Guides for
Electric Cooperative Development and Rural Electrification

USAID
FROM THE AMERICAN PEOPLE

NRECA International Ltd.
Your Touchstone Energy® Partner

Glossary of Abbreviations

A	Ampere
AH	Amp-hour
AC	Alternating current
ACSR	Aluminum conductor, steel reinforced
A&G	Administrative and general
AWG	American wire gauge
CARES	Central American Rural Electrification Support Program
CCT	Correlated color temperature
CDA	Cooperative Development Authority (Philippines)
CEF	Fronteriza Electric Cooperative (Dominican Republic)*
CFC	National Rural Utilities Cooperative Finance Corporation, also known as NRUCFC (U.S.)
CFL	Compact fluorescent light bulb
CLARITY	Cooperative Law and Regulation Initiative
CONELECTRICAS	National Consortium of Electrification Companies of Costa Rica (Costa Rica)*
DC	Direct current
DISCEL	Electric Distributor of the Hydroelectric Executive Commission of Rio Lempa (El Salvador)*
EBIT	Earnings before interest and taxes
EBITDA	Earnings before interest, taxes, depreciation and amortization.
EEGSA	Electric Company of Guatemala, PLC (Guatemala)*
ESMAP	Energy Sector Management Assistance Program (World Bank)
FUNDAP	Foundation for Economic Development
G&T	Generation and transmission cooperative
GIS	Geographic information system
GPS	Global positioning system
HVD	High voltage disconnection
I	Electrical current, measured in amperes
ICE	Costa Rican Institute of Electricity (Costa Rica)*
IEC	International Electro-technical Commission
INDE	National Institute of Electrification (Guatemala)*
INE	National Institute of Statistics (Bolivia)*
IRR	Internal rate of return
ISPRA	National Institute for Protection and Environmental Research (Italy)
K	Kelvin
klmh	Kilo-lumen hour
kV	Kilovolt
kVA	Kilovolt-ampere
kVAR	Reactive kilovolt-ampere
kW	Kilowatt

kWh	Kilowatt hour
LED	Light-emitting diode
LPG	Liquefied petroleum gas
LVD	Low voltage disconnection
LVR	Low voltage reconnection
MRT	Single wire earth return*
MW	Megawatt
MWh	Megawatt hour
NEA	National Electrification Administration (Philippines)
NESC	National Electrical Safety Code
NGO	Non-governmental organization
NOAA	United States National Oceanic and Atmospheric Administration
NPV	Net present value
NRECA	National Rural Electric Cooperative Association International, Limited
OCDC	Overseas Cooperative Development Council
O&M	Operations and maintenance
PDB	Power development board
PUC	Public utility commission
PUE	Productive use of electricity
PV	Photovoltaic
PWM	Pulse width modulation
R	Electrical resistance
R&D	Research and development
RE	Rural electrification
REA	Rural Electrification Administration, an agency of the Department of Agriculture of the United States, now known as RUS
REB	Rural Electrification Board (Bangladesh)
RFP	Request for proposal
RFQ	Request for quote
ROE	Return on equity
RUS	Rural Utilities Services, an agency of the Department of Agriculture of the United States, previously known as REA
SWER	Single wire earth return
TAG	Technical assistance guide
UL	Underwriters Laboratory
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USTDA	United States Trade and Development Agency
V	Volt
W	Watt
WH	Watt-hour
Wp	Watts peak
WtP	Willingness to pay

*English translation of Spanish abbreviation

Distribution Line Design and Cost Estimation for Rural Electrification Projects

MODULE 7 OF NRECA'S TECHNICAL ASSISTANCE GUIDES

7

EXECUTIVE SUMMARY

This module sets forth the principles and establishes the recommendations for the electrical design of a rural electrification project or system. It also describes the procedure for the determination of costs, which serve as the basis for the feasibility analysis.

An electrical configuration design greatly influences the cost of the project to be developed and the quality of the service for the final user. An optimal design ensures the supply of service under adequate technical conditions and at minimum cost. Cost estimation on the basis of an optimal system ensures that the feasibility study uses the appropriate figures and that the lines, if constructed, have the required technical capacity to supply energy to final users.

This module broadens the information and procedure described in Module 5: *Methodology for Evaluating Feasibility of Rural Electrification Projects*, and provides further information for Module 8: *Financial Analysis of Rural Electrification Projects*. Likewise, the costs presented in this module assume the use of economical line structures and an optimal mechanical design, such as developed in the *Simplified Staking Manual for Overhead Distribution Lines*.[1]

The norms, parameters, and design criteria used in this module derive from the rules established by the RUS of the United States which have also been adapted to rural electric systems in several countries. Their fundamental characteristics are the following:

- The three-phase system is configured with four wires, including three phases and a multi-grounded physical neutral.
- Single-phase primary lines consisting of a phase and neutral are the main mechanism for rural distribution.
- Application of single-phase transformers sized from 5-25kVA, with use of transformers over 25kVA only for specific cases in three-phase banks.
- Limits on the length of low voltage networks to reduce technical losses, improve service quality, and reduce possibilities for illegal connections.
- Universal metering.

This system of design represents an integrated philosophy for development of rural electrification projects. It presents a basis for design and provides the professional user with the necessary tools for its application.

The proposed procedure for project design consists of the following series of steps.

1. Compilation and documentation of technical information on the existing system serving the project area.
2. Surveys in the field on the quantity and characteristics of consumers and preparation of georeferenced information on the geographic layout and concentration of users' housing in relation to the existing system. To obtain geographic information, the design system

An optimal design ensures the supply of service under adequate technical conditions and at minimum cost.

[1]Southern Engineering Company, *Simplified Staking Manual for Overhead Distribution Lines* (Washington, D.C.: The Association, 1992).

recommends use of modern instruments based on satellite positioning or GPS, instead of older techniques based on approximate measurements by means of vehicle odometers or distance estimations.

3. The operating electric company develops a study of the economic selection of conductors, to establish standard conductor sizes for use in multiple rural projects.

4. Design of the project at hand, using a power flow model with suitable characteristics, so as to accurately simulate system performance.

5. Consideration of coordination of protection against overcurrents and as an integral part of project design.

6. Estimation of project costs.

7. Presentation of the project in a sufficiently well-grounded and documented manner, so as to ensure that the technical aspects previously enumerated have received due consideration.

An optimal design ensures provision of service with standardized levels of service quality at minimum cost.

This module presents and develops the necessary methods, and adds application examples, to enable readers to put into practice the integrated system design approach.

INTRODUCTION

This module presents the steps to follow for the electrical design and cost estimation of a rural electric distribution project, to be used as input to the feasibility study.

The definition of the electric configuration is of vital importance for the future project because it has a fundamental influence on its cost and on the quality of the service for the final user. An optimal design ensures provision of service with standardized levels of service quality at minimum cost. The estimation of costs on the basis of an optimal system thus ensures that the feasibility study uses the appropriate figures and that the lines, if constructed, have the necessary capacity to supply the users with the service quality required, at the lowest economically achievable level of technical losses, at least during the period of project analysis.

This module does not discuss the mechanical design of the lines to be constructed. Mechanical design should be done only after determining and defining the feasibility of a project and after confirming its execution with the interested parties, whether they are the financial entities or the beneficiaries. An appropriate mechanical design ensures that lines work reliably and safely and that they do not cost more than necessary. For the mechanical design of electric lines see *Simplified Staking Manual for Overhead Distribution Lines*,[2] upon which the designs used to develop the reference costs in this module are based.

BACKGROUND AND JUSTIFICATION

The design fundamentals presented in this module derive from the rules established by the RUS. These approaches have been adapted to rural electric systems in several countries, and their fundamental characteristics are:

- Configuration of the three-phase system with three-phase wires and a multi-grounded physical neutral. This configuration permits the application of overvoltage protection with protection levels lower than the phase-to-phase voltage of the system. This configuration in turn permits the use of basic insulation levels for equipment that is lower than the levels applied in three-phase systems either without neutral or with a neutral grounded only at the source. It also permits a significant reduction in the investment cost of transformers and other equipment.

[2] Ibid.

- Application of single-phase primary lines consisting of phase and neutral as a principal means of rural distribution. The use of single-phase lines, while providing adequate service for most uses and for the existing demand for electricity in the rural area. Three-phase lines are required to maintain system balance between phases in the system as well as to serve specific concentrated three-phase loads.

- Application of single-phase transformers. The application of single-phase 5-25 kVA transformers is preferred, leaving the modules of over 25kVA only for specific requirements such as three-phase banks. The use of a larger number of relatively small transformer modules, as compared with a smaller number of larger transformers used in an urban system, improves the quality of service for scattered users, reduces the investment in low-voltage systems and reduces system losses, even though the transformers themselves may cost more.

- Limit the length of low-voltage networks. This limited length reduces technical losses, improves service quality, and reduces the possibility of illegal connections.

- Application of universal metering. An individual meter should be installed for each customer, to ensure measuring of each customer's own electric energy consumption. The universal metering rule applies to public consumers, schools, and municipal buildings as well as to private consumers.

This design methodology for a rural electrification project represents an integrated philosophy, and it should be applied as a whole. Its presents a basis for design and provides the professional user with the necessary tools for its application.

PROJECT DESIGN

The process of electrical design for rural electrification projects consists of four steps:

- Compilation of available information on the area to be electrified. The electric company or jurisdictional institution in charge of supplying the electric service in the adjoining area should provide the initial information, especially if the project is connected with this entity and this entity will operate the service once the project is executed. This information is necessary, but not sufficient to characterize the area, for reasons to be explained shortly.

- Analysis of the area to be electrified. This means determining the location of consumer concentrations, based on the actual conditions of the project area. During this process the information gathered from the electric service operator in the adjoining area should be confirmed, to the extent possible.

- Analysis of the loads and configuration of the proposed system. This step determines the loads represented by the concentrations of potential users and designs the system configuration to supply them, including route design, the features of primary lines, and the location of transformer points.

- Analysis of the proposed system, to confirm that it fulfills requirements for service quality, particularly with respect to the delivered voltage levels. This step enables planners to determine whether it is necessary to improve the existing system to permit the extension of the new system to be constructed.

What follows are the details of the process of analysis development and the use of the necessary tools, and an example how the process applies to a real project. The project used as an example is an electrification project in the Tomoyo region, near the city of Sucre in Bolivia.

The Tomoyo project provides for the supply of electric service to approximately 1,000 new consumers, scattered among 11 communities. The project includes the construction of approximately

Application of single-phase primary lines consisting of phase and neutral as a principal means of rural distribution.

30 km of 14.4kV single-phase lines, up to an end point 77 km from the supply substation. This project poses a challenge in maintaining adequate service voltage and in achieving the coordination of system protection.

Compilation of Information from the Electric Operator

It is very important to start the electric design of a project with information from the company that will undertake the role of operator upon completion of the work, to obtain all existing data available on the project area and to take into account the rules of the company that is to maintain and operate the lines.

The project engineer should start the electric design from the standards established by the electric company, as long as they comply with the technical criteria included in this module.

When the project designer visits the office of the operating company, he or she should gather the following information:

Standards and Materials Used

Every distribution company has preferences as to the use of materials and line hardware. Some companies use wooden poles while others use concrete or metal or a mix of all. Normally, electric companies have standardized structures, often based on RUS standards. It is also usual to have standardized conductor sizes for a company's distribution systems. Therefore, the project engineer should start the electric design from the standards established by the electric company, as long as they comply with the technical criteria included in this module.

Plans for Network Extensions in the Project Area

The electric company may have plans to extend its lines to the area contemplated in the project, and they might even have a final design for the extension project. Many times these plans are compiled by local governments, such as the prefecture or the municipality,and can be highly politically motivated. The designs prepared under these conditions usually have many serious flaws and cannot be applied directly.

The electrical design may have been based on social pressure (such as the decision to install three-phase lines, though the demand does not justify this configuration), or the mechanical design failed to consider the criteria of the mechanical design guide. Even so, these plans may contain useful information for elaborating a final design according to the procedures of this module. Such useful information generally includes the identification of communities in the project area and the number of potential users. It is always necessary, however, to validate the data received, as these often prove to be biased, to confirm the distance between towns and communities, and to verify the technical information on the existing system to which the project is to be connected.

Options or Alternatives for Extension of the Electric System to the Project Area

The electric company may have or know about an expansion plan for the present system, which would affect the project being considered. Examples of possible expansion plans are the construction of new sub-transmission lines, substations and/or generating plants. Such information would have great value for planning the new project. Take expansion plans into account with caution, however, because most distribution companies' expansion plans for rural areas are either overly general, without financing, or based on out-of-date information about major configurations for transmission systems. Although taking into account the plans of other companies may prevent unnecessary expenditures in the development of a project, it is important not to condition the design on the existence of other projects that may not be executed in time.

When associated projects have received the necessary approval from financing sources and other approvals such as those related to environmental impact, it is valid to consider those projects in the planning of a rural electrification project.

Point of Origin or Supply for the Project

During the visit of the project designer to the office of the electric company, obtain all available information on the source or supply point for the new project. Whether or not the electric company has all the necessary information, it is also necessary to pay a visit to the project site to verify the data. The data to be obtained from the electric company are the following.

Voltage Level of the Existing Distribution Lines

Existing voltage levels may be of the 15kV, 25kV, or 35kV class, each of which comprises a number of options. For example, the 15kVvoltage class includes 11kV, 12.47kV, 13.2kV, and 13.8kV. The 25kV level includes 20kV, 22kV, and 24.9kV, etc. The 35kV level includes voltages like 33kV and 34.5kV. An electric company must have more than one voltage level in its system, e.g., 12.5kV and 34.5kV. Then, even if a line is currently energized at a lower voltage, for example at 12.5kV, the company may be willing to consider a conversion to 34.5kV, if this is technically justifiable. In Bolivia, the system voltage used by distribution companies is in the process of being standardized at 35kV, 25kV, and 15kV. Few companies there are still maintaining systems in other voltages.

Number of Phases Available

It is important to know how many phases are available in the project sector: one, two or three phases. If three phases are not available at the initial point (usually at the end of the existing line), one must find out how far the three-phase line goes, so as to take it into account if conversion to a three-phase line is necessary.

Physical Neutral

Some rural area distributors have adopted systems without a physical neutral. The system used for single-phase configurations without a physical neutral, is referred to as Single Wire Earth Return (SWER), must still comply with and respect various design criteria. If no physical neutral exists at the initial point, it is necessary to determine where the neutral of the existing system ends, so as to take into account the costs of adding the neutral.

Distance from Substation

If the electric company has updated and sufficiently detailed maps, one can determine with their help the distance from the substation to the initial point of the project. This information is necessary to model the voltage drop in the existing line, as well as to simulate the power flow and the voltage drop in the proposed project.

Existing Conductor Size from Substation to the Project

To carry out a power flow analysis, one needs to know the cross-section of the existing conductor in the line from the substation up to the initial point of the project to be studied. The cross-section of the neutral conductor (if it exists) must be determined, as well as the cross-section of phase conductors. If there are conductors of more than one cross-section in the line between the substation and the initial point, record each cross-section of the conductor in the corresponding stretch, as well as its respective length.

Load in the Existing Line

The load in the existing line is another critical component in defining the conductor cross-section and/or number of phases of the system that will be analyzed in the power flow study in order to determine the voltage drop in the existing line. If there are important loads, record their location so as to be able to model their effect in the power flow study. If the existing line has to be divided into segments, for the reasons indicated in the previous section, be sure to divide the existing load among the same segments.

Average Energy Consumption in the Last Electrified Community

In rural electrification projects it is possible to estimate energy consumption in the communities to be electrified examining the energy consumption in the nearby communities that already have electric service. Quite probably the electric company will have information on the energy consumption of existing users in these nearby communities. If the electric company furnishes financial data only, such as the monthly amount collected, the kWh consumption can be calculated using the company's current tariff structure.

Existing Penetration Rate in the Electrified Area

To size the new project, it is necessary to know how many users out of a total of potential users will be connected to the project in the first year, and the period over which the rest are likely to begin service. The penetration rate is the proportion of potential consumers who receive service in any particular year, expressed as a percentage of total potential users. One can project a penetration rate for the area of the proposed project by knowing the penetration rate in nearby areas that have already been electrified.

Substation Characteristics

Another piece of important information for the electrical model of the system concerns the characteristics of the substation. The following characteristics must be obtained from the electric company:

Source Impedance

Conducting a fault current or short-circuit study so as to specify the overcurrent protection scheme requires obtaining the impedance on the high-voltage side of the substation. Many times, the electric distribution company will have to request this information from the company in charge of transmission. The data may come directly as impedances of positive and zero sequence, but very often it is shown as magnitude of the fault current for a three-phase fault and a single-phase fault. In that case, calculate the impedances according to Equations 1 and 2.

Equation 1: $Z1 = \dfrac{Vf}{I3f}$

Equation 2: $Z0 = \dfrac{3xVf}{I1f} - (2xZ1)$

Where:

Z1 = positive sequence impedance [ohms]

Z0 = zero sequence impedance [ohms]

Vf = nominal phase to ground [volts]

I3f = magnitude of three-phase fault current [amperes]

I1f = magnitude of single-phase to ground fault current [amperes]

The reference voltage should be of the same voltage level as the fault current. That is, if fault currents are obtained at the 69kV busbar of a substation, the Vf value that should be used to derive the fault impedances in ohms is 39.837 volts. If the engineer does not have the data on the phase angles of the faults, average values are –72º for Z1 and –75º for Z0.

Capacity of the Substation

Information must be compiled on the kVA capacity of power transformers at the substation. If there is more than one transformer, compile data on all of them and record whether they are connected in a bank, in parallel, in series, or independently (serving separate low voltage buses).

Available Capacity at the Substation

After recording the capacity of each transformer at the substation, one must record the maximum demand of each transformer to be able to calculate the capacity available for the proposed project. If there is a lack of capacity in the substation transformers, either an increase of capacity would have to be budgeted at the existing substation or a new substation installed closer to the project area.

Voltages on Both Sides of the Transformer

In every transformer at the substation, record the rated (nameplate) voltage for both the high voltage winding and the low volage winding. In many instances the nominal voltages of transformers are not the same as the nominal voltages of the system and the difference may influence the results of power flows.

Available Taps in the Transformer

Always record the presence of voltage adjusting taps on both sides of the transformer, as they influence the transformation relationship and therefore the output voltage of the transformer. There are usually five taps of +/- 5% on the high voltage side, i.e. +5%, +2.5%, 0% (nominal), -2.5% and –5%, but this varies according to the manufacturer and the purchase specification of the transformer. Also determine the position of the tap switch and therefore the tap position on which the transformer is operating.

Existence of Automatic Voltage Regulation

Another important factor to model in the power flow is the presence or absence of devices for voltage regulation. If the substation has voltage regulation equipment, verify whether it is incorporated into the transformer or separated, along with whether it is automatic or manually operated.

Impedance of the Transformer and Ground Connection

One of the most important pieces of information in the substation electrical model is the impedance of transformers and the way in which the neutral, if any is grounded. This information is usually presented on transformer name plates as %Z at the self cooled or OA rating. In the case of an autotransformer or a three-winding transformer, record three impedances: primary secondary, primary tertiary, and secondary tertiary. In some substations, where it is necessary to limit the magnitude of the fault current to ground, an impedance may be installed in the ground connection. If such an impedance exists, record its value, so as to include it in the power flow model. If the relation X/R of the transformer impedance is not specified, adopt the relation 10:1.

Transformer Connections

All three-phase transformers, or single-phase transformers connected in three-phase banks, can be defined by the connection configuration of delta or star windings, both on the high voltage side and on the low voltage side. Record the configuration of the connection on both sides of the transformer. This configuration does not influence the power flow model, but it does influence the fault current model, which is normally calculated using the same model of the electric system. The calculation of these fault currents influences the determination of the protection system that the project will need so as to be reliable.

Characteristics of Overcurrent Protection Devices

At every substation there should be overcurrent protective devices (such as fuses, reclosers, breakers, etc.) both on the high voltage side and low voltage side. For each device, record these characteristics:

- the type of device,
- the brand,
- the pickup current,
- relay settings (if any)
- the current transformer taps (if any)

Always record the presence of voltage adjusting taps on both sides of the transformer, as they influence the transformation relationship and therefore the output voltage of the transformer.

This information must be recorded for two reasons. First, it ensures that all devices are properly coordinated . Second, it ensures that with the loads of the new project, the load currents in the feeder do not exceed the pickup current of the protective device.

Characteristics of Other Substation Equipment

There may be other equipment in the substation that could have a great influence on the power flow model, such as capacitors and reactors, so be sure to record their capacity and form of connection to the system.

There may be other equipment in the substation that could have a great influence on the power flow model, such as capacitors and reactors, so be sure to record their capacity and form of connection to the system. For capacitors, record the control mode, whether it is automatic or manual. For automatic capacitors, also record the operation criteria (voltage, phase current, power factor, or time of day).

Field Inspection

After compiling the available information at the office of the electric operator, it is necessary to confirm and complement that information by visiting the project area to establish the geographic relationship between the loads to be electrified. During this visit, the basic configuration of the system to be installed will take shape, subject to modification during the process of analysis. For this reason, during this visit, one needs some way to establish distances and locations of towns and probable loads. The traditional way to perform this task is to get the best map available of the area and measure the distance between key points using the odometer in the vehicle. Although this procedure meets the needs of the project, modern technology affords a more accurate and advantageous option through use of GPS satellites for establishing geographic references. A GPS unit is portable and low cost, with geographic accuracy of +/- 7 meters in autonomous operation. Additional technologies offer the capacity for greater accuracy, but for this kind of project design they are not necessary.

Apart from their ability to accurately locate key points, most GPS units allow for the recording of a "track," which serves as a basis to construct a power flow model. Given the availability of these instruments at low cost and their advantages in laying out a plan for rural systems, there is no reason to resort to old techniques. This module therefore assumes the use of a GPS device during the field visit. The field visit thus includes the following steps:

Georeference of All Sites with GPS

During the visit to the site, the engineer should use the GPS to obtain georeferenced data for the routes followed (and/or the probable route for electrical lines to be installed) and of all the points of interest, such as the substation, the end of the three-phase line, the initial point of the project and the center of each community to be considered in the project.

Tracks or Routes

All along the route, the GPS can mark out and record the route followed. The engineer must make certain that the GPS is in the right mode to mark and record the route, because upon returning to the office, this information will be very useful in determining the length of both the existing lines and those to be installed.

Waypoints

The GPS capacity can also mark the location of points of interest for the project, such as the location of the substation, the end point of the three-phase line, the initial point and the center of each community to be considered in the project. Each such point should be recorded with an indicative name, which could be the complete name of the community (according to the GPS capacity) or a simpler indicative name. In any case, keep a written file of all waypoints with the indicative name, the real name of the community, and the additional characteristics of each point.

Files vs. Active Memory

During the registration of points and routes, the active memory of the instrument fills up. The engineer must ensure that the memory does not become full, because the GPS then erases the older data or simply stops recording new data. In either case, data are lost. Depending on the model, the active memory may fill in half a day or one whole day. When the memory is full, the engineer must download the data to the computer, so as to make room in the memory. If the GPS model permits it, the instrument operator should transfer the data of the active memory to a GPS internal file, so as to empty the active memory later, without losing data. Most GPS models have room in their memory for at least eight files of route data, besides their active memory.

Record Distances and Consumers

While using the GPS to record the route followed and the points of interest, keep a record of distances between all points, as well as the accumulated distance so far, to facilitate the calculation of distances later. This record gives the engineer the distances between communities or other points of interest without having to measure them again. Record the number of users in each community in the same record.

Table 1 provides an example of a record of points of interest, associated with distances.

Figure 1 shows the file on routes and points that was recorded in the GPS for the Tomoyo project.

Substation

Although all the necessary data can be obtained in the office of the electric company, it is often necessary to visit the substation and verify personally all the data on the equipment name plates. If the engineer can obtain permission for such a visit, it enables the collection of data that are often not archived in the office, such as the voltage taps in the transformers.

Verify Key Data

If visiting the substation, the engineer must verify all data compiled in the office and obtain all the missing data. The following table list shows the minimum data to be obtained:

- Capacity of the transformer
- Maximum load in the transformer
- Nominal high voltage rating
- Nominal low voltage rating
- Existence of tap changer in the transformer
- Present position of the tap, if any
- Winding configuration of the transformer (delta-wye, autotransformer, etc.)
- Type of voltage regulation
- Impedance of the transformer
- Overcurrent protection and settings
- Other equipment?

Draw a Single Line Diagram of the Substation

To more easily remember the configuration of the substation, the engineer must draw a single lilne diagram of the substation, showing the connections of all the equipment in the substation. Figure 2 is a practical example.

Between Substation and Initial Point

After obtaining the data on the substation and its georeferenced location, survey the existing line between the substation and the initial point of the project. Along the way he must record the route track with the GPS and mark the points of interest, such as the center of the communities already electrified, the significant existing loads, the end of the three-phase line, and the initial point of the project (if it is not the same). All along the way, keep a record as previously described.

Initial Point of the Project

At the initial point, verify the data on the existing line, such as the available voltage level (15kV, 25kV, or 35kv), number of phases available (1, 2, or 3), existence of a physical neutral, and the cross-section of the existing conductor. Also verify the characteristics of the existing users in the last electrified community, such as the following:

Consumption of Energy in the Last Electrified Community

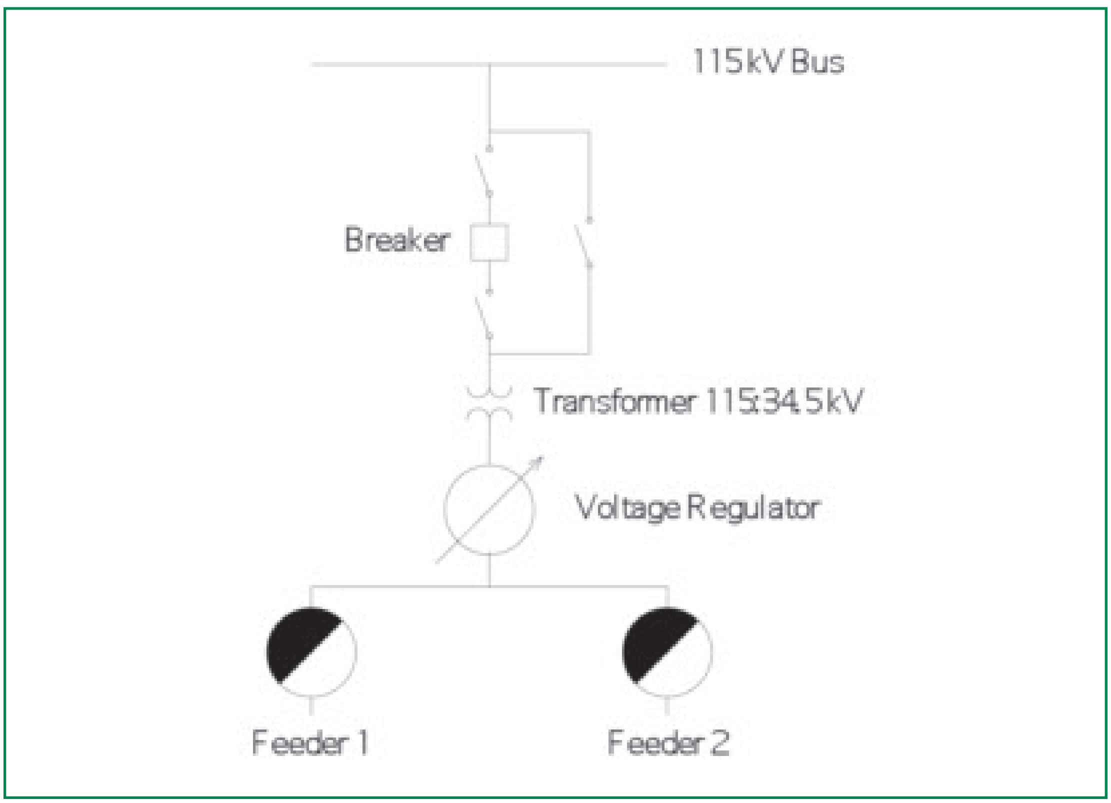
Quite probably, the communities that will benefit from the project have the same patterns of electric energy consumption as the neighboring communities that already have an electric energy supply. Therefore it is worth conducting a quick investigation on this aspect in the electrified community nearest to the initial point. The engineer must ask several community members about their present electricity consumption, especially at schools

Table 1. Record of km and users per community (Tomoyo)

Point of interest/community	km	Number of users	Notes
Substation Aranjuez	0	–	
Industrial Park	6	(3500kW)	(existing load)
Airport	8	(100kW)	(existing load)
Santa Catalina	13.3	(50kW)	End of three-phase line
Gra Loma	18.5	8	
Tawricasa	22.6	15	
Punilla	24.3	41	
Silvico	27.8	5	
Chataquila	30.6	1	Convent
Chaunaca	36.6	10	
Caraviri	41.4	30	
Colpacucho	48.9	30	
Potolo	54.3	300	End of line
Molle Molle	59.7	38	Chuquisaca
Molle Molle 2	60	102	Potosí
Sorojchi	62.6	73	
Isluco	64.6	22	
Yoroca	65.1	69	
Tomoyo	68.5	84	
Joroba	69.3	41	
Llatapata	70.6	35	
Kasapata	72.5	35	
Sorocoto	76.2	108	
Soroscopa	77.2	41	

Figure 1. Sample graphic of GPS points and routes data (Tomoyo)

Figure 2. Sample single line diagram



(if any), shops (if any) and in some houses. The average consumption obtained may be applied to potential users in the communities of the proposed project.

Present Penetration Rate in the Electrified Area

In the electrified community that is nearest to the initial point, perform a quick evaluation of the penetration rate. Check how many houses there are in the town, and how many have been connected to the electric system, and in what time spanthey have been connected. With this sample it is possible to define the penetration rate to be applied to the communities contemplated in the new project.

The project designer must survey the whole project, visit all the communities and georeference the roads as well as the central point of communities.

Survey the Proposed Project and Georeference with GPS

The project designer must survey the whole project, visit all the communities and georeference the roads as well as the central point of the communities (the square, the church, the school, etc.). Along the way, the engineer must spot and note down the features of the land that the electric lines will have to cross (many curves, gorges or streams, rocky ground, etc.). This provides an idea of the construction difficulties and helps with estimating the costs adequately. During the survey, the project designer must keep a record of the distances between communities and of the number of potential users in each community, as shown in Table 1.

Survey of Potential Users in each Community by Category

During the visit to each community, estimate the potential users in each category of consumption. Visit some of the most important loads to get an idea of the probable demand on the electric system.

One may base the estimation of the electricity demand on small generators or diesel engines that are installed and working and the energy consumption according to the liters of fuel the motor needs (daily, weekly or monthly). Typical consumers and categories found in rural areas include the following:

- Residential
- Shop
- Workshop
- Church
- School
- Sanitary post
- Water system
- Lumberyard
- Hotel
- Industries
- Three-phase loads

Table 2 shows an example of categorized users and loads for the Tomoyo project.

Evaluation of Loads

After the visit to the project area, the engineer should process all the data compiled. The first step of data processing is the calculation of the demand in each community. The best way to calculate the demand is to import all data in an Excel worksheet. Include the data illustrated in Table 2, which identifies the number of users per community, consumer category, and monthly consumption per category. From those data one can calculate the energy consumption for the entire community. The demand of each community can then be estimated, using the methodology explained in the following section.

Table 2. Count of users by class for the Tomoyo project

Community	Residence	Shop	School	Mill	Medical Center	Phone kiosk	Total
kWh/month	**25**	**75**	**100**	**250**	**150**	**120**	
Molle Molle (Chuquisaca)	54	1	1	1	–	–	57
Molle Molle (Potosi)	146	2	1	1	1	1	152
Sorojchi	105	2	1	–	1	1	110
Yoroca	98	3	1	1	–	–	103
Tomoyo	114	4	1	3	1	1	124
Llajtapata	50	1	–	–	1	–	52
Isluco	30	1	1	–	–	–	32
Jirota	60	1	1	–	–	–	62
Kasapata	50	1	–	–	1	–	52
Sorocoto	160	2	1	–	1	–	164
Soroscopa	60	1	1	–	–	–	62
TOTAL	**927**	**19**	**9**	**6**	**6**	**3**	**970**

Calculation of Total Energy Consumption per Community

The next step is to calculate the total energy consumption per community, by multiplying the number of potential users in each category by the specific consumption of that category, as included in the demographic study described in Module 5: *Methodology for Evaluating Feasibility of Rural Electrification Projects.* Table 3, column 3 shows the results of this step, taking as an example the data of the Tomoyo project, as recorded in Table 2.

Estimation of the Demand According to the REA Formula

The recommended methodology to calculate the demand of communities of predominantly residential consumer groups, described in Equation 3, is based on extensive studies of the characteristics of electric consumption in relation to the demand. It takes into account the number of consumers and the average monthly consumption, in kWh/consumer. The method defines the consumer factor (Factor A) and the kWh factor (Factor B), where Factor A reflects the fact that diversity increases with increases in the number of consumers, and Factor B reflects the improvement in the load factor with the increase in specific consumption.

Table 3. Demand and Consumption of Energy per community (Tomoyo)

Community	Users	kWh	kW
Molle Molle (Chuquisaca)	57	1,775	8
Molle Molle (Potosí)	152	4,420	19
Sorojchi	110	3,145	14
Yoroca	103	3,025	13
Tomoyo	124	4,270	18
Llajtapata	52	1,475	7
Isluco	32	925	5
Jirota	62	1,675	8
Kasapata	52	1,475	7
Sorocoto	164	4,400	19
Soroscopa	62	1,675	8
TOTAL	**970**	**28,260**	**124**

Equation 3: Demand (D) = (Factor "A") *(Factor "B")

Where:

Factor A = C*(1-0.4*C+0.4*(C^2+40)^0.5)

Factor B = 0.005925*(kWh/month/consumer)^0.885

C = number of consumers

Sometimes there is isolated power generation in some of the communities to be included in the project.

This method is empirical in the sense that its derivation was based on statistical correlation of measurements of loads in kW for consumer groups with different levels of specific consumption. The method has been verified for its use in countries with limited residential penetration of air conditioning.

In Bolivia, for example, a program of measuring and correlation indicated that the equation projects the demand of a mixed residential/commercial group, with an error margin not over 5%. This is a very good correlation indicating that the method is reliable. Table 3 shows an application of this method to calculate the demand of the communities in the Tomoyo project.

Estimation of the Demand Using Data from Existing Generation

Sometimes there is isolated power generation in some of the communities to be included in the project. In such cases, gathering generation data to estimate current demand may help to make more realistic projections. In that case, visit the power plant or system administrator to obtain the actual data available. Sometimes no direct data on loading are available due to a lack of instrucmentation or failure to record the information. However, fuel consumption data are almost always available. Use the next two points to understand how to calculate demand and energy using these data.

kWh per Liter of Fuel

The key information for calculating the energy consumed by the community is the record of fuel consumption (diesel or others), in liters or gallons per day or month. In many cases, particularly in countries where the government subsidizes the price of fuel, there are thefts and clandestine sales of the subsidized fuel, so that the engineer must try to determine how much fuel is actually used for electricity generation. With this information, the project designer can estimate the electrical energy generation, using the following conversion factor: 10 kWh/gallon or 2.64 kWh/liter diesel

Generator Size

Another point to consider is the capacity or size of the generator in HP, kW, or kVA. This does not directly indicate the real demand of a town, because generators are usually oversized, but it does indicate the maximum possible demand of a community supplied by this generator. One way to evaluate whether or not the generator is oversized is to calculate the energy generated as described in the section titled "Calculation of Total Energy Consumption per Community" and then calculate the demand using the methodology indicated in "Estimation of the Demand According to the REA Formula." Then compare the results.

Line Length

After projecting the energy consumption and calculating the demand per community, create a table recording the length of primary line required between each community and the next. This information may be compiled from the data record obtained during the visit to the site, as explained previously. Also, the information will be necessary to estimate the costs of the project. Table 4 shows a sample filled-in calculation sheet.

Analysis of Electric System Behavior

With all the information available about communities, including distances between them and energy demand, the engineer should base the electric design of the system on an analysis of power flows or voltage drops, to ensure that the project can supply the anticipated maximum demand under acceptable service conditions.

In addition to determing the voltage behavior of the project, the power flow study permits an evaluation of losses and allows the engineer to examine the required number of phases, the eventual need to reinforce the existing supply systems, or the requirement to establish a distribution system with a different voltage level from the existing one in the area.

Criteria for Analysis

To determine whether the study has met its objective, it is necessary to establish criteria for the evaluation and acceptance of results. The criteria normally used in planning studies relate to the level of voltage, the capacity of equipment and lines, the reliability of the service, and the level of losses.

Voltage Level

Minimum voltage levels are normalized in most countries, with the measuring point for purposes of application of regulations at the interconnection node between the supply system and the client, i.e. at the client's energy meter. Usually, the regulations set a range of acceptable voltage, both above and below a nominal value. Sometimes two ranges are included, one for normal conditions and another for contingencies.

In Bolivia, for example, the acceptable range is +4%/-7.5% for normal conditions and +7%/-10% for emergencies. Where there are regulations on the voltage level, apply the regulated acceptable values for normal conditions for planning purposes, leaving the additional margin for emergency conditions during the operation of the system. If there are no rules in a given country, use the values +5%/-10% for planning purposes.

It is important to point out that the limit values for voltage level have been set at low voltage at the point of delivery to the client, i.e. at the meter. For planning studies it is not customary to perform the analyses down to this level, but rather at a system level. Planning studies that use the methods presented in this module are based on the voltage at primary level, i.e., before the voltage drop represented by the distribution transformer, the low voltage (secondary) lines, and the service drop. As reference criteria, use the following values:

The engineer should base the electric design of the system on an analysis of power flows or voltage drops.

Table 4. Demand calculated per community (Tomoyo)

Community	Users	kWh	kW	Km
Molle Molle (Chuquisaca)	57	1,775	8	6.4
Molle Molle (Potosi)	152	4,420	19	–
Sorojchi	110	3,145	14	2.7
Yoroca	103	3,025	13	2.5
Tomoyo	124	4,270	18	4.2
Llajtapata	52	1,475	7	2
Isluco	32	925	5	2
Jirota	62	1,675	8	1
Kasapata	52	1,475	7	3
Sorocoto	164	4,400	19	3.5
Soroscopa	62	1,675	8	1
TOTAL	**970**	**28,260**	**124**	**28.3**

- Voltage drop in transformer 2%
- Voltage drop in secondary network 2%
- Voltage drop in service drop 1%
- Total drop in LT 5%

Taking into account an acceptable range of +5%/-10% for the service voltage, these values imply that the range to be applied to the study of the voltage drop in the primary system will be +/-5%. These values correspond to the RUS system design, which comprises single-phase transformers, whose impedance is limited by standards to 2.5%, along with very short lengths of low voltage lines.

Minimum voltage levels are normalized in most countries, with the measuring point for purposes of application of regulations at the interconnection node between the supply system and the client, i.e. at the client's energy meter.

Capacity of Equipment

For an acceptable power flow study of loading in the first year of the project, maximum demand must be limited to no more than 50% of the nominal capacity of the equipment and conductors. This criterion leaves a margin for growth without establishing an excessive level of overcapacity. Where the project involves an additional load on a line or existing substation, the criteria may be modified so as to maintain a margin of global capacity in the line or existing substation of 50% of the project load in the first year. In the last year of the analysis, the loads projected on any line or equipment should be within their normal capacity, i.e. allowing 100% demand in relation to the capacity.

Service Reliability

Service reliability, i.e. the frequency and duration of interruptions, depends more on maintenance of the system during operations than on the decisions made during the design, with one exception. This exception is the provision for a coordinated protection system against faults. A coordinated system ensures that for phase-to-phase faults, as well as for phase-to-ground faults, there are protection elements sensitive enough to detect and clear the fault. The system should be sectionalized in a planned manner, not only to help identify the location of the fault, but also to limit the number of affected consumers.

Since the most common type of fault in electric systems is the phase to ground fault, with an incidence of nearly 85% of all faults, it is important that reliable mechanisms be defined to detect and clear this type of fault. Ground faults often involve contact between one phase and some not very conductive element, like a tree or dry soil, so this is not an easy task. The criteria used by the RUS design system to identify and clear ground faults allows for a nominal resistance of 40 ohms in a series with the fault, which represents the resistance of the tree or soil contacted. This resistance is normally in series with the line impedances between the source and the fault, tending to reduce the minimum fault current. The coordination of elements that clear the fault is then designed to respond to this reduced fault current. The system used to clear faults may consist simply of fuses or a combination of reclosers and fuses, as long ast the rule of fault resistance is respected.

The minimum level of fault current for coordination purposes is a function of the nominal voltage of the system. Taking into account the specified resistance of 40 ohms and the impedance of only 5 km of line, the minimum fault current would be:

- For systems of 12.5kV phase to phase – 165 amp.
- For systems of 24.9kV phase to phase – 330 amp.
- For systems of 34.5kV phase to phase – 460 amp.

By applying the normal rules of uses the recloser/fuse coordination system, one can derive the maximum load allowable for the circuit and branches to ensure a coordinated system. By applying a similar reasoning to various voltage levels and considering the features of commercially available fuses and reclosers, the following results may be obtained:

- For systems of 12.5kV between phases:
  - Maximum load, main circuit – 70 amp
  - Maximum load, branches with fuses – 25 amp
- For systems of 24.9kV between phases:
  - Maximum load, main circuit – 140 amp
  - Maximum load, branches with fuses – 65 amp
- For systems of 34.5kV between phases:
  - Maximum load, main circuit – 200 amp
  - Maximum load, branches with fuses – 80 amp

These limitations are substantial when dealing with circuit loads, especially for systems of 12.5kV. While some devices for the electronic control of reclosers allow this range to be extended, protection coordination should be an element in the integral design of the system.

Control of Technical Losses

The control of technical losses has many aspects to be weighed, and not all of which are part of the system design process. An example of an extraneous factor is limitation of losses in the distribution transformers. When purchasing distribution transformers and evaluating their cost, one must use a formula that determines a financial value for losses, both for no load losses and load losses. This procedure applieds during the process of purchasing the equipment, not at the system design level.

However, the selection of the conductor cross-section is within reach of the system designer. This selection process optimizes investment expenses and guarantees more efficiency in the distribution of energy, considering both the cost of construction and the cost of technical losses resulting from the energy flow through the line. The process consists of applying Equation 4 for several levels of loads and of line construction costs with several alternative cross-sections of conductors.

Equation 4: $C_A = K_A*(Const) + K_L*(Loss)$

Where:

C_A = Total annual cost of one kilometer line

K_A = Fixed charge rate for investment costs, typically = 0.15

Const = Construction cost of one kilometer line with a specific conductor cross-section

K_L = Acquisition cost of one kWh energy at the beginning of the project

Loss = Annual loss in kWh of one kilometer line with the specific conductor cross-section for a specific peak demand and load factor.

$= (LLF)(n)(I^2R)*8.76$

Where:

LLF = Load factor of losses = $(\text{Load factor})^2 *0.84 + (\text{Load factor}) *0.16$

n = 3.0 if the line is three-phase, 2.0 if the line is single-phase

I = Phase current in amps for the specific load

R = resistance in ohms of one kilometer of the specific conductor

The repetitive application of this equation for different conductors and levels of demand results in a matrix of annual costs that determines the range of loads for which each conductor is optimal, thus identifying the conductor with the minimum annual cost.

This effort seems cumbersome, but its best application is to conduct a generalized study over the entire electric company system. The aim would be to select a group of no more than four cross-sections for conductors, which could reasonably cover among them the range of anticipated loads. This limits the inventory of connectors and other accessories without losing the capacity to meet the requirements of the system.

The aim would be to select a group of no more than four cross-sections for conductors, which could reasonably cover among them the range of anticipated loads.

After selecting the group of optimal conductors, repeat the analysis only when there is a substantial change in one of the factors, such as a significant increment in the cost of energy or a change in line design that seriously affects construction costs.

As an example of this procedure, Table 5 shows the result of a comparative analysis of annual cost for three-phase lines of 24.9kV under the following conditions:

- Cost of energy: US$ 0.08/kWH
- Load factor: 40%
- Power factor: 90%

Table 5: Comparison of annual costs for three-phase lines of 24.9kV

Conductor	#4 ACSR	#2 ACSR	#1/0 ACSR	#2/0 ACSR	#4/0 ACSR	397.5 MCM
Cost of Construction US$/km	$8,961	$9,140	$10,766	$12,941	$15,073	$24,314
Load kW	**Total Annual Cost US$/km**					
400	$1,406	$1,410	$1,639	$1,961	$2,273	$3,654
600	$1,483	$1,458	$1,670	$1,985	$2,288	$3,662
800	$1,591	$1,526	$1,713	$2,019	$2,310	$3,673
1000	$1,730	$1,614	$1,767	$2,062	$2,337	$3,688
1200	$1,900	$1,720	$1,835	$2,115	$2,371	$3,706
1400	$2,101	$1,846	$1,914	$2,178	$2,411	$3,727
1600	$2,332	$1,992	$2,005	$2,251	$2,456	$3,752
1800	$2,594	$2,157	$2,109	$2,333	$2,508	$3,780
2000	$2,888	$2,341	$2,225	$2,425	$2,566	$3,811
2500	$3,756	$2,887	$2,568	$2,698	$2,738	$3,903
3000	$4,817	$3,553	$2,988	$3,031	$2,948	$4,015
3500	$6,071	$4,341	$3,484	$3,424	$3,196	$4,148
4000	$7,519	$5,251	$4,056	$3,878	$3,483	$4,301
4500	$9,159	$6,281	$4,704	$4,393	$3,807	$4,475
5000	$10,992	$7,433	$5,428	$4,968	$4,170	$4,669
5500	$13,018	$8,706	$6,229	$5,603	$4,571	$4,883
6000	$15,237	$10,100	$7,106	$6,300	$5,010	$5,118
6500	$17,648	$11,616	$8,060	$7,056	$5,487	$5,374
7000	$20,253	$13,252	$9,089	$7,873	$6,002	$5,649

- Annual fixed charge rate: 0.15
- Cost of line construction based on 2005 prices of materials

The gray values represent the minimum costs for the load indicated. A #4 ACSR conductor has an application range of only up to 400kW, so it should not be considered as a conductor for standard use. Instead, #2 ACSR has an application range from 600kW to 1,600kW, which enables it to serve as a standardized conductor. A #1/0 ACSR conductor has an application range of 1,800kW to 2,500kW, although its range of advantage over #2 is not too marked below 2,000kW. A #2/0 ACSR conductor has no preferred application range, while the #4/0 conductor is preferred from 3,000kW to 6,000kW. For loads over 6,500kW, the optimal conductor is 397.5 MCM. In this example, the company would then remain with four normalized conductors, each one with a substantial application range, as follows:

- For loads up to 1,600kW: #2 AWG ACSR
- For loads of 1,601kW up to 3000kW: 1/0 AWG ACSR
- For loads of 3001kW up to 6500kW: 4/0 AWG ACSR
- For loads of 6501kW and over: 397.5 MCM ACSR

Other criteria may affect the selection of a normalized conductor. For example, the RUS recommends 1/0 AWG ACSR as the minimum standardized conductor for lines of the 35kV class, such as 33kV or 34.5kV_{LL}. (RUS 1724E-200, page 9-5). Another factor to be considered for the choice of conductor is the influence of safety standards in mechanical design. For instance, in conductors for primary lines, all conductors smaller than #2 AWG ACSR may be eliminated from the analysis, according to rule 235.B.1.b of the National Electric Safety Code (NESC).[3] This rule, which requires more horizontal separation for conductors smaller than #2 AWG ACSR, has the effect of making the spans shorter in primary lines with conductors smaller than #2 AWG ACSR. As a result, its cost per kilometer is higher than the lines using #2 AWG ACSR or those of greater sections.

After determining the cross-section of the phase conductor, the engineer must determine the cross-section of the conductor in the neutral. If the line is single-phase, the neutral should be of the same cross-section as the phase conductor, because both conductors share the same current. For a three-phase line, consider the use of a conductor with a smaller cross-section for the neutral, because in a three-phase line with balanced loads, a reduced current flows through the neutral.

The RUS Bulletin #61-4 recommends that the neutral conductor should have at least 20% of the capacity of the phase conductor in three-phase lines with balanced loads, and that they have similar characteristics in their sagging. Considering all the above, Table 6 shows a table of conductors with a reduced cross-section for the neutral.

Considerations in Power Flow Studies

A power flow study can be conducted with the help of specialized software, with general-use

[3]American National Standards Institute, *National Electric Safety Code* (New York: Institute of Electrical and Electronics Engineers, 2002).

Table 6. Reduced cross-section of neutral conductors in three-phase lines

Phase Conductor	Neutral Conductor
#2 AWG ACSR	#2 AWG ACSR-minimum size
1/0 AWG ACSR	#2 AWG ACSR
2/0 AWG ACSR	#2 AWG ACSR
3/0 AWG ACSR	1/0 AWG ACSR
4/0 AWG ACSR	1/0 AWG ACSR

spreadsheet software, by hand calculations, or with tables. However, to obtain reliable data, power flows should be carried out with a specialized engineering software package. Among the features found in such a package are some important aspects of the model method.

Model by Constant Load Instead of Constant Current

If the line is single-phase, the neutral should be of the same cross-section as the phase conductor, because both conductors share the same current.

Power flow studies that use computerized spreadsheets and simplified equation systems for manual application assume a constant load current in a given node, determined by dividing the load on the node by the nominal voltage. This is an approximation. At the end of the line, the voltage often differs from the nominal; it is the voltage at the source, less the voltage drop. If the current is then multiplied by the voltage at the end of the line, the model of constant current has effectively reduced the load in kVA of the node, yielding significant error in the voltage drop.

The method that comes closer to reality calculates a solution to the power flow, assuming a current that varies inversely with respect to the voltage of the node, to keep the load in kVA at that node constant. This model requires an iterative solution, i.e. repetition of the calculation until the differences between one solution and the previous are minimal. An iterative solution is difficult to implement in power flows based on spreadsheets or manual equations, but it is very common in specialized analysis packages.

The error caused by the difference in the load model is not very significant for voltage solutions close to the nominal. However, it becomes important with substantial voltage drops, where the difference in the current applied to the system is greater.

In the Tomoyo example of power flow, with a line of 77 km, conductor of #2 AWG ACSR and 4 MW load and using the constant load model, one could find a voltage drop of 10.3% and 38 kW of losses. But, using the constant current model, there would be a voltage drop of 9.87% and 37 kW of losses. These data represent an error over 4% in a rather small system, making for a significant difference in the evaluation of the system. The rate of error substantially increases when increasing the size and load of the system. Therfore, the program for power flow calculation should take into account a model based on constant loads and not on constant currents.

Capacity to Calculate the Capacitive Charging Current of Overhead Lines

Another simplification used by tables of voltage drops and spreadsheets is ignoring the capacitive charging current of overhead lines. This is another source of error, especially for long lines with light loads, the most common in rural electrification projects. For example, taking the small system in Tomoyo, with the technical and load characteristics described before there are 73 kVAR of capacitive effect. If this is not taken into account in the calculation of voltages, there would be an error of nearly 1% in the voltage drop and more than 5% in the calculation of losses. The error increases for systems with less load. Thus, the program for power flow should take into account the capacitive charging current effect of overhead lines.

Capacity to Model Unbalanced Loads

The reality of rural electrification lines, especially those with long, single-phase branches, is that it is difficult to achieve a balance of currents. The negative effect of the imbalance makes voltage regulation more difficult. Thus, it is important that the analysis system take this effect into account. Most programs for simplified power flow calculation use methods and equations based on positive sequence only, i.e., they cannot take into account the imbalance between phases. Many programs developed for the analysis of transmission systems also use the positive sequence approximation, because transmission lines are always three-phase and therefore always balanced. But this is not the case in distribution systems, so that the capacity to model unbalanced loads is essential.

Coming back to the Tomoyo project, the feeder for this project has 83% single-phase lines from the substation. Therefore, trying to study this system with a power flow based on values of positive sequence would not give a reliable result. Thus the power flow program for a distribution system should always have the capacity to make calculations with unbalanced loads, either with symmetrical components (an approximation) or with matrices (preferably).

Capacity to Calculate Unbalanced Impedances

Apart from their inability to model unbalanced loads, analysis programs using positive sequence approximations have no capacity to model unbalanced impedances. It is possible, though not very common, for a three-phase line to have different conductors in the different phases. For instance, it might have been constructed originally as a single-phase line with a given conductor cross-section and then converted into a three-phase line with another conductor cross-section for the two new phases. A still more common case of unbalanced impedances is a bank of single-phase transformers in which impedances are very similar but seldom exactly alike. Thus the power flow program for a distribution system should always have the capacity to calculate unbalanced impedances, preferably by using matrices.

Considerations for the Power Flow Model for the Tomoyo Project

The power flow analyses for the Tomoyo project, used as an example for this module, were performed with the Windmil analysis package (Milsoft Utility Solutions, Texas, USA). This package has all the required technical features for a power flow program and has an additional function called "LandBase," which very usefully creates the model of the system by directly importing the tracks and waypoints from GPS units. Figure 3 shows the Windmil screen with the GPS data of the Tomoyo project imported by LandBase.

This graphic shows the points of interest, such as communities included in the project and the routes between them, along the line. In the lower corner of the screen, the scale of the drawing appears along with geographic coordinates of a selected point. Figure 4 shows the communities of the Tomoyo project superimposed on GPS data.

Selection of Primary Voltage Level

After creating the geographic model, it is necessary to determine the voltage to be used for the new extension. The choice of a voltage level for a given project depends to a large extent on the levels already used in the area. Selecting a primary voltage that differs from the standard used in the project area requires the installation of substation, and possibly transmission, equipment. This decision should be carefully examined prior to final design. With that said, a voltage level of the 25kV or 35kV class may be reasonably introduced in the following circumstances:

- If the existing voltage (whether 5kV or 15kV) cannot be extended to serve the new project, without investing in substations and sub-transmission lines
- If the system has to serve large specific loads, which are scattered over a wide area, such as an irrigation project, in which case a different voltage level from the existing one that serves residential loads in the same area may be acceptable
- If the client or group of clients to be served represents a pilot project for a more extensive development of similar projects in the area
- If a sub-transmission voltage within the same company exists that may be used for distribution (In those cases in which the electric company has historically utilized a 34.5kV or 22kV as a sub-transmission voltage, these lines may be converted to fit distribution applications at an attractive cost.)

In the Tomoyo project, none of these considerations applied, so the project was developed at 14.4 kV

The reality of rural electrification lines, especially those with long, single-phase branches, is that it is difficult to achieve a balance of currents.

Figure 3. Windmil screen with GPS data (Tomoyo)

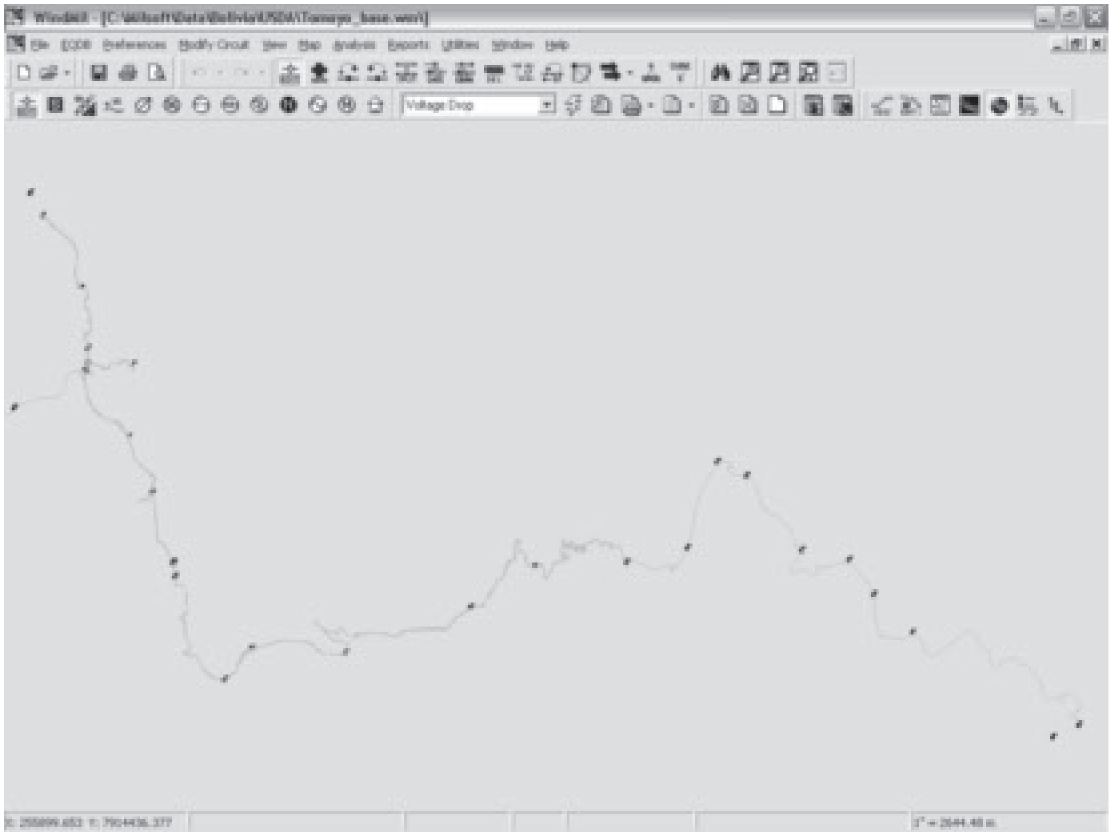
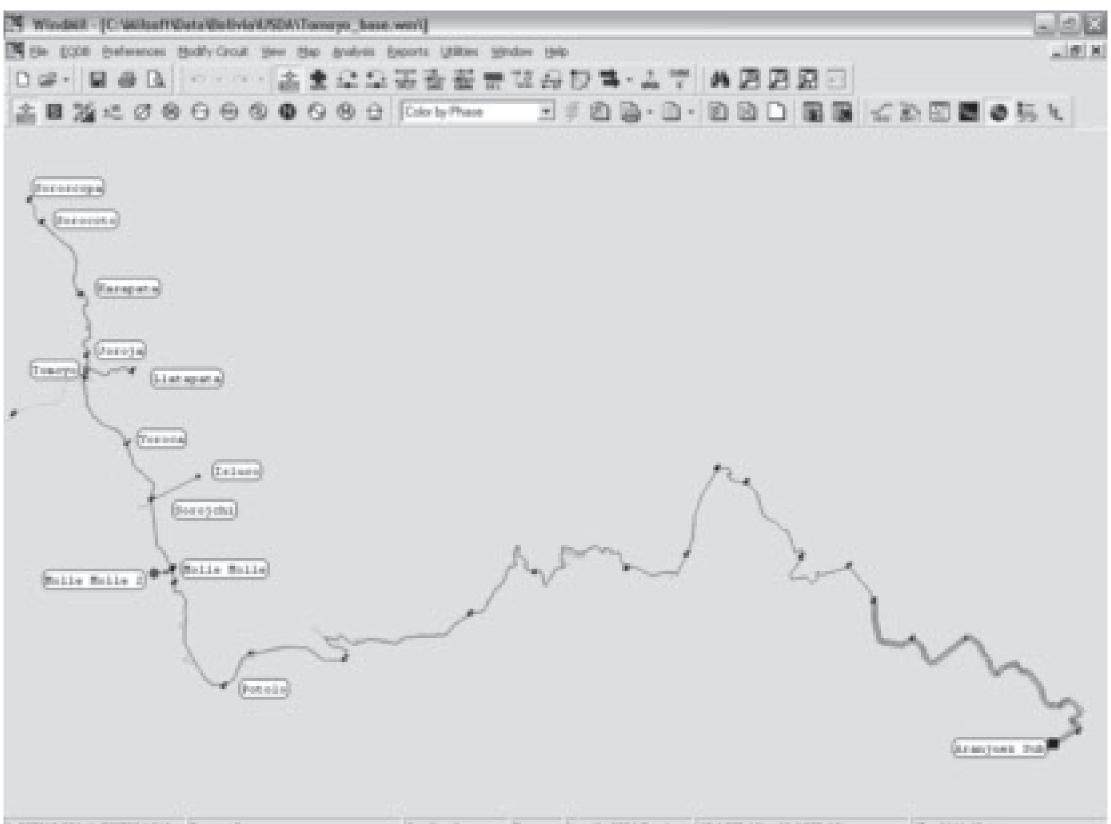


Figure 4. Windmil screen with GPS data and communities (Tomoyo)



(class 25kV) as an extension of the existing system.

Determination of the Number of Phases

After determining the length of the proposed system and calculating the demand of potential loads in existing lines and those proposed for the project, the engineer must determine the number of phases required in the proposed lines of the project. As indicated at the start, the RUS integrated design system assumes that rural lines should be single-phase, for economic reasons, i.e. phase and neutral. However, some situations require consideration of the extension of two-phase lines (two phases and neutral) or three-phase lines, for the following reasons:

- The current in one of the single-phase branches exceeds the limit established for a system of coordinated protection.
- The result of the power flow studies indicates that using a single-phase system for the projected loads will not maintain maintain voltage levels within regulatory limits.
- There are three-phase loads in the project area that are large enough to make a conversion into single-phase impossible. Generally, motors of over 10HP are three-phase, though the technology exists to overcome this limitation.
- The nature of the loads to be covered by the project rules out the use of single-phase systems. For example, a project to develop an extensive irrigation system with electric pumps of over 10HP each should be designed from the beginning with three-phase lines.
- There is a need to distribute the loads among phases to ensure a better balance of phase currents at the source. This is a necessary consideration in cases where the permissible percentage of current imbalance is regulated by law, as in Bolivia.

The need for alternative solutions to the extension of single-phase lines must always be justified on the basis of economic and/or regulatory considerations. Where the requirement for a three-phase service is only potential and not immediate, the design of the single-phase lines as standardized by RUS facilitates the conversion to a three-phase configuration, with the addition of a crossarm and two phase conductors. With the services of a properly trained contractor and with adequate equipment, it is possible to realize this conversion without de-energizing the single-phase line. For certain cases, it is possible to plan, initially, single-phase construction, to be converted to three-phase in the future, without losing the economic benefits of the initial single-phase solution.

The Tomoyo project did not require modification of the initial design, and the system was designed with single-phase lines.

In situations where loads are scattered, and with little growth potential, some companies and electric authorities have applied the SWER system.

Determine the Application of a Physical Neutral

In situations where loads are scattered, and with little growth potential, some companies and electric authorities have applied the SWER system, which consists of a single phase conductor without physical neutral. This system also can be found in areas where there are problems with the theft of the neutral conductor. The SWER system has been successfully applied in many countries, including Australia and Tunisia, among others.

The main considerations in its application are as follows:

- For situations with no anticipated hope of load growth beyond a very low initial level (8 amperes per circuit), it is possible to use steel conductors, long spans of around 250 meters, and a narrow right of way. This application achieves a 50% reduction in the construction cost of a conventional single-phase line with aluminum conductors steel reinforced (ACSR).

- When using conventional ACSR conductors to maintain capacity and facilitate service to higher loads or to permit the future conversion to three-phase systems, the economic benefits are lower. Savings would be around 12% due solely to eliminating the neutral conductor.

- MRT/SWER systems produce higher levels of interference with telephone circuits than a conventional single-phase line. This is not as much of a disadvantage as previously thought, given the trend toward the elimination of wired telephone systems.

- To control neutral-to-ground voltages in the service drops, implement a system of double grounding at the transformation points. A double grounding system uses a separate ground for the primary neutral of the transformer and another, at a certain distance, for the neutral of the low voltage system and the service drop. This arrangement slightly increases the cost for transformation points.

- To limit the voltage gradient to adequately ensure the safety of persons and pets, limit the maximum value of the resulting voltage in the grounding of the primary winding of the transformer, to 20 volts. To obtain this value for transformers of different capacities, one must ensure that ground resistances do not exceed the values indicated in Table 7. Particularly for the 7.2kV MRT/SWER system, achieving these values may increase the cost of grounding, especially in difficult types of soil.

- Another consideration is the separation between the primary system grounding and that of the low voltage system and service drop. The regulations used by the Australian Electrification Authority, which serve as the model for most SWER electrification efforts, require a 3 meter separation between the grounding of the primary winding of the transformer and the user's ground system, with that no interconnections between them. To obtain this separation, insulate the ground wire of the secondary neutral from the ground conductor of the primary neutral and install separate fields of ground rods.

Taking into account the advantages, disadvantages, and limitations of the MRT/SWER system, the decision for the Tomoyo project was to use a conventional single-phase system. i.e. with phase and physical neutral, so that the demand of the project would have 15 amperes for the year 20.

Determination of the Conductor Cross-section

The conductor cross-section should be determined according to the criteria set forth in the section on *Criteria for Analysis,* based on an economic choice and limited by considerations of protection coordination and voltage drops. For the conditions of energy costs, load factor, and power factor described in the same section, the economic matrix of conductors for 14.4kV single-phase lines appears in Table 8.

Again, the gray results represent the most economical conductors for the load indicated. The #4 conductor has an application range up to 200 kW, whereas the #2 conductor has an

Table 7. Maximum resistances for SWER ground systems

Voltage of the System	7.2kV	14.4kV	19.9kV
Module	Maximum Ground Resistance – Ohms		
10 kVA	15	30	30 (regulations)
15 kVA	10	20	27
25 kVA	5	10	16

application range of 250 kW to 550 kW, and the #1/0, from 600 kW to 900 kW. As previously, the #2/0 conductor has practically no application range and the #4/0 conductor is applicable only above 1000 kW. Taking into account that the limitation owing to the coordination of 14.4kV single-phase branches is 65 amp, or nearly 1000 kW, a #4/0 conductor cannot be considered for this application. Preferred conductors for 14.4kV single-phase lines are clearly the #2 ACSR for loads up to 550 kW and the #1/0 ACSR for loads from 600kW to the coordination limit of 1000kW. Since the load projected for the Tomoyo project is 124 kW for the first year, with a projection to be increased up to 250 kW until the year 15, the standardized, utilized conductor for this project is the #2 ACSR.

Minimum Voltage Calculation

After selecting the number of phases and cross-section of the conductor, run the power flow model to determine whether the selections made are adequate, or whether they have to be adjusted by increasing the number of phases and/or the conductor cross-section. Decisions should be based on the following criteria.

Voltage in the First Year

Upon running the program with the projected load for the first year, the result should show voltage levels of +5%/-5% with respect to the nominal voltage. The loads applied come from the analysis of the demand, which takes into account a certain

If values under 95% of the nominal voltage are found at any point in the model, increase either the number of phases or the conductor cross-section, according to the parameters specified in previous sections.

Table 8: Comparison of total annual cost for 14.4 kV single-phase lines

Conductor	#4 ACSR	#2 ACSR	#1/0 ACSR	#2/0 ACSR	#4/0 ACSR
Cost of Construction US$/km	$5,668	$6,015	$7,138	$8,163	$9,839
Load kW	Total Annual US$/km				
100	$873	$917	$1,080	$1,232	$1,480
150	$902	$935	$1,091	$1,241	$1,486
200	$943	$960	$1,107	$1,253	$1,494
250	$995	$993	$1,128	$1,270	$1,504
300	$1,059	$1,033	$1,153	$1,290	$1,517
350	$1,134	$1,080	$1,183	$1,313	$1,532
400	$1,221	$1,135	$1,217	$1,341	$1,549
450	$1,319	$1,197	$1,256	$1,371	$1,569
500	$1,429	$1,266	$1,300	$1,406	$1,590
550	$1,551	$1,342	$1,348	$1,444	$1,614
600	$1,684	$1,426	$1,400	$1,486	$1,641
650	$1,828	$1,517	$1,457	$1,531	$1,669
700	$1,985	$1,615	$1,519	$1,580	$1,700
750	$2,152	$1,720	$1,586	$1,633	$1,734
800	$2,332	$1,833	$1,656	$1,689	$1,769
850	$2,523	$1,953	$1,732	$1,749	$1,807
900	$2,725	$2,081	$1,812	$1,813	$1,847
950	$2,940	$2,215	$1,897	$1,880	$1,889
1000	$3,165	$2,357	$1,986	$1,951	$1,934

penetration rate for potential users. If values under 95% of the nominal voltage are found at any point in the model, increase either the number of phases or the conductor cross-section, according to the parameters specified in previous sections. Do not apply any voltage regulators in the first years. Figure 5 shows the result for the first year of the Tomoyo project analysis.

Voltage in the Final Year

Upon running the power flow program with the projected demand for the last (usually the 20th) year considered in the analysis of the project, the result should show that 90% of the nominal voltage is the worst situation. The loads to be applied come from the analysis of demand, which takes into account a certain penetration rate for potential users and the vegetative growth rate. From the year 2 on, the use of regulators is acceptable to maintain 95% of nominal voltage for final users, so as to comply with the profile of regulated voltage during the useful life of the line (usually 30 years). If a level below 90% of nominal voltage is observed at any node of the model, increase either the number of phases or the conductor cross-section in the first year, according to the parameters specified in previous sections. Figure 6 shows the result for the year 20 of the analysis, in the Tomoyo project.

Coordination of Protection for Overcurrents

With the same database as for the power flow, the engineer will be able to calculate the magnitudes of the fault currents, in order to conduct the coordination study on protection devices for overcurrents. Figure 7 shows the values of fault currents calculated for the Tomoyo project.

After calculating the fault currents, coordinate the protection devices. For this purpose, start the coordination process with the fuse devices of the distribution transformers. These fuses must be coordinated with the fuses of the laterals, then with the main line and finally with the recloser in the substation. A detailed explanation of the coordination procedure for the various protection devices is outside the scope of this module.

ESTIMATION OF PROJECT COSTS

After following the procedure detailed in the *Project Design* section, the project engineer has an electrical pre-design that includes the determination of line lengths, the number of potential users, primary voltage, number of phases, conductor size, and whether or not a physical neutral will be used. With these data, it is possible to prepare a detailed estimate of project costs. The following presentation lays out the procedure for estimating the cost of rural electrification projects.

Materials Database

The first step in estimating project costs consists in maintaining a database of the cost of materials, according to purchases or previous quotations. This database should include the unit price of each item of material, including the cost of shipment, and the total amounts for each purchase. Unit prices always depend on the volume of purchased materials, with greater volumes usually resulting in lower unit prices. This database must also differentiate between materials for projects of 15, 25 or 35kV,

Table 9. Format for a materials database

Description of Item	Historical Unit Price	Taxes	Inflation	Projected Unit Price

Figure 5. Sample three-line diagram of the power flow at year 1 (Tomoyo)

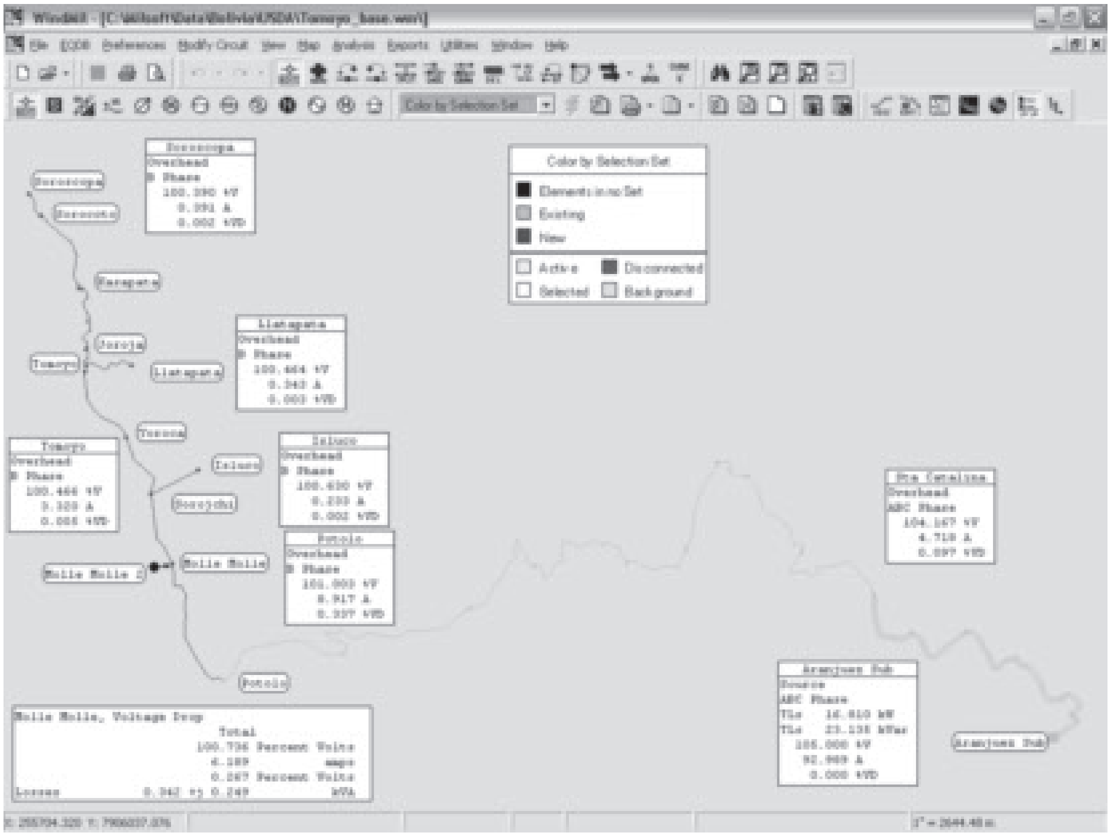


Figure 6. Sample three-line diagram of the power flow at year 20 (Tomoyo)

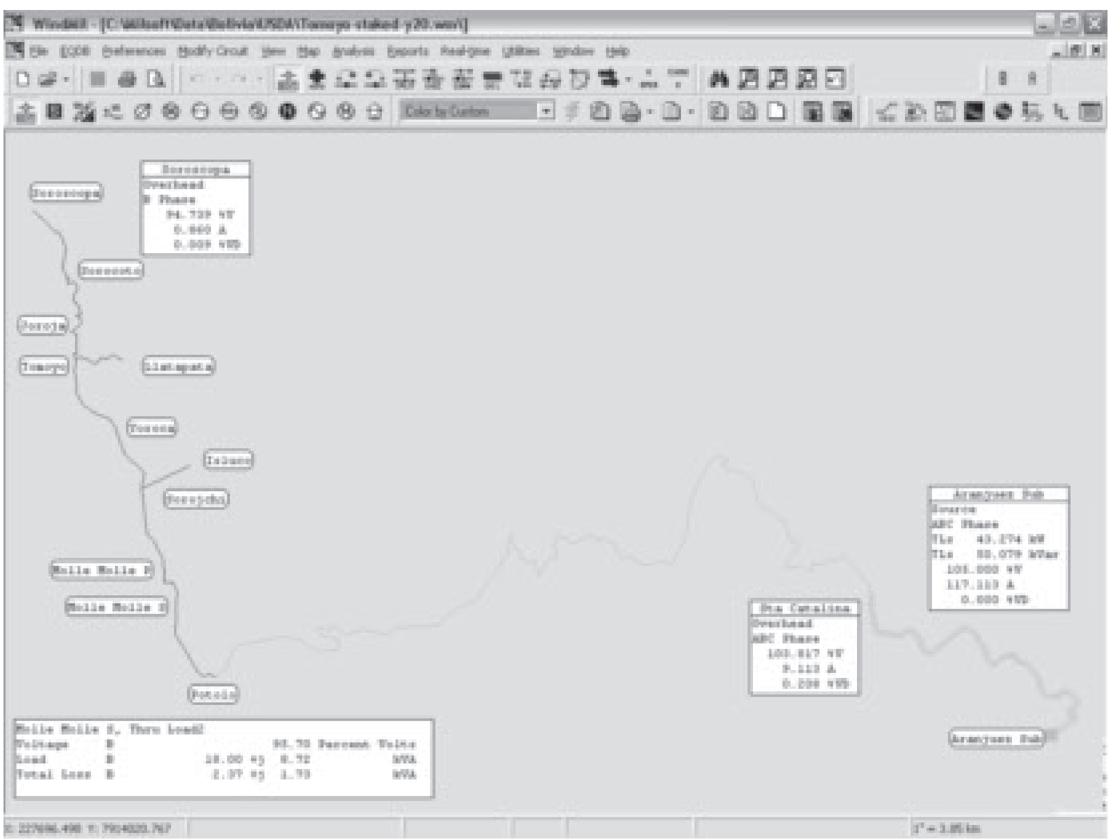
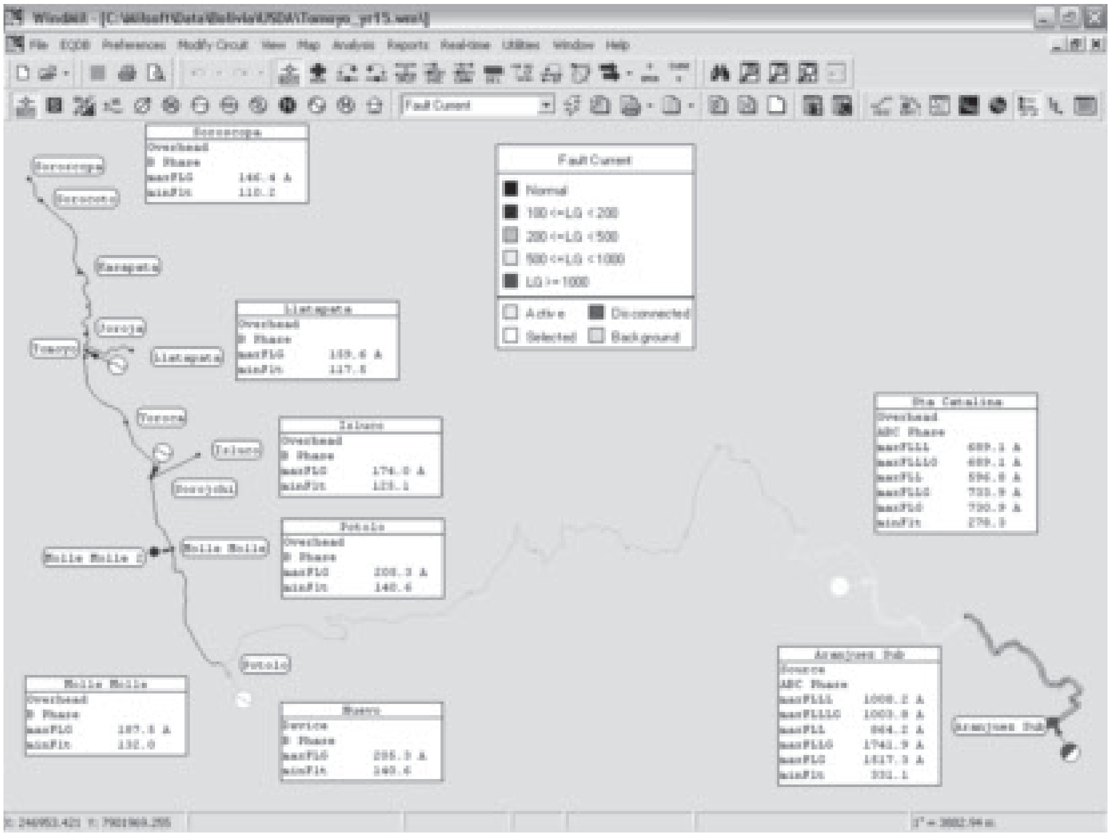


Figure 7. Sample three-line diagram of the values of fault currents (Tomoyo)



This database should include the unit price of each item of material, including the cost of shipment, and the total amounts for each purchase.

because some items differ according to their voltage level (insulators, transformers, etc.).

One must also consider taxes, if applicable to the project in question. Most projects financed with external aid are exempt from local taxes, but in other cases, one must determine the applicability of taxes and their amount. Another very important factor, in being able to apply historical costs to future projects, is the projection of the cost itself. The historical cost of materials may be projected to the future by using an inflation rate or a percentage of change in the cost of metals.[4]

Labor Database

Apart from a database for the cost of materials, the designer should maintain a database for the cost of labor, using the construction costs of previous projects. The costs on this database must be disaggregated by construction unit and not by kilometer, to be able to differentiate lines with different features. To apply historical costs to future projects, the engineer has to apply an inflation rate. Table 10 shows a typical format for a labor database.

Database by Construction Unit

The next step in determining project costs consists in calculating the investment costs by construction unit. Calculate these costs by adding the cost of materials for all the items included in the unit, plus the cost of labor for that unit. Table 11 shows a typical format for the database on cost by construction unit.

Database on Previous Designs

The engineer in charge needs to maintain another database on construction units by kilometer of line,

[4]A good database for metals is the London Metal Exchange at: http://www.lme.co.uk.

Table 10. Format for a labor database

Description of the Unit	Historical Unit Price	Inflation	Projected Unit Price

for the feeders between communities (called trunk lines or main feeders), and on construction units for distribution networks in the communities (i.e., taps off the primary line, transformation points, and low voltage distribution networks). The database for feeders between communities must include poles, primary structures, conductors, anchors and all the primary line hardware. The database on distribution networks for the communities must include all the units used in primary lines, underbuild, and secondary lines, and the transformation points in the communities.

In the database on feeders between communities, distinguish between three-phase and single-phase lines. Likewise, the database on feeders between communities must distinguish between lines in flat, level areas and broken terrain or areas with many line angles, because construction costs of electric lines differ greatly between these two types of land. Then, when going to the field, the engineer will evaluate the line to be built and will be able to determine its cost per unit.

Table 12 shows a format for a database on construction units by kilometer/feeder.

Database on the Costs of Service Drops

After developing the cost by kilometer of primary lines for feeders between communities and the cost by user for the distribution network in each community, develop cost estimations for the service drops. As in the preceding steps, base these estimations on a database of historical data, which includes the cost of materials and labor. There are various types of service drops to take into account, each with its particularities.

Apart from a database for the cost of materials, the designer should maintain a database for the cost of labor, using the construction costs of previous projects.

Table 11. Format for a database on cost by construction unit

Unit: ZA1			
Description	**Quantity**	**Unit Cost**	**Total Cost**
Square washer, 2-1/4″(5/8″)	3	$0.13	$0.39
Locknut, 5/8″	2	$0.11	$0.23
Spool insulator, 1-3/4″	1	$1.22	$1.22
Compression connector, ground to neutral	1	$0.33	$0.33
Preformed armor rods, single support, phase	1	$3.01	$3.01
Preformed armor rods, single support, neutral	1	$2.17	$2.17
Machine Bolt, 5/8″ x 10″	2	$0.55	$1.10
Spool bolt , 5/8″ x 10″	1	$2.43	$2.43
Pin-type insulator, ANSI 56-3	1	$30.22	$30.22
Pole top Pin , 20″	1	$3.68	$3.68
Aluminum tie wire, feet	15	$0.07	$1.04
Total Material Cost			$45.81
Labor Cost			$5.79
Total Unit Cost			**$51.60**

Table 12. Format for a database on construction units by kilometer

Unit	Quantity	Unit Cost	Total Cost
ZC1	71	$165.28	$11,734.65
ZC1-1	1	$310.71	$310.71
ZC2	9	$311.45	$2,803.08
ZC3	5	$221.28	$1,106.41
ZC6-10	2	$490.96	$981.92
ZC7-1	6	$230.48	$1,382.86
ZC7H	1	$259.57	$259.57
ZC8H	3	$422.10	$1,266.30
E1-2	49	$22.95	$1,124.64
E6-2	6	$38.80	$232.79
F1-12	61	$20.46	$1,247.79
M2-11	48	$17.71	$849.93
ZM3-3	1	$455.90	$455.90
ZM5-7	3	$42.79	$128.36
ZM5-18	1	$42.24	$42.24
Poste 11-6	78	$107.22	$8,362.93
Poste 12-6	10	$130.67	$1,306.73
Poste 13.5-5	6	$144.30	$865.79
1/0 ACSR	35,679	$0.55	$19,671.74
#2 ACSR	11,893	$0.46	$5,527.81
RM6	10,225	$0.44	$4,547.43
TOTAL			**$64,209.60**
Units 12Km			
Unit Price $5,398.94 /km			

Table 13 shows an example of a database on the distribution of different types of service drops.

Database on the Cost of Staking

The only cost component still to be determined is that of staking (design) of the proposed project. To have an idea of its cost, keep a database of the historical costs of staking in recent projects. This database must include the cost by kilometer for feeders between communities and the cost by user for the staking of the distribution network in each community. With this, the engineer can make a projection of the annual cost, taking into account an inflation rate. Table

Table 13. Distribution of different types of service drops

Type of Service Drop	K10M	K10E	K10L	K10P	K10P-X	TOTAL
Description	Fixed on wooden wall	Embedded in earth wall	Fixed on brick wall	On 6 m. pole	On 9 m. pole	
Quantity	414	494	530	3,122	180	4,740
Percentage	9%	10%	11%	66%	4%	100%

Table 14. Costs of electric line staking

Project	Cost/km	Cost/User
Nº 1	$218.76	$7.56
Nº 2	$248.25	$8.07
Nº 3	$246.90	$8.97
Nº 4	$222.22	$9.88
Nº 5	$195.00	$10.00
Nº 6	$215.00	$13.00
Average:	$224.35	$9.58
Inflation rate: 5%		
Projected:	**$235.57**	**$10.06**

14 shows an example of a database on the costs of staking.

Total Investment Cost of the Project

Upon arriving at this step, the engineer now has all the cost components necessary to estimate the total budget for the project.

Add these costs to the Excel worksheet described previously.

Table 15 shows an example of a worksheet that arrives at the total cost of the project.

Tables of Indicative Line Costs

To aid in calculations of project costs, Table 16 shows costs of projects recently carried out by NRECA in Latin America.

REQUIREMENTS FOR THE PRESENTATION OF THE PROJECT

After completing the electrical design of the project, as explained in *Project Design,* the engineer is in a position to estimate the total cost of the project, according to the section on *Estimation of project costs* of this module.

There are various types of service drops to take into account, each with its particularities.

The engineer must next prepare the presentation of the project. This presentation contains a description of the project and a power flow, as explained in the previous sections. The description should contain many engineering tables or catalogues of materials, which add volume but do not assist in the description of the project.

Description of the Project

Keep the description simple, so it is useful for the evaluation of the project's feasibility. Table 17 shows a scheme for clarifying the description

Table 15. Sample cost evaluation (Tomoyo)

Tomoyo	km	phases	users	KWh	kW	Staking	Feeder	Distribution	Total Cost	$/User
Molle Molle (ambos)	6.4	1	200	6,000	25	$4,723	$28,160	$94,000	$126,883	$634
Sorojchi	2.7	1	105	3,150	14	$2,240	$11,880	$49,350	$63,470	$604
Yoroca	2.5	1	98	2,940	13	$2,084	$11,000	$46,060	$59,144	$604
Tomoyo	4.2	1	114	3,420	15	$2,893	$18,480	$53,580	$74,953	$657
Llatapata	2	1	50	1,500	7	$1,326	$8,800	$23,500	$33,626	$673
Isluco	2	1	30	900	5	$1,086	$8,800	$14,100	$23,986	$800
Jiroja	1	1	60	1,800	8	$1,083	$4,400	$28,200	$33,683	$561
Kasapata	3	1	50	1,500	7	$1,689	$13,200	$23,500	$38,389	$768
Sorocoto	3.5	1	160	4,800	20	$3,191	$15,400	$75,200	$93,791	$586
Soroscopa	1	1	60	1,800	8	$1,083	$4,400	$28,200	$33,683	$561
	28.3	**10**	**927**	**27,810**	**121**	**$21,397**	**$124,520**	**$435,690**	**$581,607**	**$627**

Table 16. Costs of NRECA projects

	Bolivia	Nicaragua	Dominican Republic	Guatemala
Voltage Class	**35 kV**	**25 kV**	**15 kV**	**15 kV**
Three-phase US$ per km	$5,300	$9,534	$9,365	
Single-phase US$ per km	$3,100	$6,329	$5,472	$4,000

of the project. The numerical values correspond to the Tomoyo project.

Power Flow

The power flow proves that the design is adequate for the project throughout the period evaluated. Consequently, there will be at least two power flows: one for the first year of the project and another for the last. A third power flow may be included when the study warrants the inclusion of some voltage regulation equipment during the life of the project, or during the time allowed for project analysis, so as to show where, when, and with what capacity this equipment is required to be installed. In these cases, the power flow should include a table of results showing the data for each point of the study and a three-line diagram that displays the results in a graphical format.

Table 17. Sample project description (Tomoyo)

Name of the Project	Tomoyo
Location of the Project	Department of Potosí
Names of the communities favoured	Molle Molle (ambos), Sorojchi, Yoroca, Tomoyo, Llatapata, Isluco, Joroja, Kasapata, Sorocoto, Soroscopa
Number of users favoured	927
Kilometers of primary lines	28.3
Primary voltage	14.4 kV
Number of phases	One
Section of conductor	#2 AWG ACSR phase and neutral
Estimated cost of parking	$21,397
Estimated cost of feeders	$124,520
Estimated cost of distribution networks	$435,690
Total estimated cost of project	$581,607
Estimated cost by user	$627