kV–50 Hz lines. One of the shield wires is an insulated OPGW.
- **Burkina Faso:** Three phase 34.5 kV SWSs are in operation in 330 km of 225 kV–50 Hz lines. One insulated shield wire is an OPGW.

Further Reading

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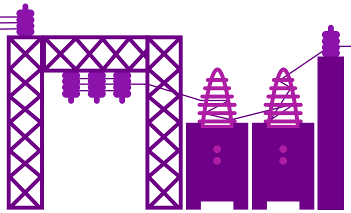

2.4 Supplying Three Phase Loads

MV single phase networks enable rural areas to be supplied at optimum cost. However, in such situations **the supply of three phase power to small industries** has been a major challenge. This deficiency has been a major stumbling block to the widespread use of single phase lines in many developing countries. In some instances public authorities were forced to convert the single phase networks to three phase within a short time of the commissioning of the systems at considerable cost due to public protests and demand for three phase supply.

Many areas benefiting from rural electrification have seen the development of small industries, initially with the conversion of a few existing diesel engine powered industries to electricity and thereafter the gradual proliferation of a number of new industries. In fact the existence of a few diesel engine powered agricultural or industrial applications in a village indicates a higher economic level and a greater potential for an economically beneficent rural electrification scheme. The lower cost of grid-based power – compared to diesel-generated electricity – enables rural industries to become competitive and leads to the gradual economic development of the area. Hence all efforts need to be made to ensure that the power supply needs for productive use of energy are addressed.

There are large capacity **single phase motors** which can satisfy loads of 20 kW more. However, unless the demand reaches a sufficient critical mass, the facilities for securing such motors often remain out of reach of the rural industrialist in developing countries. Phase converters are also available for consumers supplied off a single phase line who require three phase power. In general, however, there is the problem of maintenance of the new type of motors and the durability of the available phase converters.

Further Reading

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Technical considerations

Three phase motors are more efficient, have a better starting torque, are smaller in size for comparable power output and involve lower cost than single phase motors. However, if the added cost for obtaining three phase service is also taken into consideration (i.e. added service connection costs and internal installation[7]), the capital costs are often lower for a single phase solution. Hence it is preferable to seek out avenues of **retaining the single phase network** development while providing alternatives for consumers requiring power for higher motor loads.

Use of large single phase motor sizes
Single phase motors can be effectively used for small industrial loads at much larger capacities than currently applied in most developing countries. Usually there is a good supply of single phase motors up to about 5 kW. The upper limit for availability of single phase motors can be treated at about 15 kW in most countries. Written-pole single phase motors are available over 20 kW up to 60 kW, but usually not readily available in developing countries. In addition, increase in size of single phase motors results in higher cost of the motors and lower efficiencies relative to three phase motors of the same capacity. It may be noted that attempts are being made in some countries to locally manufacture efficient high capacity single phase motors, e.g. by Witwatersrand University in South Africa.

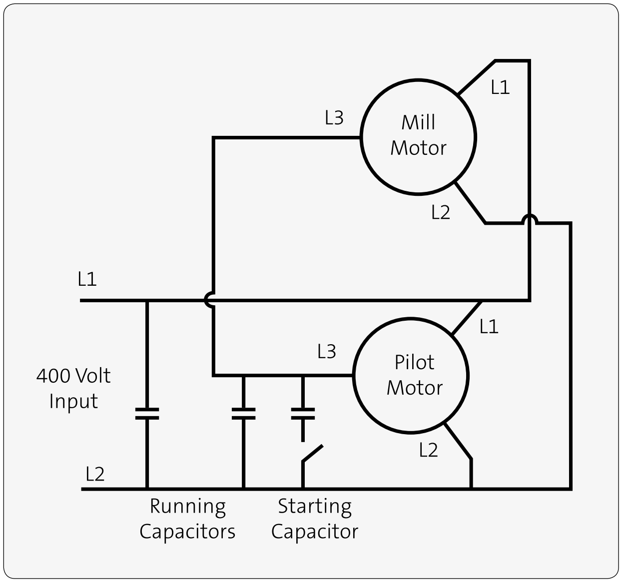
7) This does not include the added costs to the utility of upgrading the system to three phase which will be substantially more that the costs to the consumer

Phase converters
The use of phase converters has been the traditional approach to larger capacity motive power in countries that have extensive single phase networks, such as the United States. The insistence of the electrification authorities in South Africa and Tunisia on providing only single phase power in rural areas has also led to the development of a local industry for phase converters in these countries.

Phase converters work on the principle that 3-phase motors can be started **using a capacitor in series**, with the third terminal of the motor to create a phase shift. Phase converters usually employ two capacitors – one for starting, and the other for running conditions. The starting capacitor is in series with a voltage sensing relay, and is switched off when the motor is running. The running capacitor is sized to balance the voltages at one particular load rating (generally around 50 % full load). Since the running capacitor is fixed, the voltage balancing at either end (near 0 % and 100 % full load) is quite poor. Without a running capacitor, a static converter produces about 50 – 60 % of the name plate power. When a running capacitor is added, the rated power goes up to around 70 %. In practice, motors should therefore be derated to about two-thirds of the stated power, unless they operate only for short periods when heating effects will not play an important part.

A **static converter** is the simplest of the phase conversion technology; including only the capacitors and the starting relay. It is applied to the terminals of the given 3-phase motor.

Figure 10 Schematic diagram of a rotary phase converter



Source: Jim VanCoevering, NRECA

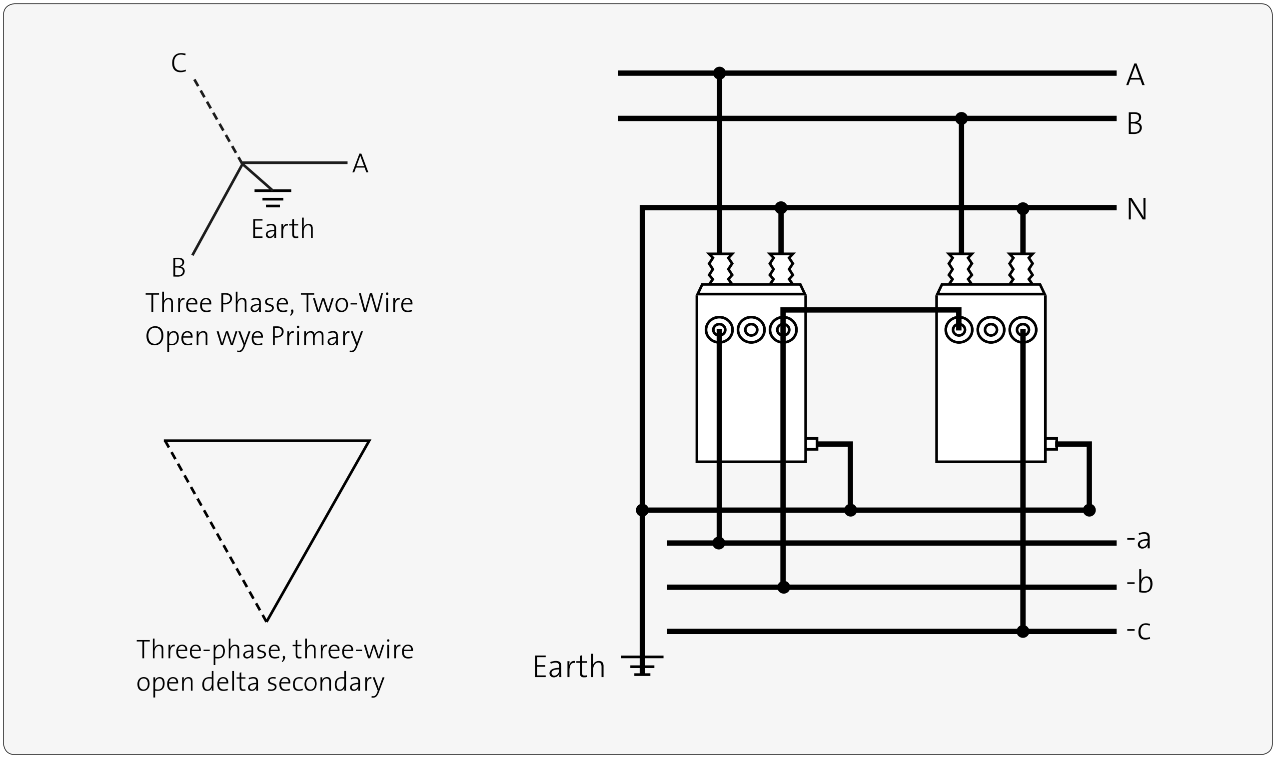
A more superior technology is the **rotary converter**: A pilot motor is provided with the starting and running capacitors; the three phase terminals of the pilot motor provide three phase power to one or more three phase motors that are to be operated. Rotary converters achieve a better voltage balance and can be used very efficiently for most common applications found in rural areas. They are rated for the maximum motor load that can be carried. They also have the advantage of being able to power more than one motor appliance off the same pilot motor.

However, when using rotary phase convertors, the **quality of power** does not equal a fully balanced three phase supply: starting torques may not be of the same quality, and the voltage balance is not uniform over a wide range of operation. Further, the supply voltage should be 400 V which requires a separate step down transformer (such as 19 kV/400 V) along with a 400 V/230 V transformer for the lighting load. The pilot motor capacity may be about 125 % of the expected motor load at the premises. Phase convertors will also create an additional inductive load – using power factor correction capacitors across the single phase input terminals when supplying large loads can counter this issue.

Digital solid-state phase converters are the latest advancement in phase converter technology. This state-of-the-art technology uses a digital signal processor (DSP). The DSP continually and immediately monitors the phase conversion process, adjusting the input and output of the converter to maintain balanced power to all three legs under all variable load conditions. These phase converters enable excellent starting torque and are also maintenance friendly as they have no moving parts.

The most demanding applications for a perfectly balanced three phase supply comes from computer numeric control (CNC) machines which are used in special applications. The digital solid state phase converters are the ideal solution for such applications which produce widely variable current demand from the three-phase power supply. Such specialized applications are however rarely encountered in rural loads of developing countries.

Figure 11 Open Wye – open delta transformer connection



Source: Jim VanCoevering, NRECA

Open wye – open delta transformer connection

When two-phase MV supply is available, it is possible to create an LV three-phase supply by connecting two transformers in an 'open wye-open delta' formation and using an earth return. A schematic diagram for this connection is given above.

In order to facilitate this connection, the transformers should be 33 kV/400 kV – unlike the 19.2 kV/230 V units normally used in a phase-neutral system, or the 33 kV/230 V units used in a phase-phase system to provide single phase lighting power at 230 V. Hence when constructing an open wye – open delta transformation, a separate transformer 400/230 V needs to be used to supply the lighting load at the premises. Thus when this technology is used there will be (i) a 400 V three-phase three-wire motor load circuit, and (ii) a separate 230 V single phase power supply to the premises. Each supply also needs a separate meter.

Recommendations

At a recent study for pilot rural electrification schemes carried out in Tanzania, NRECA consultants have recommended the following strategy for addressing the three phase load requirements experienced in rural areas:

- For motor loads of 5 kW or less: Use single phase 230 V supply. The cost difference between single and three phase service drop does not make a three phase solution more cost effective to the consumer and the supply of single phase motors up to 5 kW can reasonably be achieved.
- For loads larger than 5 kW: Use phase converters to convert single phase power to quasi-three phase service to power standard 400 volt three phase motors.
- To secure a well-balanced three phase supply to meet larger motor loads: Use phase-phase, two wire MV laterals and open wye-open delta transformer connections.

The above can be a reasonable approach to resolve the issue of three phase loads in rural electrification schemes. However, the situation in each country needs to be examined in the context of the expected motor loads, the availability of equipment and consumer preferences. Further, it may be noted that consumer education and facilitation of available equipment is an essential part of a sustainable rural electrification programme.

2.5 Comparison of Distribution Technology Options

A summary of the main characteristics along with the respective advantages and disadvantages of various options for distribution system development to feed low density rural loads are indicated below:

The selection criteria of low cost distribution alternatives for rural areas can be summarized as follows:

- **SWER** is best applied when the load density is sufficiently small and expected load growth rates are not high enough to need an upgrade of the system in a few years.
- **SWS** offer the best solution to reach remote areas where access through a transmission line is readily available.
- **Single phase laterals** (Phase-Neutral or Phase-Phase) are most suitable for application when the load density does not allow the lower cost MV distribution options described above. The new development may include a three phase backbone or the single phase laterals can be tapped from existing three phase lines.
- **Three phase backbones and laterals** is standard technology; applicable when the load density is sufficiently high.

Table 2 Comparison of distribution technologies

Characteristic	Single Phase	SWER	SWS	Three Phase
Load supply capability	Ph-Ph: 2 x Ph-N	≈1.5 x Ph-N	Substantially more as conductor cross section is higher	6 x Ph-N
% Voltage drop as times 3-Ph drop	Ph-N: 6 times Ph-Ph: 2 times	≈4 times	Small	1
Investment costs as ratio of 3-Ph cost	About 70 % to 75 % of 3-Ph (inclusive of LV network savings)	Less than 40 % of 3-Ph lower cost depending on terrain and use of longer spans	No significant MV cost at close proximity to Transmission line	1
Usual MV Voltage ranges used in kV	Ph-N: 19.05, 12.7 kV Ph-Ph: 33, 22, 11 kV	19.05, 12.7 kV	Usually around 33 kV	33, 22, 11kV
Issues related to selection of technology	Ph-N will need a 4 wire MV system Ph-Ph can conveniently be extended from a 3 wire MV	Earthing system design needs special attention. Precautions need to be taken for theft and vandalism of the earthing system	Supply locations need to be close to transmission line	Standard technology
Use of single phase transformers	Possible	Possible	Possible	Possible
Use of three phase transformers	Ph-N: Not possible Ph-Ph: Possible with openY – openΔ	Not possible	Possible with 3-Ph SWS	Possible
Countries with successful application	USA, Canada, South Africa, Tunisia, Philippines, Thailand, Bangladesh, many south American countries	New Zeland, Australia, Brazil, South Africa, Tunisia	Ghana, Laos, Brazil, Togo, Bakina Faso	Widely used in all countries

Note: The comparison is on MV systems. Single phase includes both Phase-Neutral (Ph-N) and Phase-Phase (Ph-Ph). Three phase is indicated as 3-Ph. Load supply capabilities and voltage drops expressed in approximate terms as these will vary with conductor sizes used. The load transfer ratios are based on the use of the same conductor size and voltage drop is computed based on the same power transfer.

2.6 Related Design and Construction issues

This handbook focusses on the selection of appropriate low cost supply technology options. However, once a technology option is selected and when designing a network, attention should also be given to other design and construction issues that might result in appropriate cost reduction. While there are many opportunities for such cost optimization in the practices followed in developing countries, the main areas which may be focussed on are briefly indicated below:

Selecting appropriate spans: Often line spans are arbitrarily selected, due to past practice or even the economic interests of contractors; and therefore often result in over-investment. Limiting the number of line supports and associated pole top hardware can result in substantial cost reduction. If needed, high strength conductors with greater steel wire content should be selected to increase the line spans.

Selecting appropriate conductor sizes: Often standardizing on conductor sizes (e.g ACSR 100 mm² in many African utilities) has unnecessarily increased costs in rural areas. The conductor sizing should be determined with careful consideration of the load to be carried (inclusive of future needs). Furthermore, the function of the line (i.e. backbone or lateral) needs to be considered.

Minimizing of LV networks can yield substantial cost reduction. For this purpose, small single phase transformers can be used together with an increase of the MV laterals at lower conductor size. The single phase transformers used are often in the range of 5, 10, 15 and 37.5 kVA. These transformers can also be 240/480 volt split type if justified by the load to be supplied. The LV networks could also be constructed with lower gauge covered conductors (areal bundled conductors – "ABC" or "airdac") which is facilitated by the use of smaller size transformers.

Cost optimization of grid extension in Benin

In Benin's rural electrification programme, substantial cost savings for grid extension were achieved through an optimised approach, including

- optimisation of conductor sizes and strand mix (Aluminium/steel),
- optimization of design spans,
- use of LV bundled cables with a small cross-sectional area,
- use of wood poles for straight lines and small angles,
- reduction of the minimum ground clearance for stranded LV conductors, and
- construction of mixed MV/LV lines with intermediate poles.

The cost savings associated with the measures above enabled a substantial increase of the initial connection target with the same budget.

Further Reading

ESMAP (2006). World Bank Energy Sector Management Assistance Program (ESMAP) Technical Paper 104/06: Sub-Saharan Africa –Introducing Low Cost Methods in Electricity Distribution Networks. Available online at http://www-wds.worldbank.org/servlet/WDSContentServer/IW3P/IB/2007/11/21/000310607_20071121120956/Rendered/PDF/415990AFR0Elec1n0ESMAP010401PUBLIC1.pdf

Club-ER (2014). Benin: Cost optimisation of grid extension for rural electrification. Best practices of CLUB-ER's Members. Available online at http://www.club-er.org/index.php/en/ressources-et-forum/ressources-documentaires/viewdownload/88-les-bonnes-pratiques-du-club-er/701-benin-cost-optimization-of-grid-extension-for-rural-electrification.html

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3. Low Cost Transmission Expansion[8]

A particular challenge for rural electrification in sub-Saharan Africa is the vast extent of the territory to be covered, combined with dispersed loads of relatively small quantities. These characteristics have made the application of the technologies usually adopted for transmission extensions highly uneconomical. In the previous chapter, the inappropriateness of the traditional methods used for developing distribution networks have been discussed along with appropriate alternative technologies that serve the particular characteristics of low load density rural areas. A similar problem exists with respect to extensions from the transmission network and associated grid substations. This chapter will deal with appropriate technologies for cost effective design of the transmission system extensions to meet low density rural loads.

Currently in most developing countries, transmission grid expansions to serve rural loads are based on the same **standards used for the main transmission network**, developed for a high reliability system with:

- Steel tower line construction
- High reliability substations often with double bus bars
- Non acceptance of spur lines
- Back up transformer capacity with an additional transformer to meet outage of any one unit
- A high level protection philosophy necessitating the use of station batteries.

These robust and high reliability systems are needed for a national transmission grid and to serve major urban loads taking account of the economic importance of the loads served. **Rural loads** however involve different requirements:

- The priority is to enable economic transport of bulk power over long distances while meeting technical standards of voltage drop and line losses.
- The lines do not need to be as robust and fail proof as used in urban areas; greater supply interruptions in an emergency may be tolerated.
- Alternative feeding arrangement – when one item in the network is lost in an outage (the N-1 philosophy) – is usually not required for rural loads.

Another aspect is the **limitation of MV networks** in meeting the long distances needed to serve rural areas. In the absence of appropriate standards for low cost rural transmission line extensions, many countries have extended MV lines over inappropriately long distances, resulting in poor voltage profiles. Further, extensions to feed adjacent towns and settlements are also not possible and addition of new loads over time makes these MV lines unusable in a few years due to further degradation of the voltage. Often MV extensions have been constructed from a number of adjacent grid substations to feed an area intermediate between these grid substations, while still being incapable of serving the developing load.

8) This section is prepared using information in the presentation of Mr. Jim VanCoevering of the National Rural Electric Cooperative Association (NRECA) International, at the Arusha workshop on September 3rd – 4th 2013. The presentation is available at http://euei-pdf.org/dialogue-events/aei-workshop-on-low-cost-on-grid-electrification-technologies

The concept of **reliability of power** supply has often been confused with voltage level. In the general case it is correct that reliability of supply should increase at each higher supply voltage; i.e. from Low Voltage (LV, 230 V) to Medium Voltage (MV, 11 kV and 33 kV) to High Voltage (HV, 132 kV, 230 kV etc). However, this is due to the fact that at each higher voltage level the load served and the area covered is greater. A more thoughtful assessment of the required reliability levels should take into account the amount of load served, the economic impact of outages (e.g. industrial loads served) and non-tangible aspects such as security (strategic nature of locations served, lighting requirement for roads and public places, police stations etc.) and public service (hospitals, government installations). From this point of view the reliability level requirements of a rural 132 kV line should be equivalent to or even lower than that of an 11 or 33 kV network which serve more dense urban areas. It must be remembered that, in the context of supplying such rural loads, the issue is often between the provision of a power supply at an acceptable reliable level and reasonable costs vs. no supply at all.

The problem at hand can thus be summarized in the following terms:

- There are numerous rural loads at considerable distances from existing grid substations which are too small to economically justify the use of currently used standards for transmission lines and grid substations.
- MV lines cannot meet the voltage requirements posed by long distances and possible load additions in the course of time.
- The economic choice is often between supplying electricity at reasonable cost with standards of reliability and supply conditions lower than that of urban areas versus no supply at all.

Transmission lines in the USA

Rural electrification schemes in the USA have successfully refrained from using urban standards when extending transmission lines and substations to serve rural areas. Wooden poles lines at 138 kV and 161 kV are standard practice. Rural substations are also built using simplified techniques at reduced reliability levels.

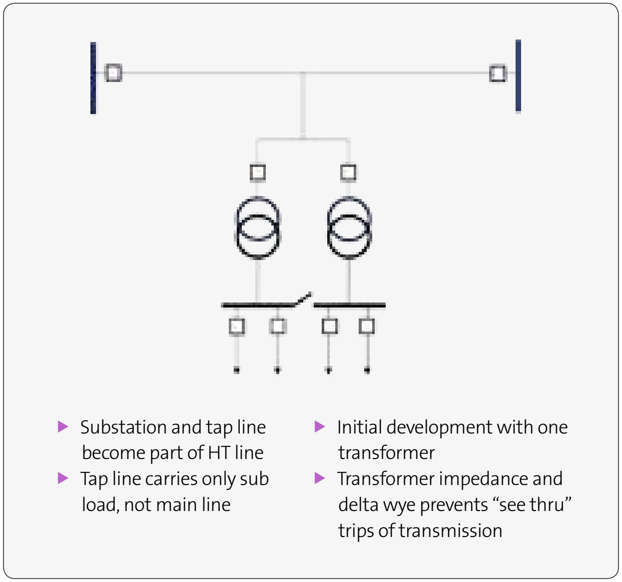
3.1 Low Cost Transmission Lines

When the highest distribution voltage (usually 33 kV in sub-Saharan countries) is insufficient to meet present and expected near term future loads of unserved areas, transmission extensions need to be built if supply is to be provided. In view of the smaller loads and lower reliability demands, some of the standards used for urban areas can be relaxed. The resulting lower costs will also satisfy the economic justification for provision of such supply to far-flung rural areas. The following techniques have been successfully applied in the USA and elsewhere under similar circumstances:

Short tap lines off existing transmission lines
In certain instances, it is possible to tap an existing transmission line passing through the area to be served. The new substation can then be fed using a short spur line. This application is ideal for use when the nearest grid substation is at a considerable distance as it reduces the costs of new HV bays and long transmission lines to feed the new substation. Such **intermediate substations** can also be used to reduce the line lengths of MV coverage of adjoining grid substations.

When this method is used, the short tap line and the HT bus of the substation effectively become part of the main transmission line. In most situations this would increase the risk of outages for the rural substation – compared to a substation fed from a dedicated transmission line. The reliability of the transmission line itself serving other loads is not appreciably affected if the spur line is small. Thus, the trade-off should be acceptable for supplying rural loads, particularly where substantial cost reductions are possible.

Figure 12 Example of use of tap connection off a transmission line



Source: Jim VanCoevering, NRECA

Distance protection zoning

When using the above line tapping option, distance protection zoning of the particular transmission line needs to be addressed. The tapping point should be within zone 1 (usually about 90 % of the line length) of the distance protection schemes from both ends to enable speedy clearance of any fault on the spur line or substation. However, this should not be a problem as there is usually adequate MV capability within the 10 % of line length from an existing substation to feed any new rural area and no new grid substation is required at such close proximity.

The HV/MV transformer impedance should be high enough to prevent the zonal relay reaching past the transformer to the MV side. This again is not a problem particularly for the smaller size transformers used for rural grid substations. The spur line distance should also be kept within limits so that it is well covered by the zonal relay. Additionally, any faults of the HV equipment up to the transformer (such as surge arresters, disconnect switches, circuit breakers) are included within the zone. However, failures of such equipment are expected to be extremely infrequent to cause any impact on the performance of the main transmission line.

Selection of line supports

Usually transmission lines are built with lattice steel towers and are of a robust construction. They are designed to be rigid and therefore have catastrophic failure modes. A tower failure results in a complete destruction; restoration involves a complete reassembly of a new tower and takes considerable time. For this reason the factor of safety is also high. However, the high safety factor also increases costs. While this is acceptable for the main components of a national grid, the practice is uneconomical in rural areas. It is therefore appropriate to consider various alternative forms of construction which provide the level of reliability appropriate for the low density rural areas while keeping the costs down to acceptable levels.

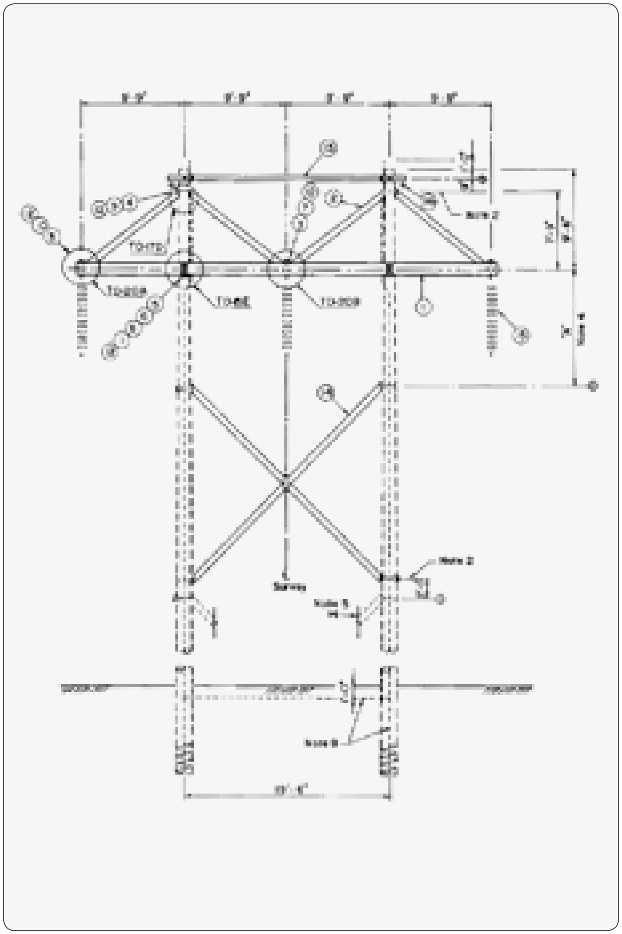
In the USA, transmission lines of 69 kV, 115 kV, 138 kV, 161 kV and even at 230 kV are regularly constructed using poles for line supports. These can be wood, concrete or steel poles. The supports could be single poles or double pole structures with or without the use of bracings. Stays are used for angle positions and dead ends.

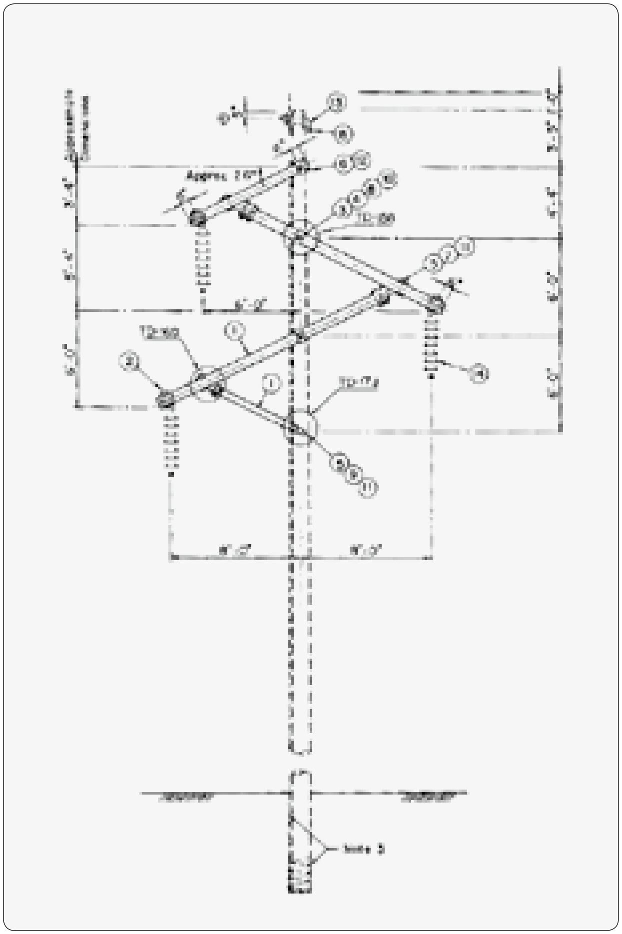
Wood poles used in the USA

Species used for wood poles in the USA are mainly Western Red Cedar, Northern White Cedar, Douglas Fir, Larch and Southern Pine. The clearances to ground for 138 kV transmission lines in the USA practice is 23.1 ft. along roads, and driveways accessible to vehicular traffic while it is 19.1 ft for areas accessible only for pedestrian traffic. Thus 138 kV lines can easily be built with poles of the order of 50 or 60 ft. Well-developed preservative treatments, specification of minimum retention levels and testing regimes specified in the US practice have enabled these poles to be used on transmission lines for life spans of over 50 years. The specifications also require deep incision or radial drilling to reach a minimum depth of preservative penetration to reach the sapwood, particularly for the area around the intended ground line (up to 2 ft above and 4 ft below the ground line) to ensure extended usage in service. However, such high quality wooden poles would need to be imported to Africa from USA, Norway or Sweden. The cost of such imported wooden poles would still be lower than the cost of steel towers.

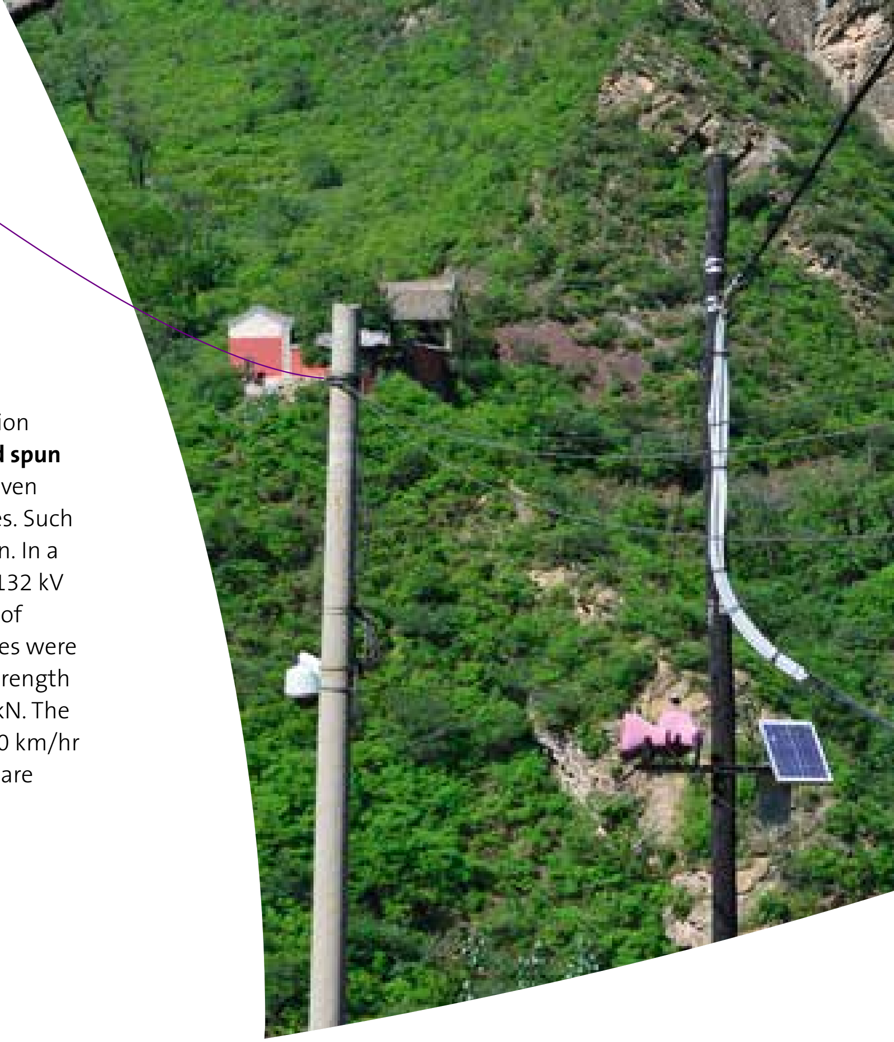
It may be noted that Bangladesh imported wooden poles from the above countries for distribution lines for a considerable period (until pre-stressed concrete poles became locally available) with very successful results for longevity in service.

Figure 13 and 14 Examples of pole configurations used in the USA:
230 kV H-pole construction (left) and Tangent Wishbone Double Arm for 115 kV (right)





Source: U.S. Department of Agriculture, Rural Development agency, http://www.rd.usda.gov/files/UEP_Bulletin_1728F-811.pdf



A feasible and convenient alternative for transmission line supports are **locally manufactured pre-stressed spun poles**. These poles can be manufactured in two or even three sections which can be joined by bolted flanges. Such multi-section poles also lead to ease of construction. In a recent study[9] on possible use of concrete poles for 132 kV rural transmission lines in Bangladesh, two classes of 20 m long double section pre-stressed concrete poles were recommended for use; one with a rated breaking strength (RBS) of 13.8 kN and the other with an RBS of 16.8 kN. The recommended design spans for wind loading of 200 km/hr for (i) single pole and (ii) double pole X-braces lines are given on Tables 3.1 and 3.2.

9) The study was carried out by National Rural Electric Cooperative Association (NRECA) International Ltd of USA.

Table 3.1 Maximum spans for single concrete pole 132 kV lines for wind speeds of 200km/hr

Conductor size	Conductor code	Pole length and class	Structure limit span in meters	Level ground limit span in meters
4/0 ACSR	Penguin	60ft/N1	90	106
336.4 MCM ACSR	Linnet	60ft/N0	94	105
477 MCM ACSR	Hawk	60ft/N0	90	99
636 MCM ACSR	Grosbeak	60ft/N0	89	88
795 MCM ACSR	Drake	60ft/N0	94	80
954 MCM ACSR	Cardinal	60ft/N0	87	75

Source: NRECA International study carried out in Bangladesh for concrete pole 132 kV lines

Table 3.2 Maximum spans for double pole X-braced concrete pole 132 kV lines for wind speeds of 200km/hr for wind speeds of 200km/hr

Conductor size	Conductor code	Pole length and class	Structure limit span in meters	Level ground limit span in meters
4/0 ACSR	Penguin	60ft/N1	202	418
336.4 MCM ACSR	Linnet	60ft/N1	210	371
477 MCM ACSR	Hawk	60ft/N1	209	338
636 MCM ACSR	Grosbeak	60ft/N1	208	311
795 MCM ACSR	Drake	60ft/N1	213	291
954 MCM ACSR	Cardinal	60ft/N0	202	277

Source: NRECA International study carried out in Bangladesh for concrete pole 132 kV lines

3.2 Low Cost Grid Sub Stations

The cost of rural grid substations can be substantially reduced in a number of ways without adversely affecting its major functional requirements. Most grid substations constructed exclusively or partially to supply rural areas would be with a high voltage (HV) supply of 132 kV. While some systems at 66 kV exist; higher voltages of 220 kV etc. are not used in sub-Saharan Africa as this voltage is normally used for bulk power transmission (e.g. from large generation plants to major load centres). A number of possible measures for cost reduction of HV grid substations to feed rural areas are presented below:

Omission of HV line circuit breakers and HV bus bars
Most rural grid substations are fed from a HV line that terminates at the substation. Alternatively, a short HV spur from an existing transmission line can be constructed to feed the substation (as aforementioned under transmission lines). In both instances, a rural substation can dispense with HV line circuit breakers and a complex bus bar arrangement with separate bays for each line and supply sections, as the requirement is a simple step down transformation to feed a few rural MV lines. The substation design can thus be simplified by including only the connection to the transformer with a circuit breaker, or circuit switcher for each substation transformer, leaving out the HV line breakers and bus bar arrangements.

Circuit switcher
A circuit switcher is essentially a lower fault current rated circuit breaker. In the USA it is also called a 'candlestick' breaker in view of its vertical construction. Such light duty breakers are available with interruption ratings upwards of 25 kA and can be obtained at lower cost than the more common standard circuit breakers which have fault ratings of over 40 kA. Due to the low fault levels generally present in transmission network peripherals that supply rural areas, it is possible to use breakers of lower interruption ratings with lower costs. Thus, it is advisable to determine the applicable fault ratings at the particular site before making a choice on the circuit breaker to be used.

Figure 15 A 132 kV disconnect switch

Omission of MV side circuit breakers
The MV side breakers for each transformer can also be omitted and switching affected by the HV side circuit switcher or breaker. Each outgoing MV feeder can be protected with reclosers at lower cost than a conventional circuit breaker.

Protection arrangement
The protection arrangement for a simplified rural grid substation can be carried out as follows:
On the HV side, the current transformers of the power transformer is used for sensing differential and over-current (as back up) protection, and operates the circuit switcher for the transformer.
In the MV side too, the current transformer in the power transformer acts as the input for both over-current and earth fault protection on the MV bus, and acts once again on the transformer circuit switcher. The circuit switcher is of live tank design and contains no current transformers.

Omission of a second transformer
The usual practice of having two transformers to enable an outage of one to be picked up by the other (N-1 reliability for transformers) may be dispensed with. Transformer failures are very rare, particularly with lower loaded transformers to be expected in a rural setting. In the unlikely event of a transformer winding short circuit, the outage will last until a fresh transformer can be transported and installed at site. In order to cope with such a rare event it would be more economical to retain a couple of extra transformers of similar rating for the entire utility rather than duplicating transformers at each grid substation.

Voltage regulation
Transformers in rural networks do not need to be fitted with on load tap changers (OLTC). To address any HV system voltage drop, the transformers can be supplied with off-load tap settings; supply can be interrupted momentarily for the purpose of voltage control on the LV side. Free standing MV (usually 33 kV) single phase voltage regulators are also available and could be installed as needed. When installing a new rural grid substation it is preferable to keep a space provision for such voltage regulators to be used if the need arises when the load develops.

Service and maintenance
The substations can be unmanned units obviating the need for a substantial complement of service personnel as well as facilities such as water and sewer services. A localized system control and data acquisition (SCADA) system could be installed to communicate loading information and provide alarms for breaker trips etc., which can be attended by trouble call teams.

Figure 16 Low cost grid substation in Tennessee, USA

Small capacity integrated substations

A promising development that offers great potential for provision of supply to remote villages near a transmission line are pre-fabricated mini-substations with built-in features of a circuit breaker, disconnector, current transformer and surge arrester. Based on the design concept of a voltage transformer, these units were first developed to provide station supply to remote HV switching stations without power transformers, and for special applications such as mining sites and pumping stations close to HV lines. They are available at various capacities from ratings up to 500 kVA. The secondary voltage can be MV (33 or 11 kV) or LV (240V). All the key features of a substation are integrated to a single maintenance free unit which can be installed in a few days.

Figure 17
Integrated low capacity voltage transformer type substation.

Source: ABB publication "TIP (SF6 Station Service Voltage Transformer)"

Further Reading

USDA (2001). Design Guide for Rural Substations. Rural Utilities Service (RUS) Bulletin 1724E-300. Available online at http://www.rurdev.usda.gov/supportdocuments/uep_bulletin_1724e-300.pdf

USDA (2011). RUS Specifications for Wood Poles, Stubs and Anchor Logs. Rural Utilities Service (RUS) Bulletin 1728F-700. Available online at http://www.nreca.coop/wp-content/uploads/2013/11/UEP_Bulletin_1728F-700.pdf

USDA (1998). Electric Transmission Specifications and Drawings, 115kV through 230kV. Rural Utilities Service (RUS) Bulletin 1728F-811. Available online at http://www.rurdev.usda.gov/supportdocuments/uep_bulletin_1728f-811.pdf

4. Maximizing Connections

A key objective of any rural electrification scheme should be to connect as many households, commercial establishments and industrial users as possible in the electrified area – the final goal is increasing electricity access rather than building lines. However, in many sub-Saharan African countries connection rates remain low in completed rural electrification schemes; many houses and small shops within reach of the lines remain unconnected.

Barriers for increasing the number of connections in completed rural electrification schemes include:

- restrictions imposed on dwelling types;
- high investment costs of service connections;
- limited consumer access to financing needed for connection charges and internal wiring; and
- logistical hurdles faced by consumers in obtaining a service connection.

4.1 Restrictions on Dwelling Types

In many sub-Saharan countries, electricity connections are restricted to households constructed with permanent materials, such as brick and mortar, and often require permanent roofs. Low-income households usually apply less stable construction materials, such as mud walls and thatched roofs. This **limits access to electricity** for the poorest share of rural households, often the female headed households, due to substandard housing. The rationale often used for these higher standards is that providing electricity to such households can cause fire hazards from electrical short-circuits. This however ignores the hazards of alternatives normally used – kerosene and candles – which present a larger fire risk than from electricity supply.

Figure 18 Thatched house provided with safe electricity connection in Namibia: A short wooden pole is used for the ABC service dropper and a shorter pole is installed inside the house to mount the ready board and meter. Alternatively the meter can be fixed on the outside pole.

Using **appropriate technologies** can guarantee the safe use of the electricity supply in such households (*Figure 18* left). Supply can be provided by a safe ready board fixed securely to the inferior building materials or on a separate short pole inside the house (if the wall material is not dependable) without incurring undue risks. The ready board could be a simple wooden board on which is mounted a Miniature Circuit Breaker (MCB), a plug outlet and one or two switches for lights. In some instances utilities have been making this item complex leading to higher costs defeating the objectives of its use; hence particular care is needed in this respect. Also insulated conduits can be used for the service wire entry and along the sub-standard wall ensuring a safe system. It is recommended that any restrictions on dwelling types be removed and safe supply of electricity provided at reasonable cost to such houses, thus ensuring the increase in the access rate from completed schemes.

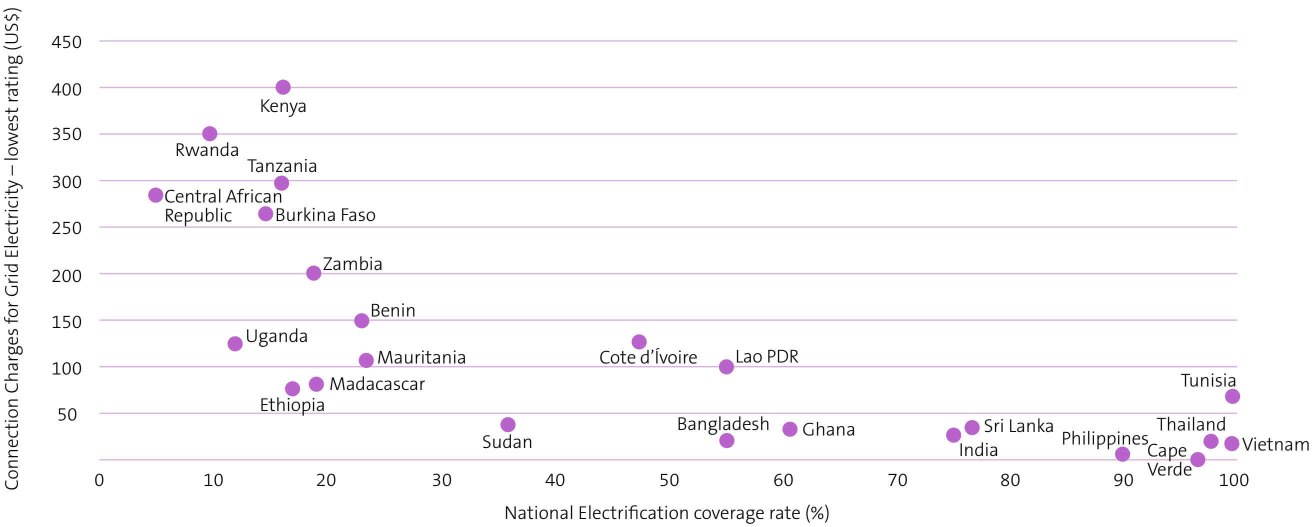
4.2 Reducing Service Connection Costs

In many sub-Saharan African countries, charges for service connection in rural areas are disproportionately high and often constitute the main barrier for increasing the connection rate. A recent study carried out by the World Bank examined the relationship between service connection charge and access rates of a large number of countries. The cost for the smallest rated consumer service is often of the order of USD 100 to 300. These costs are in stark comparison to connection rates in South and East Asia and South America which range from about USD 10 to USD 75. The strong inverse relationship of the two variables is obvious from *Figure 19* below.

The reasons for the high connection charges[10] mainly include inappropriate sizing of service connection conductors, and addition of extra charges such as testing

10) Connection charges are those that are levied by the utility in order to connect a new consumer. They do not include the costs associated with the internal wiring of the premises (which also has to be incurred by the consumer)

Figure 19 Connection charges vs. national electrification rates



Source: World Bank report 'Connection Charges and Electricity Access in sub-Saharan Africa': Raluca Golumbeanu and Douglas Barnes 2013

fees, travel and visit costs, and overheads which often exceed what could be incurred under a good practice scenario. In addition, the consumer has to incur the cost of wiring the premises which are also not optimized in most rural households. The following recommendations are made for the cost reduction of rural service connections:

Conductor sizing

The minimum standard conductor size used for rural service connections by most sub-Saharan utilities is 16 mm². This is considerably oversized for the needs of most rural households or small shops. The current carrying capacity of 16 mm² aluminium cables is of the order of 70 Amps whereas the maximum load carried is often less than 2 Amps. For instance, a consumption of 50 kWh per month with a load factor of 20 % at 230 V gives a maximum demand of 1.5 Amps. Hence minimal size service cables would suffice. Several utilities are already using 6 and 10 mm^2 cables for their lowest rated service. To enable all consumers to be adequately served, service connections ratings should be specified: e.g. 2 Amps for a load limiter based service, 5 Amps for the next tier including meters, 15 Amps and 30 Amps for the next higher tiers. The first two tiers should accommodate over 90 % of rural consumers and can be supplied with 6 mm^2 service drops. Suitable education campaigns must also be carried out to appraise the households of the number of lighting points and equipment that can be connected for each level of service.

Meters

Households with low consumption patterns can well be supplied off standard electronic or even electromechanical meters available at low cost. However, due to the reducing cost of the standard electronic meters the production of electromechanical meters have now greatly declined.

Many sub-Saharan utilities have programmes to convert the consumer metering systems to **pre-payment meters** which address problems related to revenue collections. As the higher cost of pre-payment meters is passed on to the consumer, it may prevent some consumers from getting a service in the first place. Common pre-payment meters will not offer a major safeguard against theft and non-technical losses – however, there are sophisticated 'smart' meters which provide an alarm in the event of tampering, which again involve higher costs. Further, it may be noted that much of the power theft occurs by bypassing the meter and this cannot be resolved by increasing meter complexity if the meter is located in the consumer's premises. This difficulty can be overcome by using split type prepayment meters with the meter fixed on the pole (to reduce any attempts at tampering) and the consumer console inside the house. Once again it may be noted that this will involve higher costs; a standard meter fixed on the utility pole outside the premises will offer a low cost solution to power theft.

The **selection of meter types** should therefore be madeafter an evaluation of logistical arrangements available for meter reading, the prevalent non-technical losses and the relative trade-offs – convenience of revenue collection vs. the added costs incurred. If a choice is made on pre-payment meters, a common vending system with standard transfer specification (STS) should be selected to prevent any tie-up to any particular manufacturer.

Internal wiring costs

Internal wiring costs for households can be lowered through

- the development of simple standards appropriate for rural household loads
- bulk procurement of materials facilitated by the supply authority or a local organizer
- the organization of the house wiring on a group basis.

The use of a 'ready board' can reduce wiring cost to a minimum for the poorest consumers who need only a few lamps and a plug point. Sufficient care should be taken to ensure that the standards used are appropriate to the expected loading levels of rural households. The second and third recommendations are best carried out through a third party organization such as an NGO or a community based effort embedded in the electrification programme. If such a community based effort can be mobilized the impacts will transcend cost reduction and can also lead to greater awareness and participation by consumers and an overall improvement of the connection rate.

Additional costs and fees

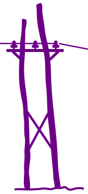
Costs such as inspection and testing charges, travel and overheads (including also the labour cost of providing the service connection) levied on rural consumers are often substantially high and act as a deterrent for securing a new connection. These costs are usually charged by utilities on the basis of the cost of vising the consumer's premises and carrying out the related work for a single applicant. Such costs can be substantially reduced by carrying out rural service connections and other related work collectively, and not on an individual basis. Such a collective arrangement is particularly effective at or close to the commissioning of a new scheme. The supply utility should carry out a publicity campaign for new connections when a new scheme is about to be completed and make arrangements for sharing the related costs among many users. On a single visit by utility personnel, a large number of houses can be tested and services provided, thus reducing the costs incurred. The procedure can also be carried out after line commissioning by giving the prospective consumer a lower rate if they wish to join a scheme to be serviced jointly with other applicants. For those wishing to obtain an expedited service (without waiting for cost sharing) the full cost of a visit for a single consumer can be charged.

4.3 Financing of Upfront Costs for Households

Several studies on willingness to pay for electricity services concluded that most households can afford monthly electricity bills between USD 3 to USD 10 per month. An electricity service will cause a considerable reduction of monthly expenditure for kerosene lighting, candles and batteries which can be used to pay for the electricity bills. However, this is not the case for the initial charge for obtaining an electricity connection. These costs, even at USD 100 per connection to be paid up-front, are a considerable burden on the poorer households. Their access to loan financing is also limited and as a result many households opt out of joining the rural electrification scheme. The problem is not related to affordability, but to financing.

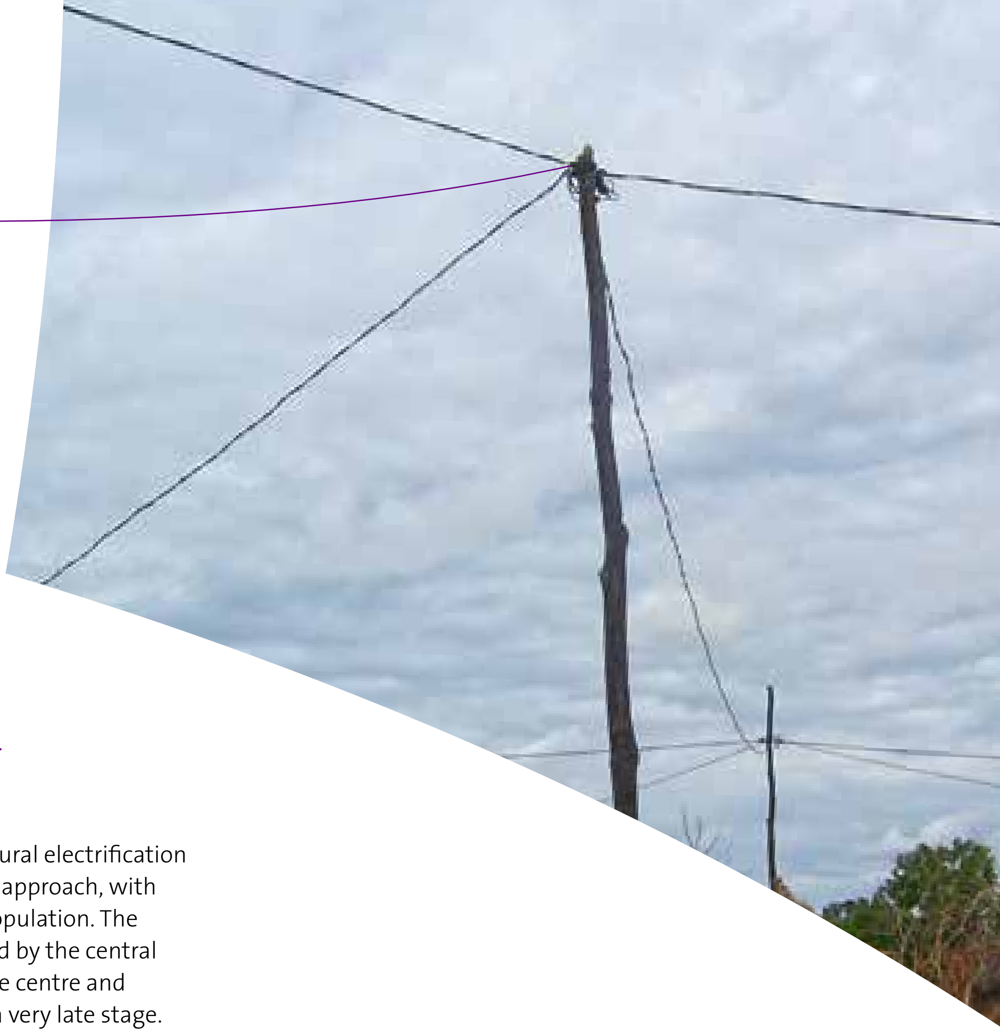
A simple solution to this problem is for the utility to finance the service connection costs; and recover it through monthly payments along with the consumer bills. If the utility finances are insufficient for such pre-financing arrangements, these costs need to be built into the project funds. The repayments received through monthly billing can form a revolving fund to continue the practice of pre-financing service connections for poorer households.

An alternative mechanism currently used in some sub-Saharan countries is to provide a direct subsidy to selected low-income households, often based on donor funding. Such direct subsidies may however distort the markets for electricity and create additional problems related to sustainability issues. Because they are limited in scope and incapable of replication after the donor support for subsidies is over, it could even fuel resentment and foment dissent among villages or households that are not selected for subsidies. Such subsidies would also invite political interference in selecting the villages that benefit from the subsidy. Since the problem of affordability is in relation to paying the full cost up front, the simpler and sustainable method of providing instalment payments is recommended instead of any subsidy mechanism.



Pre-payment programmes for service connection charges

- **Cote d'Ivoire** has set up a revolving fund that allows customers to finance 90 % of the connection charge with interest free loans over a maximum of two years.
- **Botswana:** The government offers loans to the rural customers for 95 % of the standard connection charge. The loan is payable over fifteen years at the prime interest rate.
- **Kenya:** Four different attempts to tackle upfront costs have been identified:
  - Kenya Power and Lighting Company (KPLC) has initiated a **partnership with Equity Bank** to offer connection charge "Stima loans" to all customers within a transformer radius of 600 meters. These loans carry a 30 % upfront payment and three year loan terms with an annual interest rate of 15 %.
  - In a second programme, the Ministry of Energy finances the **Rural Electrification Deferred Payment Plan**. The customers pay 30 % of the connection charge upfront and the remaining balance over 10 months.
  - A third program is based on a **revolving fund** administered by KPLC. The scheme is open to all customers and it requires them to pay 20 % upfront with the balance due over one or two years. A 2 % administration fee is charged on the 80 % balance.
  - Finally, for customers beyond 600 meter radius, KPLC offers a **group programme** called "Uneme Pamoja". The group programme enables people more distant from power company lines to finance the transformer and LV network construction. The total power company cost estimate to reach such households is divided equally among the group of customers.
- **South Africa:** One program in Cape Town allows households unable to pay the connection charge of US $24 to charge this amount to their prepayment account. This prepayment is essentially turned into a loan that is paid off when the customer pays for electricity use. For one dollar of electricity consumption, a charge of 14 cents is added to the electricity bill until the initial connection charge is paid in full.
- **Uganda:** A recent project has developed an inbuilt mechanism to secure service connection materials from project funds, collect the charges from consumers in instalments, and use the revenues to establish a revolving fund for service connection materials.



4.4 Consumer Mobilization and Education

In many sub-Saharan African countries, rural electrification programs are carried out in a **'top down'** approach, with limited or no participation of the local population. The schemes and coverage area is determined by the central authority, contracts are awarded from the centre and the local population is informed only at a very late stage. Often the organization handling construction is not the organization responsible for operation and maintenance (O&M) of the lines. In many cases, the construction authority has no responsibility to ensure that sufficient service connections are made, while the final operations unit has not been in touch with the local population during construction stage. As a result, there is a poor relationship between the power utility and the community served.

Another crucial factor is the considerable **logistical difficulty in arranging for a service connection** in many utilities. In fact, this difficulty is present even in urban areas in close proximity to the utility offices. The procedures of

Further Reading

Golumbeanu and Barnes (2013): Connection charges and electricity access in sub-Saharan Africa. Available online at http://documents.worldbank.org/curated/en/2013/06/17933875/connection-charges-electricity-access-sub-saharan-africa consumer installation testing, obtaining estimates, making payments and finally securing the service connection are often a challenging ordeal and might involve bribery. In rural areas the situation is compounded by the fact that the consumers are often unaware of utility practices and regulations, and are residing at considerable distance away from the utility offices. Often trained wiremen are not readily available in remote areas and consumers struggle to have the houses wired to the standards required by the utility. Repeated testing of the house wiring and multiple visits to the utility office also leads to higher costs and delays, often frustrating the consumer's efforts at securing an electricity connection.

These difficulties can be avoided by adopting a **'bottom-up'** approach and developing mechanisms for consultation with the local population starting at the earliest stage of planning an electrification scheme. Community involvement in all stages of the project cycle is essential for any successful electrification programme. Community participation should include local consultations, be based on local organizational structures and can involve the establishment of a community committee. Women should be represented and involved in project planning in a culturally acceptable way; not least, because women are often responsible for the household budget and, thus, often for any electricity payments.

Utilities, especially those serving rural areas, should strive to develop a good consumer relations program although it does not require the establishment of cooperatives as in the examples in the box below. Until this is achieved, a utility could appoint a **'consumer mobilization consultant'** to redress the situation. The objective of this assignment would be to provide prospective consumers with all the relevant information and assistance for securing an electricity connection. The consultant should be a local person, if possible from the community or having interests in the community, with a rudimentary knowledge regarding electricity supply issues and also be a good communicator. A list of recommended responsibilities is given below:

- **preparing documentation** for disseminating information on house wiring and service connections to prospective consumers;
- listing out and clarifying to consumers possible **alternative wiring options** (number of points and the related impact on service connection costs, the ready board option);
- **explaining service connection methodologies**, costs and procedures to consumers;
- developing appropriate **communication channels** (e.g. village level meetings) including specific communication channels to reach the low-educated, the illiterate and women;
- arranging for the **wiring of houses on a group basis:** selection of licensed wiremen, arrangements for the provision of required material by local dealers, and negotiation of respective prices for a group based supply/service;

- coordination of **service connection application forms** to be presented to the utility, having these prized, collecting the money from the consumer and deposition with the utility;
- **coordination of testing** the house wiring by the utility; and
- coordinating service connections **installation** with the utility.

Rural Electric Cooperatives in Bangladesh and the Philippines

Examples for community-based approaches can be found in Bangladesh and the Philippines, where *Rural Electric Cooperatives* have been developed to organize rural electricity supply activities. Particular attention has also been given to the participation of women. The programme has allowed for early consumer participation and process facilitation mechanisms; resulting in large number of service connections from the initial days of line commissioning.

Chapter 5: Planning of Rural Electrification Networks

The importance of a systematic planning effort in addressing rural electrification network development cannot be over-emphasized. It is a key basic activity that should be used to direct all rural electrification decisions related to choice of technology, selection of areas to be electrified and the progressive development of the power network. Rural electrification programmes that are addressed in an ad hoc manner – sometimes to utilize available funds from an external source – often result in the development of a poorly coordinated network with increased costs over the long term.

Sufficient attention has to be given to preparing overall development master plans for electrification at national, regional and local levels. Typically, these plans examine the expected load profile over a reasonable time period (say 10 to 15 years) in a particular area or region and develop the least cost network development needed to meet such loads economically in a phased manner. This approach will lead to an optimal programmed development over time. It is also crucial to review the master plan's validity periodically, in the context of changing circumstances such as load expectations and technologies available and to carry out the required updates.

5.1 Accurate Load Projection

The first step in any planning exercise is the development of a load projection over time for the given area. This is based on available information on the number of households, prospective consumers, commercial and industrial users as well as government and public institutions. Typical consumption patterns of the above-mentioned groups should be determined. This is done by information available from revenue metering as well as load measurements taken from existing consumers, feeders and substations. In this context it is important to consider information from 'similar' areas rather than use average values for the utility or region – which are often higher than that of the rural area.

In addition to data from consumer billing and substation load readings, the use of **portable load measuring instruments** is highly recommended. So called 'load loggers' can be installed at various locations in the network, including selected consumer feeding points, to measure the load at regular intervals and store this data for download when the instrument is retrieved. Some 'smart meters' also have this capability of retaining pre-set load characteristics. A well-organized planning unit collects such data at regular intervals from various consumer classes in different areas to establish a good basis of future load estimation in new areas to be electrified. The 'load logger' type instruments can also be placed on MV feeders to give useful results on a larger area under consideration.

The **consumer and feeder loads** should be computed both in energy terms (kWh per month or year) as well as in peak load terms (kW). The kWh demand is useful for computing revenue streams; the kW demand for determining the maximum load flow to be expected along the lines. The load flow information will be used to decide on the configuration of network components (backbone lines and laterals) as well as the conductor sizes to be used.

Once the characteristics of specific consumer categories are determined, the aggregate load of a group of such consumers is worked out on the basis of their **'After Diversity Maximum Demand'** (ADMD). This is the simultaneous maximum demand to be expected from a group of consumers. Usually ADMD is worked out for both a homogenous group (such as all households), as well as among a mix of consumer types (for a given area). When ADMD of a mix of consumers is determined, one needs to consider that the maximum demand of different consumer types occur at different times; e.g. for a household the maximum demand occurs at night whereas for rural industry it may occur during day time. Since the network feeders contain a mix of consumers, the contribution of ADMD of each consumer class at the system peak load time is aggregated to give the overall ADMD of the feeder.

A common error often encountered in load projection is the use of aggregated figures (sometimes for the whole utility) to determine the expected load of a rural area to be electrified. This often leads to over-investment as well as overstatement of the project benefits. If a database of the loads in towns and villages is maintained with reference to the time lapse after electrification and classified to the various types of areas existing in the country, much more accurate projections are possible. The 'areas' for such demarcation can be such as rural housing only, housing with some agriculture, small market towns, growing industrial areas etc. Other sub classifications such as 'low', medium' and 'high' can also be used along with the type of loads to be expected. Thus the load growth realized over time in previously electrified areas, suitably classified, will provide a good basis for load projection in new areas to be electrified.

5.2 Establishing a GIS Database

Many utilities have now migrated to Geographic Information Systems (GIS) to plan and manage their power networks. GIS maps providing information on roads, geographic features such as rivers, lakes and mountains, cities and settlements etc. are now freely available. In addition, many countries have updated the GIS maps with information on housing, population, location of schools and government facilities etc. which provide the information needed for load projection.

In addition to securing such geographic information maps it is necessary to include the positions and routes of **existing transmission and distribution lines** to enable a planning exercise to be conducted. This is done using Geographic Positioning System (GPS) instruments and conducting a field inventory of existing lines and substations. Less accurate GPS coordinates can also be obtained using a drive by technique and post-processing the captured coordinates. High resolution aerial photography can also be used to capture the location of existing lines and facilities.

In addition to developing precise maps of existing facilities, **compiling equipment data** by a system of attribute labelling of each component on the network map is required. This includes the conductor size of lines, details of support structures, capacity of transformers, year of installation etc. Armed with the above information the task of the system planner will be much simplified and the accuracy of the plans improved.

The **developed GIS database** can also be useful for other areas of company operations. These include asset management facilities, outage call management and operations, link with SCADA facilities, etc. Another issue worth mentioning is that developing the system planning function is an ongoing process where various activities such as improving knowledge on consumption patterns, migration to a GIS platform, securing planning software and undertaking load flow analysis, etc., have to be improved on a parallel basis. The different activities should not be treated in a serial manner stalling the latter activities until the former ones are completed – all related planning activities need to be developed simultaneously while constant improvement and updating is required over time.

Figure 20 Example of network reticulation maps used by the Bangladesh Rural Electrification Board to plan their network development. The rectangular squares are 'cells' used for load forecasting. Network lines at different voltages are indicated by separate codes. Primary distribution substations convert power from 33 kV to 11 kV.

5.3 Distribution Network Planning Support Tools

The basic tool for network planning is the information from **'load flow analyses'**. The key information required are:

- the loadings of feeders and line sections;
- the voltage drops at line peripherals; and
- the overall network losses.

Such data is collected at various load levels and at conductor sizes that may be hypothecated for new network components for each proposed network development. A typical network planning exercise includes the estimation of loads to be served by the network during a number of future years (e.g. next 5, 10 and 15 years), identification of alternative system development configurations for each year of analysis and the collection of data produced by the load flow analysis for each year and for each alternative development plan.

The most efficient way of securing load flow analysis is the use of a software package developed for this purpose. A number of highly versatile software packages are available in the market some of which are indicated below.

Examples of commercially available software for distribution system planning

- CYME –Dist (Canada)
- DigSILENT (Germany)
- ETAP (USA)
- TEKLA (Finland)
- PSS (Sincal) (Germany)
- PSCAD Manitoba Hydro (Canadia)
- SynerGEE (USA)
- Milsoft (USA)

These programs usually link with GIS data bases for data retrieval and the analysis can be carried out within minutes for each proposed development when the data base has been set up. It takes only a minimum time to change a component (e.g. adding a new line or change the conductor size) and obtain the results of a new system development. Thus, the quality and cost efficiency of the network planning can be considerably improved with the use of such software.

When such programs or respective data are not available, it is possible to use simple modelling techniques combined with spreadsheet based analyses to obtain the required information for planning purposes. Simple spreadsheet-based analyses often give sufficiently adequate information for selecting the optimum network configuration to be used and the required conductor size.

Support tools for power flow calculations and results of studies at practitioners' workshops

The Appendix at the end of this document provides information on simplified spreadsheet-based techniques which can be used for carrying out a network planning exercise. It also provides a summary of the results of the case studies carried out at the two workshops at Arusha and Cotonou. The details provided in the Appendix are:

- Annex T1: Calculation of Impedance of distribution lines
- Annex T2: Computation of Voltage Drop and Line Losses of Power Distributors
- Annex T3: Power Flow Calculations for MV Networks –a workbook containing a convenient format for the calculation of voltage drops and power losses for different technologies and power flow charts to meet a given voltage drop
- Annex T4: Power Flow Calculations for LV Networks – with information on LV lines similar to Annex T3
- Annex T5: A comparison of costs of an appropriate low cost technology verses that of a standard three phase network development based on examples studied at the two workshops
- Annex T6: A discussion note on solutions to the three phase vs single phase (MV) distribution based on examples studied at the two workshops

When planning the distribution network of a particular area, it should be borne in mind that not all consumers require the same **quality or reliability of service**. The willingness-to-pay for higher reliability standards also differ greatly among consumers and supply areas. Customers with continuous production facilities and sophisticated machinery will suffer substantial losses if the supply is interrupted even for a few minutes; in urban areas, outages will cause greater disruption than in rural areas.

Higher reliability demands require alternative supply routes to serve a particular area in the event of an outage, while simple **radial networks** suffice for rural areas with lower loads and reliability requirements. Similarly, rural substations can have a single transformer and the added cost of a second transformer for security of supply can be dispensed with. As discussed in Chapter 3 on transmission options, different class of line supports can be used in rural areas and substations designed to simpler standards.

5.4 Financial Health and Economic Analyses

The financial health of the system as a whole, as well as that of the utilities which provide rural electrification services have to be built on a sound footing. Rural electrification programmes require funds for both the initial investment (capital) and revenue expenditure (for O&M). Capital funds are often provided by public grants or loans. To service these loans, tariffs need to be appropriately structured; the programme carried out efficiently; and sufficient time allowed (usually by a grace period for capital repayment) for building up the load base to generate the required revenue.

Loan recovery at the Bangladesh rural electrification programme

In the Bangladesh rural electrification programme, all investment funds were passed through at a concessional interest rate to the rural electric cooperatives; a period of 5 years was provided before repayment would commence. Many of the cooperatives were able to service the loans as agreed while some took a longer time to build up the revenue stream. However, the programme was able to sustain itself as a whole with the better performing cooperatives (by nature of their higher consumption patterns), generating additional cash flows to offset the cooperatives which could not meet the loan requirements as they fell due. The disproportionate profitability of each rural area based on the particular consumer characteristics need to be taken into consideration while developing a financing scheme for rural electrification.

The tariffs of any rural electrification scheme should be able to recover in full the revenue expenditures needed to sustain its day-to-day operations. In addition, sufficient funds should be generated over time to reimburse at least a portion of the capital expenditures incurred while the balance needs to be met by well-structured subsidies. While tariff schemes may have cross-subsidy mechanisms to meet the needs of the lower income categories, the overall average tariff rate should be capable of meeting such financing needs. Any tariff setup short of this should be considered as unsustainable, which can endanger the sustainability of the programme.

Prior to making a decision on the implementation of a project, **economic and financial analyses** to compare costs versus benefits of electrification should be carried out. This is usually carried out by discounting both costs and benefits over the life span of the investment to present values. The cost stream includes the investment required for project execution and the annual costs for O&M. For a more refined analysis the cost of losses can also be incorporated in the cost stream. The benefit stream is based on the sales expected each year. A brief note on the economic and financial analysis of projects is provided at Annex T7 of the Appendix where the use of discount factors appropriate for the treatment of sales and losses is explained.

Further Reading

Annex T7 of Appendix: Economic and Financial Analyses

NRECA (2013). Distribution Line Design and Cost Estimation for Rural Electrification Projects. https://www.nreca.coop/wp-content/uploads/2013/07/Module7DistributionLineDesignandCostEstimationforRuralElectrificationProjects.pdf

Club-ER (2010): Planning tools and methodologies for rural electrification. http://www.club-er.org/images/slideHomePage/Vert%20OutilPlanif_GB_BD.pdf

IEA (2010). Comparative Study on rural electrification policies in emerging economies. Chapter 5.1.8. Available online at http://www.iea.org/publications/freepublications/publication/rural_elect.pdf

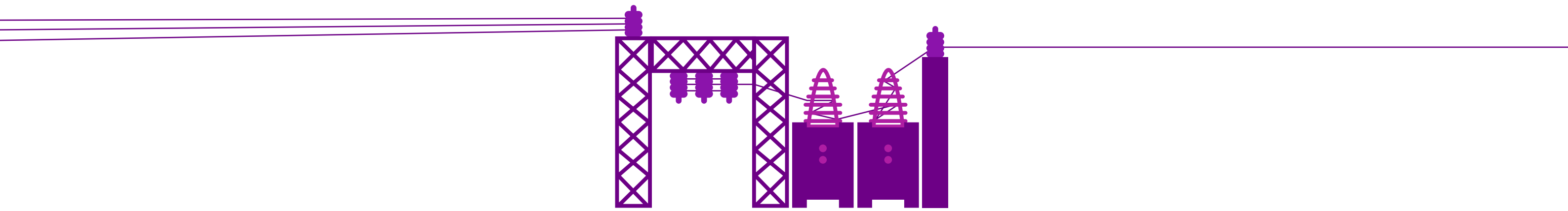
Appendix

The appendix presented here consists of an abridged version of the documents presented at two workshops on low cost electrification technologies, held in Arusha and Cotonou. It includes technical documents describing the main technical formulae associated with the computation of voltage drop and line losses of distributors, as well as indicative extracts of the studies carried out at two workshops.

Associated MS Excel calculation tools as well as a description of the studies carried out along with suggested solutions are available for download at http://euei-pdf.org/thematic-studies/low-cost-on-grid-electrification-technologies.

A list of annexes is provided below.

Figure 21 Particpant at the Workshop on Low Cost Grid Electrification Technologies in Cotonou, Benin; March 2014



List of Annexes

Annex T1: Calculation of Impedance of Distribution Lines (below)
A paper providing a summary of the formulae used for the calculation of resistance and reactance of distribution lines including how these formulae are worked out with respect to SWER lines.

Annex T2: Computation of Voltage Drop and Line Losses of Power Distributors (below)
A paper providing the basic theory of calculating the voltage drop and line losses of a line segment; easy to use 'multiplication factor' to convert 'tail end-load condition' to that of a distributor; and a more rigorous method of obtaining such multiplication factors using the 'load moment' concept.

Annex T3: Power Flow Calculations for MV Networks (Excel spreadsheet, available online[11])
A workbook in three worksheets, including:

- a tool to calculate the voltage drop and line losses of a distributor using impedance values of various conductors under different technologies (three phase, phase-phase, single phase, SWER);
- tables and calculations indicating the power flow possible for a given voltage drop; and
- the derived power flow capability vs. distance curves.

Extracts of the spreadsheets are provided below.

Annex T4: Power Flow Calculations for LV Networks (Excel workbook, available online[11])
Annex T4 repeats the computations above in respect of LV networks.

Annex T5: Comparison of technology costs (below)
Comparison of costs of an appropriate low cost technology versus that of a standard three phase network development based on the studies carried out at the two workshops.

Annex T6: Three phase distribution vs. single phase distribution (below)
Discussion note on solutions to the three phase vs. single phase (MV) distribution based on the studies carried out at the two workshops

Annex T7 economic and financial analysis (below)
Methodologies for economic and financial analysis of power distribution projects

11) All annexes can be downloaded at http://euei-pdf.org/thematic-studies/low-cost-on-grid-electrification-technologies

Annex T1: Calculation of Impedance of Distribution Lines

The formula presented in this document provides guidance in the computation of impedance of distribution lines. Examples of typical conductors for MV and LV lines are also provided in Annex T3 and T4 (Excel spreadsheets, available online[12]) to enable practitioners to use these figures as well as the calculation formats to conveniently estimate the voltage drops and losses in networks to be designed.

Conductor resistance

The DC conductor resistance is calculated from the formula:

$$\mathbf{R_{DC} =} \ \rho \ \frac{L}{A} \quad \textit{(equation 1)}$$

Where

ρ = resistivity of the conductor ($2.8264 \times 10^{-8}\,\Omega$m for Aluminum at 20°C with a temperature coefficient of $0.00403\,K^{-1}$)

L = conductor length and

A = conductor area

However, the resistance values to be used should be the AC resistance with adjustments for the skin effect for the appropriate system frequency (50 cycles/sec or 60 cycles/sec), bundling effect accounting for the spiralling of strands as well as the conductor temperature at the particular time. The conductor temperature will depend on the current carried (as well as duration of the load), solar radiation and wind conditions. Usually values at 75 °C may be considered as appropriate for peak time loading. Both DC resistance and AC resistance values at various temperatures can be found in conductor manufacture's catalogues (obtained from test data) and these values can conveniently be used in the calculations without computing them from the basic formula. Usually the ratio between the AC resistance at 75°C and DC resistance at 20°C is of the order of 1.22 to 1.34.

12) Annex T3 and T4 can be downloaded at http://euei-pdf.org/thematic-studies/low-cost-on-grid-electrification-technologies

Inductance between conductors

The formula for inductance is best described in the Westinghouse Transmission and Distribution Handbook[13]. The following extracts have been taken from Chapter 3. For a single round straight wire in a two conductor single phase circuit the Inductance is:

$$\mathbf{L = \frac{\mu}{2} + 2L_n \frac{\underline{D}}{r}} \quad \textit{(equation 2)}$$

Where:

L = inductance in Abhenris per cm per conductor
μ = permeability of conductor material
$\underline{D}$ = distance between conductor 1 and 2
r = radius of conductor

$\underline{D}$ and r must be expressed in the same units for the formula to be valid.
This equation is generally transformed to a more convenient expression as follows:

$$\mathbf{L = 2L_n \frac{1}{GMR} + 2L_n \frac{\underline{D}}{1}} \quad \textit{(equation 3)}$$

Where GMR = Geometric Mean Radius of the conductor and represents the mathematical radius assigned to the conductor to account for both the internal flux $\frac{\mu}{2}$ and the external flux $\mathbf{2L_n \frac{1}{r}}$ up to a unit distance, and $\mathbf{2L_n \frac{\underline{D}}{1}}$ represents the external flux from an unit distance to the return conductor. The inductance is thus separated to 2 terms representing that due to the characteristics of the conductor alone and that due to the distance between conductors.

The GMR for a single circular solid conductor is $e^{-1/4}$ r and for a bundle of n conductors it can be worked out by calculating the n^2 root of the product of n^2 terms consisting of GMR of every strand times the distance of each strand to every other strand. However, the GMR can also be conveniently taken from conductor manufacturer's catalogues. Simplified formulae are also presented in textbooks and the following representative formula can be used to compute GMR for ACSR conductors at 50 Hz frequency:

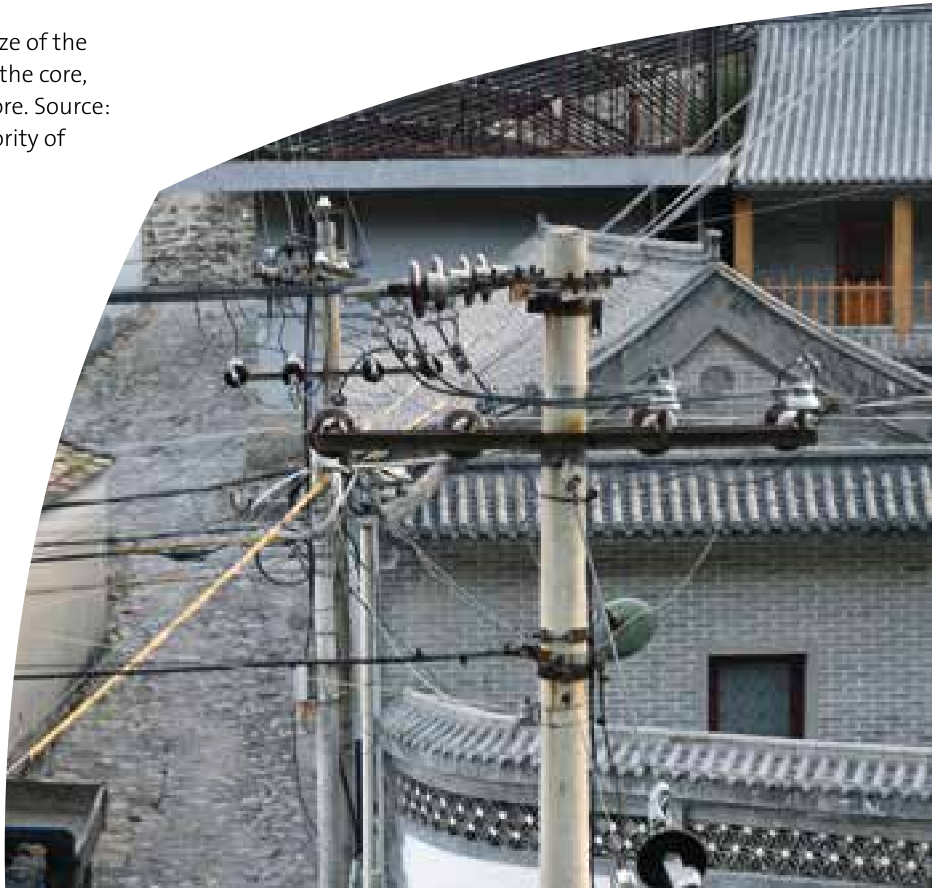
13) Westinghouse Electric Corporation (1964). Electrical Transmission and Distribution Reference Book. Available online at http://de.scribd.com/doc/146376164/Electrical-Transmission-and-Distribution-Reference-Book-of-Westinghouse

Table 4 Calculation of GMR for ACSR conductors

3/4 stranding	GMR = 0.000232d	4/3 stranding	GMR = 0.000274d
6/1 stranding	GMR = 0.000358d	12/7 stranding	GMR = 0.000372d
30/7 stranding	GMR = 0.000378d	54/7 stranding	GMR = 0.000383d

Where d = overall diameter of the conductor in mm,
and GMR is given in meters

Note that the GMR will vary due to the relative size of the steel and aluminum conductors, permeability of the core, frequency as well as the current flowing in the core. Source: 'HV Earth Return for Rural Areas' Electricity Authority of new South Wales



The inductance in Ohms

$$\mathbf{X = 2\pi f\, L}\ \textit{(equation 4)}$$

Where
X = inductance in Ohms per km
L = inductance expressed in Henries per km

Equations 3 and 4 are combined and conveniently recast to practical units as follows:

$$\mathbf{X = 0.1447\ L_{10}\frac{1}{GMR} + 0.1447\ L_{10}\frac{D}{1}\quad in\ \Omega/km}\quad \textit{(equation 5)}$$

Where GMR is the Geometric Mean Distance and is the distance between conductors, both to be expressed in the same units (usually in meters). Frequency: 50 Hz.

This expression is usually presented as follows:

$$\mathbf{X = A + B}$$

in Ohms per km for each path (forward and return)

Where
$A = 0.1447\ L_{10}\frac{1}{GMR}$ the internal and external reactance to one meter distance (based on the Geometric Mean Radius)
and,
$B = 0.1447\ L_{10}\frac{D}{1}$ the inductive reactance dependent on the spacing r between conductors (Geometric Mean Distance)
The total inductance for a 2 conductor system = 2 (A+B)

Inductance of three Phase lines

In the case of a balanced three phase line, calculation of positive and negative sequence reactance is that of a single line given above (i.e. A+B). It can be considered that the 'reactance of the return path' is nil because the "return" is balanced by that of the other two phases.

In the case of three phase lines:

$$\mathbf{GMD = (D_1.D_2.D_3)^{1/3}}$$

where D_1, D_2, D_3, are the distance between conductors.

For a flat equally spaced conductor configuration with distances,

$D_1 = D_2$, and $D_3 = 2.D_1$ the GMD = 1.26 D_1

For an equilaterally spaced conductor configuration with distances,

$D_1 = D_2 = D_3$, the GMD = D_1

Impedance of SWER lines

The impedance of SWER lines has been worked out using complex mathematical modelling and is provided in a simplified version in Carson's formula for the case of a single wire with earth return as follows:

$$\mathbf{Z = r_c + 0.00159f + j0{:}004657f \log_{10} (D_e/GMR)}$$

Where:

- Z = Impedance in Ω/mile
- r_c = resistance of metallic conductor (Ω/mile)
- D_e = 2160√/f) (feet) = depth of fictitious earth–return conductor
- ρ = earth resistivity in Ohms per meter cube
- GMR = geometric mean radius of conductor (feet).

Ref: Westinghouse "Electrical Transmission and Distribution Reference Book" (Chapter 3)

Expressed in metric terms the formula is:

$$Z = r_c + 0.000988f + j0{:}002894f \log_{10} (De/GMR) \text{ in } \Omega/\text{km}$$

or

$$Z = r_c + 0.0494 + j0{:}1447 \log_{10} (De/GMR) \text{ in } \Omega/\text{km for 50 Hz systems}$$

Where:

- r_c = resistance of metallic conductor in Ω/km
- D_e = 658√(r/f) (meters) = depth of fictitious earth–return conductor. Alternatively, De = 93√ρ (meters) for 50 Hz systems
- ρ = earth resistivity, usually about 300 or 250 Ohm meters
- GMR = geometric mean radius of conductor (meters).

The following may be noted for the calculation of impedance of SWER lines:

- The calculation is for the total loop unlike the previous formula given for single phase two wire systems where the formula is applicable for each path, forward and return.
- The distance of the fictitious earth return path, is D_e is about 1470 meters (for earth resistivity of 250 Ohm-meters)

The inductance can still be expressed in the form A + B, for the total loop

Where $A = 0{:}1447 \log_{10} (1/GMR)$ and $B = 0{:}1447 \log_{10} (De)$

- The resistance of the earth return path is about 0.0494 ohms irrespective of the distance.

Annex T2: Computation of Voltage Drop and Line Losses of Power Distributors

Introduction

This paper provides a convenient and simplified methodology for the computation of voltage drop and line losses for power distributors at medium and low voltages. The formulae presented can be used when there is no facility to use computerized network analysis software for power distribution networks. The networks can be modelled to a set of single line distributors and the formulae presented in this paper can be used to obtain the required values for the tail end voltage and line loss.

Single section power distributor

A short power line is represented by its resistance and reactance (with capacitance effects being minimal and neglected). In the case of a tail end load the situation is as represented by the following diagram and vector diagram:

Figure 22 Representation of a single section power line:

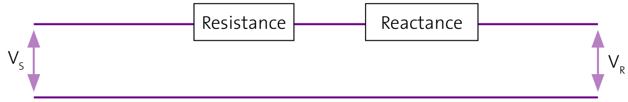
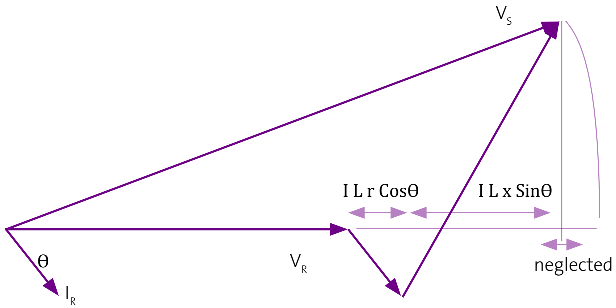


Figure 23 Vector diagram of a single section power line



The line end voltage drop phase to neutral is:

$$\Delta V = I \cdot L \cdot (r \cos\Theta + x \sin\Theta)$$

and power loss along a single conductor is:

$$\Delta P = I^2 r \cdot L$$

We thus have the following representation for voltage drop and losses for three phase and single phase systems respectively:

$$\Delta V = K \,.\, I \,.\, L \,.\, (r \cos\Theta + x \sin\Theta)$$

$$\Delta P = K_1 \,.\, I^2 r \,.\, L$$

Where:

K = √3 for balanced three phase and 2 for single or dual phase

K_1 = 3 for balanced three phase and 2 for single and dual phase

I = line current

L = line length

r = resistance in Ohms per unit length

x = inductance in Ohms per unit length

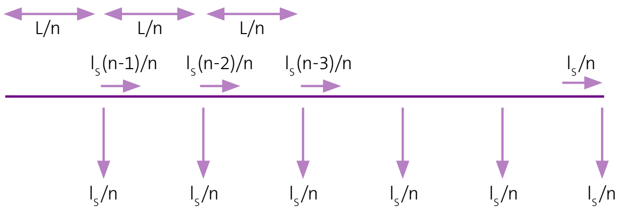
Θ = power factor angle

Distributors

In practice however, a distribution line consist of a number of sections and branches and is loaded at various points along its length at irregular intervals. In such instances the power flow characteristics including line voltages at various points and line losses can only be accurately determined by using suitable computer programs that can address the solution by using iterative processes. However, a simplified methodology can be developed to obtain an approximate solution which will yield results well within acceptable accuracy limits.

The computation is made with the distributor modelled as a simple radial line with a number of equally spaced sections at the ends of which are applied loads of equal magnitude. The total load of the distributor will be equal to the total of the section loads and the total direct length of the distributor (omitting any branch lines) will be equal to the length of the model line. Experience has shown that it is very convenient to model distribution lines by this method ignoring the voltage levels of the branch lines as only the lowest voltage of the system is of relevance. Also the line losses of branches are often negligible in comparison with the losses in the main line which carries the main load. If any branch line is of significance it can be modelled separately while for the performance of the main network the total load of the branch line can be taken as acting at the branch point. The representative model is shown in *figure 24* below:

Figure 24



n = No. of sections

I_s/n = Load at each node

The current flowing along the sections, commencing with the start of the distributor will be:

$$I\,,\ \ \mathrm{I}\,\frac{(n-1)}{n},\ \ \mathrm{I}\,\frac{(n-2)}{n},\ \ \mathrm{I}\,\frac{(n-3)}{n},\ldots\ldots\ldots.\ \mathrm{I}\,\frac{(n-i)}{n},\ldots..\ \ \mathrm{I}\,\frac{1}{n}$$

Voltage drop of distributor

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

$$= \mathrm{K}\,\mathrm{I}\,\frac{(n-i)}{n}\,(\mathrm{r}\cos\Theta + \mathrm{x}\sin\Theta)$$

Accordingly summing up the voltage drops (ignoring the negligible phase angle shift)

Line end voltage drop is:

$$= \mathrm{K}\,(\mathrm{r}\cos\Theta + \mathrm{x}\sin\Theta)\ \frac{\mathrm{L}}{n}\ \mathrm{I}\,\left(\frac{n}{n}+\frac{(n-1)}{n}+\frac{(n-2)}{n}+\frac{(n-3)}{n}+\cdots\ +\frac{1}{n}\right)$$

$$= \mathrm{K}\,(\mathrm{r}\cos\Theta + \mathrm{x}\sin\Theta)\ \frac{\mathrm{L}}{n}\ (1 + 2 + 3 + \text{--------} + n)$$

$$= \mathrm{K}\,(\mathrm{r}\cos\Theta + \mathrm{x}\sin\Theta)\ \frac{\mathrm{L}}{n}\ \left(\frac{(n+1)n}{2n}\right)$$

$$= \mathrm{K}\,(\mathrm{r}\cos\Theta + \mathrm{x}\sin\Theta)\ \mathrm{L}\ \frac{(n+1)}{2n}$$

$$= \textbf{(voltage drop of an equal tail end load).}\ \frac{\boldsymbol{(n+1)}}{\boldsymbol{2n}}$$

Power loss of distributor

The Power loss along section (i+1) will be:

$$= \mathrm{K}_1\,\mathrm{r}\,\frac{\mathrm{L}}{n}\ \left[I\ \frac{(n-i)}{n}\right]^2$$

Accordingly summing up the power losses, total loss of distributor is:

$$= \mathrm{K}_1\,\mathrm{r}\,\frac{\mathrm{L}}{n}\ \ \mathrm{I}^2\ \left[\left(\frac{(n)}{n}\right)^2+\left(\frac{(n-1)}{n}\right)^2+\left(\frac{(n-2)}{n}\right)^2+\cdots+\left(\frac{2}{n}\right)^2+\left(\frac{1}{n}\right)^2\right]$$

$$= \mathrm{K}_1\,\mathrm{r}\,\frac{\mathrm{L}}{n}\ \ \mathrm{I}^2\ [(1^2+2^2+3^2+\text{--------}+n^2)/\ n^2$$

$$= \textbf{(losses of an equal tail end load) } \boldsymbol{[(1^2+2^2+3^2+\text{--------}+n^2)/\ n^3]}$$

Using the above relationships, a set of multiplying factors could be derived to convert the tail end load situation (i.e. entirety of the load to act at end of line) to that of a distributor with the same length and sending end load. The *Table 5* below presents the multiplying factors (MF) that could be used to determine the line end voltage drop and line losses of a distributor.

Table 5 Multiplying factors for voltage drop and line losses

No of line sections	MF for Volt drop	MF for Losses
1	1	1
2	0.750	0.625
3	0.667	0.519
4	0.625	0.469
5	0.600	0.440
6	0.583	0.421
7	0.571	0.408
8	0.563	0.398
9	0.556	0.391
10	0.550	0.385
11	0.545	0.380
Infinite	0.500	0.333

It may be noted that for a perfectly uniformly distributed loading situation ($n \to \infty$) the multiplying factor for voltage drop is 0.5 and for losses is 0.333. Usually a distributor may be modelled by a 4 to 6 sections single line depending on the branches etc. and values to be used for voltage drop and losses can be in the range of 0.625 to 0.583 and 0.469 to 0.421 respectively.

Alternative method

In some cases the distribution system is not easily amenable to be modelled as a network with equal loadings at equal distances. In many such networks there are only a few sections with irregular loading and distances.

In such cases the multiplying factor (MF) can be determined by:

MF for voltage drop = [the sum of moments of (the section length x sum of downstream loads)] divided by [total length x total load]

MF for losses = [the sum of moments of (the section length x (sum of downstream loads)^2)] divided by [total length x (total load)^2]

Annex T3 and T4: Power Flow Calculations for MV and LV Networks – Voltage Drop and Loss Calculations[14]

Power Flow Calculations for MV Networks -Voltage drop and loss calculations

The workbook can be downloaded at http://euei-pdf.org/thematic-studies/low-cost-on-grid-electrification-technologies

	Calculation of Voltage Drop	**Calculation of Inductance**			
Three phase =	SQRT 3 * I * L * (r cosΘ + x sin Θ)	GMR for conductors		Inductance, X =	A + B
Single Phase =	2 * I * L * (r cosΘ + x sin Θ)	0.000358	x Dia for 6/1 strand ACSR	A =	0.1446 * Log$_{10}$ (1/GMR)
SWER =	I * L * (r cosΘ + r_e cos Θ + x sin Θ)	0.000378	x Dia for 30/7 strand ACSR	B =	0.1446 * Log$_{10}$ (GMD)
	Where r_e, Earth resistance = 0.05 Ohms/km	GMD for 33 kV lines =	1227 mm		and 0.1446 * Log10 (De) for SWER Lines
		Note: GMD assumed same for 3 phase, 2 phase and S/Phase			
		D_e for SWER line =	1470 meters		

Conductor characteristics				SWER react			**Calculation of reactance**		
Conductor	X-section	Resist/km	React/km	React/km	Diameter	GMR	A	B	B for SWER
Goper (ACSA25)	26.3	1.344	0.388	0.834	7.08	0.002535	0.376	0.013	0.458
Weasel (ACSR30)	31.6	1.116	0.383	0.828	7.77	0.002782	0.370	0.013	0.458
Rabbit (ACSR60)	61.7	0.667	0.366	0.811	10.1	0.003616	0.353	0.013	0.458
Hare (ACSR122)	122.5	0.336	0.345	0.790	14.2	0.005084	0.332	0.013	0.458
Wolf (ACSR194)	194.4	0.225	0.326	0.771	18.1	0.006842	0.313	0.013	0.458
SWER Earth resistance/km	0.05								

Distribution Factors		
Line sections	MF for Volt drop	MF for losses
1	1	1
2	0.750	0.625
3	0.667	0.519
4	0.625	0.469
5	0.600	0.440
6	0.583	0.421
7	0.571	0.408
fully dist	0.500	0.333

How to use the spreadsheet:

Choose type of system: 3 phase, 2 phase, single phase or SWER

Enter values (overwrite in a row or copy out a new row) for:

distance, total kWH, power factor, conductor resistance and reactance (from table above) and distribution factors as appropriate to the line

Result: Percent voltage drop and percent power loss

Note: The rows already entered are those used in the various example studied. Any row can be used with corrections for the line under study

Line voltage	**33** kV				Dist./n Factor		Resistance	Reactance			Volt drop		Power loss	
Section	Length, km	Load kW	Amps	Cond size	volt drop	losses	Ohms/km	Ohms/km	Cos	Sin	Volts	Percent	kW	Percent
Three phase 33 kV conventional system														
AB	15	2,000	36.88	ACSR 122	1	1	0.34	0.34	0.95	0.31	409	1.24	20.55	1.03
CD	25	670	13.81	ACSR 60	0.583	0.421	0.67	0.37	0.85	0.53	265	0.80	4.01	0.60
Two phase system														
BE	40	350	12.48	ACSR 60	0.583	0.421	0.67	0.34	0.85	0.53	435	2.28	3.50	1.00
CF	35	400	14.26	ACSR 60	0.583	0.421	0.67	0.34	0.85	0.53	435	2.28	3.99	1.00
Single phase system														
BE	20	350	21.59	ACSR 60	0.583	0.421	0.67	0.34	0.85	0.53	377	1.97	5.23	1.49
BG	40	265	16.34	ACSR 60	0.583	0.421	0.67	0.34	0.85	0.53	570	2.99	6.00	2.26
SWER System														
BE	20	350	21.59	ACSR 60	0.583	0.421	0.72	0.81	0.85	0.53	261	1.37	2.81	0.80
BG	40	265	16.34	ACSR 60	0.583	0.421	0.72	0.81	0.85	0.53	395	2.07	3.22	1.22

14) Annex T3 and T4 can be downloaded at http://euei-pdf.org/thematic-studies/low-cost-on-grid-electrification-technologies

Annex T3 – Extract of Worksheet 2:
Power Flow Calculations for MV Networks – Distance vs. Powerfor given voltage drop

The workbook can be downloaded at http://euei-pdf.org/thematic-studies/low-cost-on-grid-electrification-technologies

Calculation of Inductance

GMR for conductors		Inductance, X =	A + B	
0.000358	x Dia for 6/1 strand ACSR	A =	$0.1446 * \mathrm{Log}_{10}$ (1/GMR)	
0.000378	x Dia for 30/7 strand ACSR	B =	$0.1446 * \mathrm{Log}_{10}$ (GMD)	and $0.1446 * \mathrm{Log}_{10}$ (De) for SWER Lines
	GMD for 33 kV lines =	1227	mm	
	Note: GMD assumed same for 3 phase, 2 phase and S/Phase			
	D_e for SWER line =	1470	meters	

	Conductor characteristics			SWER react			**Calculation of reactance**		
Conductor	X-section	Resist/km	React/km	React/km	Diameter	GMR	A	B	B for SWER
Goper (ACSA25)	26.3	1.344	0.388	0.834	7.08	0.002535	0.376	0.013	0.458
Weasel (ACSR30)	31.6	1.116	0.383	0.828	7.77	0.002782	0.370	0.013	0.458
Rabbit (ACSR60)	61.7	0.667	0.366	0.811	10.1	0.003616	0.353	0.013	0.458
Hare (ACSR122)	122.5	0.336	0.345	0.790	14.2	0.005084	0.332	0.013	0.458
Wolf (ACSR194)	194.4	0.225	0.326	0.771	18.1	0.006842	0.313	0.013	0.458
ER Earth resistance/km		0.05							

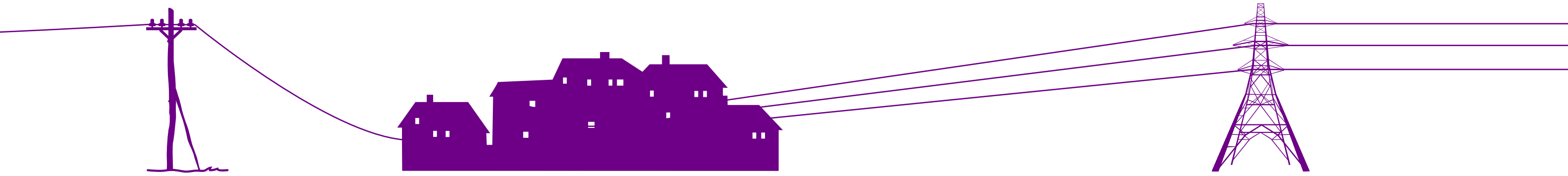
Calculation of Voltage Drop

hree phase	SQRT 3 * I * L * (r cos Θ + x sin Θ)	For 3 Phase, P=	[(p.u. voltage drop)/k * V_L^2]/[d * (r + x tan Θ)]
ngle Phase	2 * I * L * (r cos Θ + x sin Θ)	For duel phase, P=	[(p.u. voltage drop)/k * V_L^2]/2 [d * (r + x tan Θ)]
SWER Line	I * L * (r cos Θ + r_e cos Θ + x sin Θ)	For S/Phase, P=	[(p.u. voltage drop)/k * V_{ph}^2]/ 2[d * (r + x tan Θ)]
Where r_e, Earth resistance = 0.05 Ohms/km		For SWER, P=	[(p.u. voltage drop)/k * V_{ph}^2]/[d * (r +r_e + x tan Θ)]

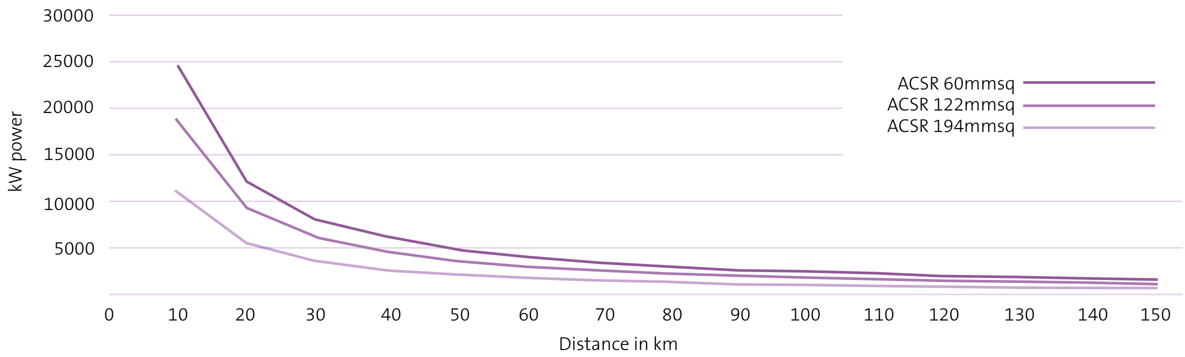
MV Power Flow Capabilities by technology, conductor size and distance for distributed loads

									For SWER	
factor (k)=	0.583	Power factor	0.9	angle	0.451027			Extra volt drop of earthing rods		
volt drop=	0.05	Sin =	0.436						in kV	in p.u..
Power	is given in kW	Tan =	0.484						0.035	0.001837
ne voltage	33 kV			33 kV		19.05256 kV			19.05256 kV	

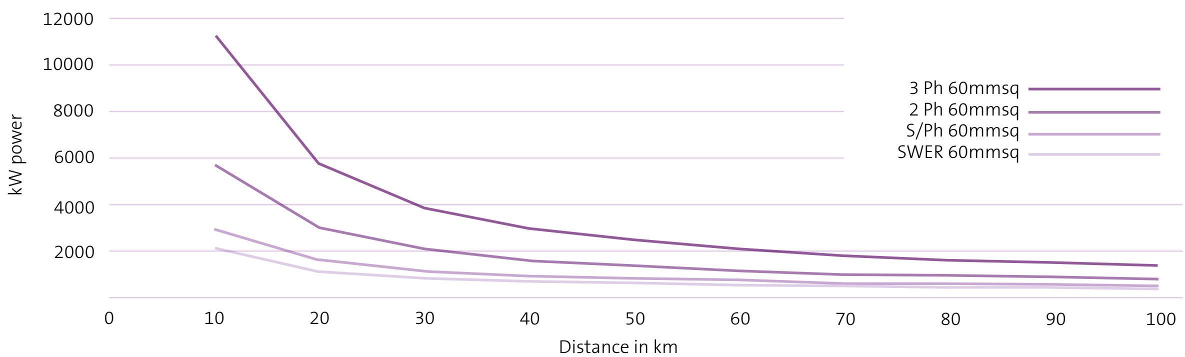
	3 Phase Power			Dual Phase Power			Single Phase Power			SWER Power				
dist.	ACSR 60	ACSR 122	ACSR 194	ACSR 60	ACSR 122	ACSR 194	ACSR 60	ACSR 122	ACSR 194	ACSR 25	ACSR 30	ACSR 60	ACSR 122	ACSR 194
km	Power	Power	Power	Power	Power	Power	Power	Power	Power	Power	Power	Power	Power	Power
40	2767	4644	6098	1383	2322	3049	461	774	1016	417	478	676	976	1156
50	2214	3715	4878	1107	1858	2439	369	619	813	334	383	541	781	925
60	1845	3096	4065	922	1548	2033	307	516	678	278	319	450	650	771
90	1230	2064	2710	615	1032	1355	205	344	452	185	213	300	434	514
100	1107	1858	2439	553	929	1220	184	310	407	167	191	270	390	462



Annex T3 – Examples of Charts Power Transfer Capability:
Three Phase Distributed loads for 5 % volt drop and power factor 0.9



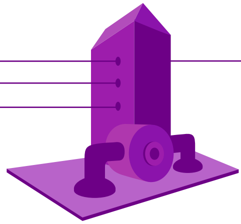
Annex T3 – Examples of Charts Power Transfer Capability:
Alternative technologies with 60mmsq conductor distributed loads for 5 %volt droop and power factor 0.9



Annex T5: A comparison of costs of low cost technologies and standard three phase networks

The following are results of some case studies carried out at the two workshops in Arusha and Cotonou showing the costs of an appropriate low cost technology verses that of a standard three phase network development:

Study S1 – MV network using SWER								
			Selected system			Typical standard used		
Section	Distance (km)	Load kW	section characteristic	Rate in $/km	Cost in $	section characteristic	Rate in $/ km	Cost in $
AB	15	No loads	3Ph 120	15,400	231,000	3Ph 120	15,400	231,000
BC	20	50	3Ph 120	15,400	308,000	3Ph 120	15,400	308,000
CD	25	670	2Ph 120	11,396	284,900	3Ph 120	15,400	385,000
BE	20	350	SWER 25	5,344	106,878	3Ph 120	15,400	308,000
BG	40	265	SWER 25	5,344	213,756	3Ph 120	15,400	616,000
CF	35	400	SWER 120	6,834	239,189	3Ph 120	15,400	539,000
CH	20	265	SWER 25	5,344	106,878	3Ph 120	15,400	308,000
nos.	4		SWER Isolation TFs	7,800	31,200			
				Total cost	1,521,802			2,695,000
				Savings realized %	43.53			



Study S1 – using Single Phase lines instead of SWER

Section	Distance (km)	Load kW	section characteristic	Rate in $/km	Cost in $	section characteristic	Rate in $/km	Cost in $
AB	15	No loads	3Ph 120	15,400	231,000	3Ph 120	15,400	231,000
BC	20	50	3Ph 120	15,400	308,000	3Ph 120	15,400	308,000
CD	25	670	2Ph120	11,396	284,900	3Ph 120	15,400	385,000
BE	20	350	S/Ph 60	9,930	198,606	3Ph 120	15,400	308,000
BG	40	265	S/Ph 60	9,930	397,211	3Ph 120	15,400	616,000
CF	35	400	S/Ph 120	11,396	398,860	3Ph 120	15,400	539,000
CH	20	265	S/Ph 60	9,930	198,606	3Ph 120	15,400	308,000
				Total cost	2,017,183			2,695,000
				Savings realized %	25.15			

Study S2 – Ntenjeru Example from Uganda

A to P1	22.3	1275	3Ph120	15,400	343,420	3Ph 120	15,400	343,420
P1 to P305	22.2	700	Sw60	5,988	132,923	3Ph 120	15,400	341,880
nos.	2		SWER Isolation TFs	7,800	15,600			
				Total cost	491,943			685,300
				Savings realized %	28.21			

Study S2 – using Single Phase lines instead of SWER									
1 to 11	22.3	360	S/Ph 60	9,930	221,445	3Ph 60	13,371	298,169
1 to 8	22.2	160	S/Ph 60	9,930	220,452	3Ph 60	13,371	296,832
				Total cost	441,898			595,002
				Savings realized %	25.73			

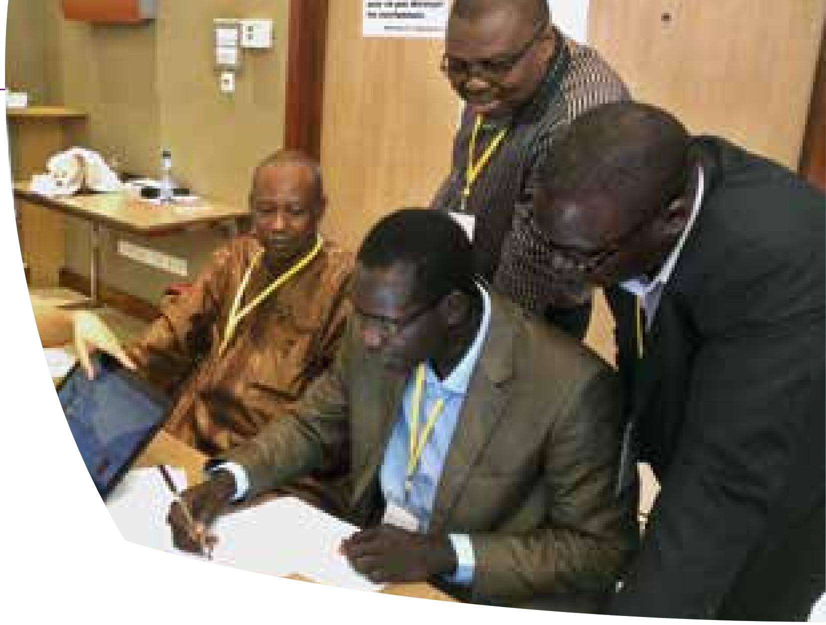
Study S3 – Wolita example from Ethiopia									
SS to 2	9.8	480	Sw 60	5,988	58,678	3Ph 60	13,371	131,034
2 to 10	79.4	480	Sw 60	5,988	475,409	3Ph 60	13,371	1,061,643
SS to 2	9.8	300	Sw 60	5,988	58,678	3Ph 60	13,371	131,034
2 to 14	33.3	300	Sw 30	5,344	177,952	3Ph 60	13,371	445,248
nos.	2		SWER Isolation TFs	7,800	15,600			
				Total cost	786,317			1,637,926
				Savings realized %	51.99			

Study S4 – Hosaina example from Ethiopia

			Selected system			Typical standard used		
Section	length in km	Load in kVA	section characteristic	Rate in $/km	Cost in $	section characteristic	Rate in $/km	Cost in $
1 to 11	9.8	360	SWER 25 mm²	5,344	52,370	3Ph 60	13,371	131,034
1 to 8	33.8	160	SWER 25 mm²	5,344	180,624	3Ph 60	13,371	451,934
nos.	2		SWER Isolation TFs	7,800	15,600			
				Total cost	248,594			582,968
				Savings realized %	57.36			

Study S4 – using Single Phase lines instead of SWER

1 to 11	9.8	360	S/Ph 60	9,930	97,317	3Ph 60	13,371	131,034
1 to 8	33.8	160	S/Ph 60	9,930	335,644	3Ph 60	13,371	451,934
				Total cost	432,960			582,968
				Savings realized %	25.73			



Annex T6: Cost Comparison of the use of Single Phase vs. Three PhaseMV Distribution

A cost comparison of the use of three phase transformers requiring three phase MV and long LV networks versus the use of single phase transformers with single phase MV and minimal LV conductors was carried out at the two workshops using typical examples. Three load dispersion arrangements were presented for study and the network development for the two possible alternatives examined. The main details of the three cases and the results of the studies are presented below.

Example 1: This example has a common road junction with four LV supply areas each of 1 km distance spreading out from the junction. A MV line is passing through the junction along one of the roads. A distributed load of 20 kW is present in each line. In the three phase alternative a single 3 phase 100 kVA transformer can feed the network with four 1 km LV lines of AAC 60 mm² (and 25 mm² neutral). For the single phase alternative, four 10 kVA transformers will be used per km (16 nos in all). In addition, two MV single phase extensions of 1 km each will be required for the road where the MV line is not present. ABC duplex conductor is used for the LV reticulation, estimated as 60 % of the total length of that needed for the three phase LV network. The reduction of the LV network is due to the fact that the single phase transformers are placed near housing clusters thus requiring only a portion of the length required for the three phase alternative where the line has to be extend from the transformer to the last house. In practice, a much lower LV length can be achieved. In this example the single phase alternative works out to 94 % of the cost of the three phase alternative.

Example 2: This example has three supply areas along a road, each of 2 km with a distance of 5 km between each supply area. The nearest MV supply point is 5 km from the first LV supply area. Each supply area has a distributed load of 20 kW per km. In the three phase alternative, a three phase line is drawn along the road and three 50 kVA double pole mounted transformers placed at the centre of each supply area. The LV line is three phase AAC 50 mm^2. In the single phase alternative, 8 nos 10 kVA transformers are used per supply area (24 nos in all) and a single phase MV line is drawn along the road to supply all three areas. As before ABC duplex is used for the LV network where required. In this example the single phase alternative works out to 74.2 % of the cost of the three phase alternative.

Example 3: This example is similar to example 2 with each LV supply area increased from 2 km to 3 km, the load density remaining at 20 kW/km. The distance between supply areas remain the same at 5 km. In this case a 100 kVA transformer will be needed per supply area for the three phase alternative and the LV line will need to be 100 mm^2 conductor. In the single phase alternative we will have 12 nos 10 kVA transformers per supply area (36 nos in all). In this example the single phase alternative works out to 76.9 % of the cost of the three phase alternative.

It may also be noted that as the distance between supply areas increases, the advantages of the single phase system development is enhanced. When the MV network is already present in the area to be supplied as in example 1 and the load density is high enough to use three phase transformers, the difference in costs would be marginal. In contrast large cost savings will occur when the loads at each transformer location is small (say less than 50 kW) and the overall area to be served by the MV network is large.

Annex T7: Economic and Financial Analyses

Both economic and financial analyses of prospective projects need to be carried out to demonstrate the viability of a project. Furthermore, it is also important to carry out such analyses for different supply options which may involve different technology applications or different network configurations. Such a comparison of alternative developments[15] will facilitate making an informed choice. The economic analysis will demonstrate the viability in terms of the entire economy while the financial analysis will demonstrate its viability in terms of the power company finances. The analysis is based on a comparison of costs and benefits computed on a life time basis and discounted to Present Value (PV) to represent the 'time value of money'. The results can be presented in in a number of ways such as:

1) Benefits to cost ratio (B/C ratio): the ratio of the present value of the stream of benefits to the present value of the stream of costs.

2) Net present value (NPV): The present value of the stream of benefits less the present value of the stream of costs

3) Internal rate of return (IRR): The interest rate which will make the present value of the stream of benefits = the present value of the stream of costs

The cost stream consists of investment costs, operations and maintenance (O&M) costs, and the cost of losses[16]. The benefits stream usually consists of electricity sales over the years[17].
The annual discount factors applicable to each of the above items are as follows:

15) Each conforming to the required technical standards

16) The cost of losses is of secondary importance in rural schemes

17) System reliability benefits can also be included in the analysis particularly when comparing alternative developments. However, this is more relevant to urban systems where system outage rates are more important

Table 6 Annual discount factor to be used

	Discount factor	Legend	Comment
Investment costs and constant benefits	$\frac{1}{1+r}$	r… discount rate	Each years' cost being brought back to the previous year
Sales	$\frac{1+g}{1+r}$	g… growth rate	Sales increase each year by (1+g) as load grows
Losses	$\frac{(1+g)^2}{1+r}$	g… growth rate r… discount rate	Losses increase each year by the square of the growth rate, as they are proportional to the square of the current

The analysis may be simplified if a constant annual growth rate for sales is assumed leading to 'Present Value Factors' (PVF) which will convert the first year's value to the discounted value for a given number of years. Some examples are provided in the tables below for typical values of 10 % discount rate and 5 % sales growth rate:

Table 7 Present value factor for sales benefits

Discount rate = 10 %; Growth rate = 5 %							
Year	1	2	3	4	5	6	7
Discount rate	1	0.909	0.826	0.751	0.683	0.621	0.564
Sales growth rate	1	1.050	1.103	1.158	1.216	1.276	1.340
Discount factor for Sales row 1 x row 2	1	0.955	0.911	0.870	0.830	0.792	0.756
Present Value Factor is obtained by summing up the discount factors for each year							
PVF for 7 years	6.115						
PVF for 10 years	8.184						
PVF for 15 years	11.050						

Table 8 Present value factor for losses

Discount rate = 10 %; Growth rate = 5 %							
Year	1	2	3	4	5	6	7
Discount rate	1	0.909	0.826	0.751	0.683	0.621	0.564
Loss growth rate	1	1.103	1.216	1.340	1.477	1.629	1.796
Discount factor for Losses row 1 x row 2	1	1.002	1.005	1.007	1.009	1.011	1.014
Present Value Factor is obtained by summing up the discount factors for each year							
PVF for 7 years	7.048						
PVF for 10 years	9.960						
PVF for 15 years	13.994						

Value of sales: Sales are computed on the basis of kWh of units sold to consumers. For an economic analysis, the sales benefits should be computed at the rate of the economic value of a kWh of consumption which will vary among consumer categories. For industrial and commercial consumers the economic value will be quite high depending on factors such as lost production or loss of business. A suitable proxy for the economic value is the cost (per kWh) of alternative supply such as by standby generators. For domestic consumers the economic value will be the benefits foregone or alternative costs of supply using kerosene oil lamps etc. The economic value to be used for different class of consumers as well as the average value to be used in a study can be achieved by carrying out socio-economic surveys and related studies. Another proxy is the 'willingness-to-pay' for an electricity supply which will vary among different class of consumers. For a financial analysis the value of sales will be the average tariff rate as this is what the utility will gain from the sale of electricity. Various studies carried out in different countries indicate that the economic value is considerably higher than the tariff rate, often in the range of 5 or even 10 times the tariff rate.

If the **value of losses** is also taken into account it could be computed based on the long range marginal cost (LRMC) of producing and transporting a unit of energy to that area for both the economic and financial analysis. Investment costs can also be differentiated to economic and financial terms but this is often of secondary importance and neglected in a distribution system development study.

To summarize: the costs and benefits of a distribution development can be worked out as given below to compute B/C ratio, NPV or IRR of a proposed investment in both economic and financial terms

Costs = Discounted value of investment stream + discounted value of O&M costs each year + (kWh losses yr. 1) x (PVF for losses) x (LRMC for distribution)

Benefits = (kWh sales yr. 1) x (PVF for sales) x (value of kWh)

Abbreviations

ABC	areal bundled conductors
ABERME	Agence béninoise d'électricité rurale et de maitrise d'énergie
AC	alternating current
ACSR	Aluminium conductor steel-reinforced
ADMD	After Diversity Maximum Demand
AEEP	Africa-EU Energy Partnership
AEI	Africa Energy Initiative
ARE	Alliance for Rural Electrification
BIL	Basic Insulation Level
CLUB-ER	the Club of African agencies and structures in charge of rural electrification
CNC	computer numeric control
DC	direct current
DDLO	Drop Down Lift Off
DSP	digital signal processor
EPR	Earth potential Rise
ERT II	Second Energy for Rural Transformation (World Bank Project)
ESCOM	Electricity Supply Commission (South Africa)
EUEI PDF	EU Energy Initiative – Partnership Dialogue Facility
ft	foot (0.3048 m)
GIS	Geographic Information System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GMD	Geometric Mean Distance
GMR	Geometric Mean Radius
GPS	Geographic Positioning System
HV	High Voltage
Hz	Hertz
IEA	International Energy Agency
IRR	internal rate of return
km	kilometre
KPLC	Kenya Power Lighting Company
kVA	kilovolt-amps
kW	kilowatt
kWh	kilowatt-hour
LRMC	long-range marginal cost
LV	Low Voltage
MCB	Miniature Circuit Breaker
MCM	Miles de Circular Mil
MF	multiplying factor

mm²	millimetre square
MV	Medium Voltage
NGO	Non-Governmental Organisation
NPV	net present value
NRECA	National Rural Electric Cooperative Association
O&M	operation and maintenance
OLTC	On Load Tap Changer
OPGW	optical ground wire
Ph-N	Phase-Neutral
Ph-Ph	Phase-Phase
PVC	Polyvinyl chloride
PVF	present value factor
PWF	Present Worth Factor
RBS	rated breaking strength
REN21	Renewable Energy Policy Network for the 21st Century
R-L	Resistor-Inductor
SBEE	Société Béninoise d'Energie Electrique
SCADA	System Control And Data Acquisition
SHS	Solar Home System
STS	Standard Transfer Specification
SWER	Single Wire Earth Return
SWL	Shield Wire Line
SWS	Shield Wire Systems
USD	US Dollars
USDA	U.S. Department of Agriculture

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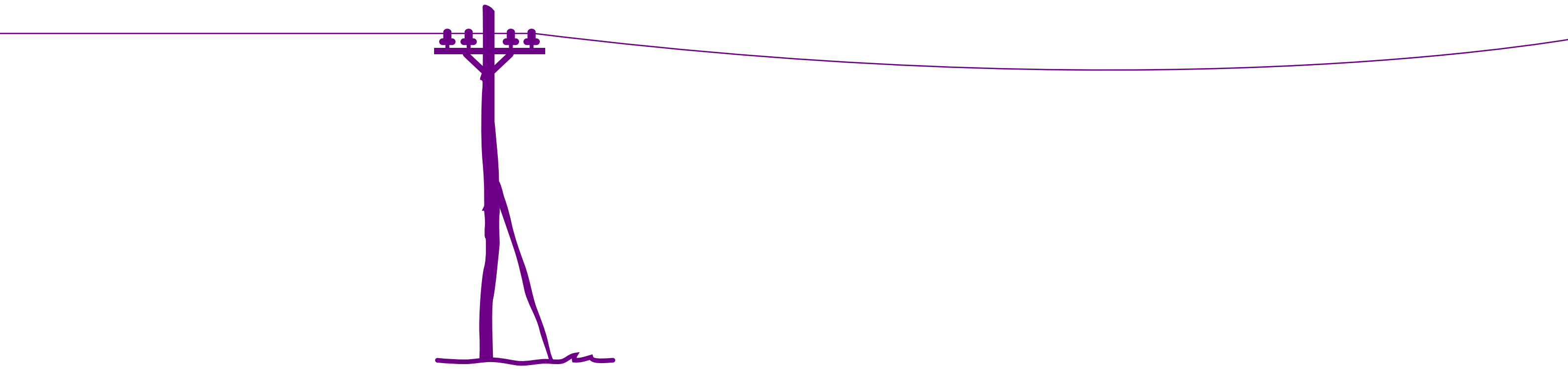
Figure 25 Particpants at the Workshop on Low Cost Grid Electrification Technologies in Arusha, Tanzania; September 2013



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