DEVELOPMENT OF A COST OPTIMIZED LV DISTRIBUTION SYSTEM EMPLOYING THE POLYGON-BASED PLANNING

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Degree of Master of Science in Electrical Engineering

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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Dr. J.V.U.P. Jayatunga

Signature of the supervisor: Date

Dr. P.S.N. De Silva

ABSTRACT

Network planning is a critical task in an electrical utility. A network should be capable of suppling the demand continuously with minimum disturbances. The responsibility of the network planner is to ensure a reliable supply, confirming the network parameters like loading levels, voltage drop, loss levels, etc. within the defined limits. Loss is one critical parameter since it is directly related to the income of the utility. So utilities strive to reduce the loss while maintaining other network performance indices at satisfactory levels. Using various methods and developed tools, High Voltage (HV) and Medium Voltage (MV) networks are planned to fulfill the above requirements.

However, being at the bottom of the network structure, utilities pay less attention to Low Voltage (LV) network planning. The largest share of loss is associated with LV networks due to the flowing higher currents and higher number LV feeders. So a systematic planning approach is essential for LV networks. Further, unlike the MV networks, LV networks have a number of alternative criteria for planning to deliver the same outcome. As an example various transformer sizes and conductor sizes are available for using in planning the LV networks. Identification of the proper planning criteria is essential to select the best alternative for satisfactory performance at minimum cost.

This project proposes a novel methodology to design a cost optimized LV distribution system employing the polygon-based planning, based on the load density of the area, while maintaining all network operational parameters within required limits. In this project, polygons-based planning method in which transformer feeding areas are represented by regular polygons has been adapted for identifying the optimum planning criteria. Further the identified criteria have been validated through an analysis performed on an existing network.

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LIST OF ABBREVIATIONS

ABC	- Arial Bundle Conductor
CEB	- Ceylon Electricity Board
ENS	- Energy Not Served
GIS	- Geographical Information System
HV	- High Voltage
LECO	- Lanka Electricity Company (Private) Limited
LF	- Load Factor
LV	- Low Voltage
MV	- Medium Voltage
NPV	- Net Present Value
PS	- Primary Substation
SCM	- Standard Cost Manual
UTL	- Utilization Time of Losses

CHAPTER 1

1 INTRODUCTION

1.1 BACKGROUND

The main sectors that an electricity network is comprised of are Generation, Transmission and Distribution. The power generated through the generation points are conveyed through the transmission networks and distributed over the distribution networks. Based on the technical, geographical and economic constraints the voltage levels and configurations for transmission and distribution networks are determined. Transmission networks are generally maintained as ring circuits in order to uphold the best possible reliability levels. Distribution network can be sub divided in to MV and LV based on the voltage level and both MV and LV networks are maintained as radial circuits. However, MV networks are interconnected by means of switches and contain the reconfiguration capability in the event of an outage to enhance the reliability levels.

Though the LV network holds the lowest reliability margins being the bottommost layer of the electrical network, its criticalness of the performance plays a vital role. In LV networks magnitude of the currents are very high and due to that power losses and voltage drops are inevitable. LV network is the point that the utility meets its consumers. Due to numerous reasons like geographical constraints, socio-economic factors, etc. consumer addition to the LV network does not guarantee an equal loading level of the network. This unequal loading as well as complex network configurations directly affect the performance of LV network like voltage drop, power loss levels, loading levels of the components, etc. So owing to the above issues planning and maintaining of the LV network is a challenging task.

In Sri Lankan context the Ceylon Electricity Board (CEB) and the Lanka Electricity Company (Private) Limited (LECO) hold the responsibility of whole electrical network being only the 2 utilities operating in the country. 132kV and 220kV voltages are being used for transmission and the network is entirely handled by CEB. Except for highly residential areas like Colombo and Kandy cities in which MV distribution is 11 kV, MV distribution consists of 33 kV under CEB. 11kV is used by LECO) for its entire area of distribution and CEB prefers 11kV in Colombo and Kandy city areas for MV distribution. 400V is the typical voltage used for LV distribution by both utilities. TT is the standard earthing system followed in Sri Lanka and hence the 4 wire system is used for LV distribution which includes 3 phases and the neutral.

33/0.4 kV or 11/0.4kV distribution transformers installed on convenient places do the MV to LV conversion.

Unlike the HV and MV networks, reliability of LV network is less due to the unavailability of alternative feeder arrangements. Further current flow through the LV network is high and hence the I^2R loss of the conductors is significant. Planning and Operation of LV network is very crucial, since it is the interface where the utility meets the consumer. However, regarding the both aspects of LV network planning and operation utilities have given less priority when compared with MV and HV networks.

1.2 PRACTICES USED BY UTILITIES FOR LV PLNNING- GENERAL INFORMATION

A methodology of LV planning shall be decided carefully by the utilities by considering various factors, among which load density of the targeted area is the most dominant factor. For instance, planning strategy preferred by LECO is maintaining the network with small transformers with short feeder lengths. Since the LECO operates in highly urbanized areas, the load density is higher and transformer capacity is fully utilized within few hundred meters of feeder length. Further, another objective of the particular strategy is to increase the performance of the network by reducing the power loss levels and unnecessary voltage drops. However, infrastructure cost of the network is comparatively high.

However, as far as CEB is concerned most of its distribution areas falls under rural and semi-urban categories in which the load density is comparatively low. So CEB prefers to install comparatively bigger transformers and to draw the lengthier feeders for LV distribution. Though the methodology is financially beneficial due to the reduction of infrastructure cost, performance of the network should be evaluated to identify whether this strategy maintains the required margins especially with regard to voltage regulation.

1.3 PROBLEM STATEMENT AND MOTIVATION

LV network planning is a challenging task which almost all the utilities are greatly concerned. In order to satisfy the regulatory requirements and also for having economic advantages proper planning methodology is essential, since appropriately planned network is beneficial to both the customer and the utility. So using commercially available tools, spending lot of engineering hours, utilities have put great effort for network planning. Since the higher infrastructure cost, planning of HV and MV network are among the top most priority tasks of the utility.

However, the effort put for planning of LV network is in a very low level. Being at the bottom of network structure and also due to the lesser complexity planning engineers have lesser attraction towards LV networks. But due to the flowing of higher magnitude currents, higher length of LV feeders and usage of small conductor cross sections for feeder wiring, I^2R loss of the LV network is significant. Further core losses and the copper losses of the LV transformers also add up to the LV losses. Being the point where consumer is connected with the utility, performance like voltage drops, loading of the network, and loss levels of the LV network is essential to be at lower levels. So in present days proper planning of LV network has also become a crucial task.

When compared with HV and MV level networks, number of alternatives are available for planning LV networks which fulfill the same requirement. Following figure depicts the above idea graphically.

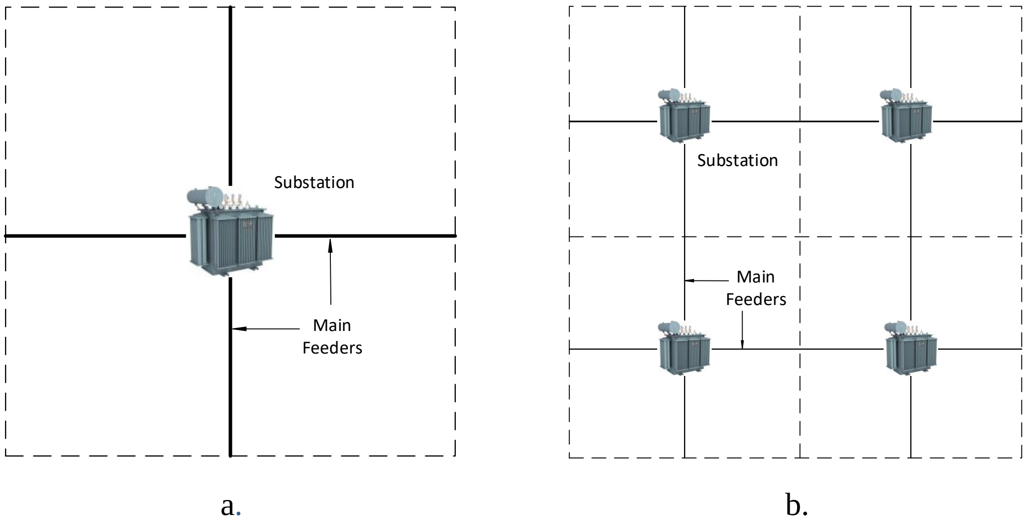


Figure 1.1. Planning Alternatives

According to Figure 1.1.a, LV network could be designed with a single transformer having higher capacity with lengthy feeders containing comparatively large conductor. The same area could be facilitated with another design configuration with a few smaller size transformers with shorter feeder lengths comprising of small conductor size as shown in Figure 1.1.b. Usually the cost per unit size/capacity of a component is reduced when the size/capacity is increased and vice versa as indicated in the Figure 1.2.

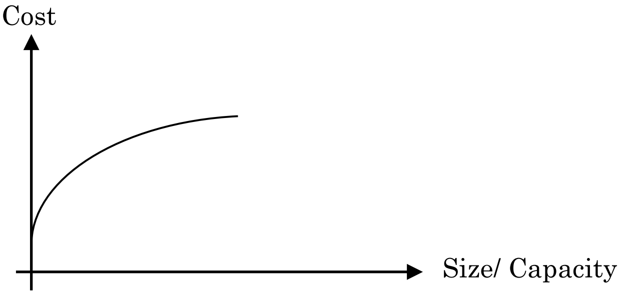


Figure 1.2. Relationship with Cost vs Size

When comparing above 2 alternatives of LV network design, first option might be the most economical solution. However, performance might be better in the design of the second option. So the planning of LV network is complex since it is important to identify which transformer and conductor combination gives the best network topology under minimum cost.

Currently the most common methodology used in network planning is to locate the substations at load centers. Otherwise substations are located at the places convenient for maintenance and easy access. After locating the transformer of sufficient capacity to cater the demand, conductors are drawn to deliver the power to customers. Though there are lot of alternatives to select over various transformer and conductor sizes utilities prefer to lie on prevailing practices. For instance, LECO uses only 70mm^2 Arial Bundled Conductor (ABC) for main feeder wiring. Further if there is a capacity deficiency of the installed transformer due to the load growth of the network normal practice is to put the next available transformer size or divided the particular area to two and supplied with two properly sized transformers.

Though there is a bit concern about the performance indices of the network no attention has been given regarding the cost of operation of the network. Due to usage of various transformer and conductor sizes the network arrangement does not appear to be well planned. Further availability of differently sized components will complicate the maintenance of the network. So appropriate planning criteria is essential for LV networks to select the best alternative for satisfactory performance under minimum cost.

This research expects to develop a methodology for finding the best optimized LV distribution system based on the load density and the total demand of the area. For the particular purpose deviating from most prevalent load center based planning technique, novel theoretical approach is preferred. This is called polygons-based planning method in which geometric configurations equivalent to polygons are used to represent the service area of a substation and its associated feeders for planning.

Polygons-based planning method is a theoretical approach which is being used for decades to develop mathematical algorithms for planning purposes. Here loads are assumed to be equally distributed over the geometric area. Then substation feeding areas are represented by shapes of regular polygons (Squares, Hexagons, etc.) and substation is located at the center of the defined polygons. The number of sides of the polygon shall be equal to the number of primary feeders radiating from the substation as depicted in the following Figure 1.3.

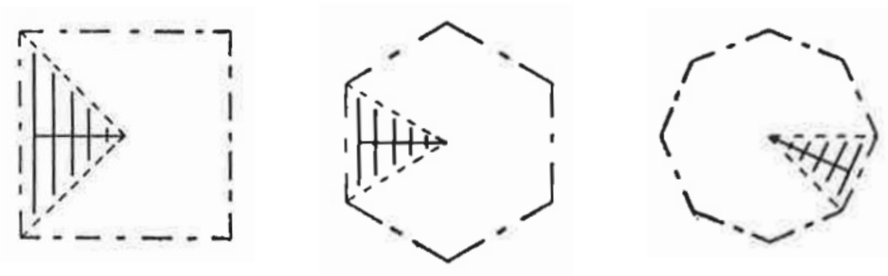


Figure 1.3. Polygon Representation

1.4 PROJECT SCOPE

A cost optimized polygon based design criteria is proposed for LV distribution network planning based on the load density and total demand for a given area considering all the available transformer and conductor combinations. For costing purposes actual market prices of the equipment are used.

Detailed mathematical derivations of the network parameters and relative equations of costs associated with networks, employing the polygon based planning methodology are discussed in Chapter 3. Main inputs to the algorithm are load density (kVA/km^2) and the total load (kVA) of the area. Cost of the equipment were fed according to the sizes of the equipment. Optimization algorithm was derived and the transformer conductor combinations which gave minimum cost per kVA while satisfying all network parameters within their required margins was identified by modeling it on the Matlab software.

A LV distribution system of Pamunuwa, Maharagama area owned by LECO was selected for the validation of the proposed algorithm. LV network of selected island was evaluated using observed optimum transformer conductor combination and calculated the actual cost of operation of the network. Observed actual cost was compared with the cost observed through the algorithm. Geographical Information System (GIS) and Neplan software were used for the analysis purpose.

GIS is the asset management software which is currently used by LECO and contains all infrastructure data of LECO distribution network including both MV and LV with respective geographical reference. So required data was extracted from GIS database which contained the most updated picture of this rapidly evolving distribution network. Neplan is the tool used for network planning and capable of performing various analysis including load flow, short circuit, protection, reliability, etc. So the network topology was directly extracted from the GIS database to the Neplan software for load flow analysis.

The methodology, data analysis, results and conclusion on the proposed method have been presented in the report.

1.4.1 Research Objective

Major research objectives can be stated as the development of a cost optimized LV network design criteria employing polygons-based planning methodology for a given area based on the load density.

Then the outcomes of the proposed criteria shall be,

- Transformer capacity and number of transformers
- Conductor size and length for main feeder wiring

for planning the LV network of a selected area respect to the load density.

1.4.2 Methodology

Steps of the methodology of the study are listed as below.

a. Studying the existing methods used in LV distribution planning for identifying the available resources, limitations of the existing models.
b. Developing comprehensive mathematical model to represent costs functions associated with various cost components (Infrastructure and Operational) and performance indices (Voltage, Loss, etc.) of the network based on polygon-based planning.

c. Developing an algorithm to find the transformer conductor combination which offers the minimum cost of operation for planning.
d. Verifying the observed outcome through proper analysis applying for a real world scenario.

1.5 THESIS ORGANIZATION

The first part of the Chapter 1 is the background of the research study: features of LV distribution network and general description about LECO and CEB network. The second part of this chapter provides the problem statement and the motivation for the study. The final part outlines the base of the study, the polygon-based planning technique and project overview, which includes research objective and the methodology.

Literature review has been included in the Chapter 2, where previous research works have been reviewed. Research gaps to be filled and important concepts identified have been described in this chapter. Theoretical approach for the research is described in the Chapter 3. Derivation of equations based on the polygon-based planning technique, derivation of the algorithm of finding the minimum cost combination and output are detailed here.

In Chapter 4, explicit description about the verification of the proposed methodology has been provided. How the output of the proposed algorithm can be applied and the comparison of theoretical and practical approaches have been compared in this chapter. Ultimately, Chapter 5 contains the conclusion, in which a detailed description has been provided about the practical usage of the outcome of the research.

2 LITERATURE REVIEW

2.1 INTRODUCTION

Electric power distribution planning is an important topic for both utility engineers and academic researchers for a long time. Developing of inherent planning methodologies was started few decades back by the utilities along with the experienced professionals as stated in [1]. Conventional electric power distribution is uni-directional, from distribution substation to the end use customers. However, network planning has become more complicated due to diverse distribution of consumers over a geographical area making distributed nature of loads and disperse feeder arrangements. So number of theories, methodologies and concepts have been developed through various researches and some of them have already been implemented by the utilities for their planning purposes. So publications of some researches have been referred and reviewed in this chapter to identify any supplements, limitations and research gaps that can be filled regarding previous research works under the particular topic.

2.2 INFLUENTIAL FACTORS: OVERVIW OF PREVAILING DISTRIBUTION PLANNING METHODS

Prior moving to the detailed analysis of the research area, background study was required to be carried out in order to identify the existing practices, constraints considered and the outcomes of the previous research works. The [2] fulfills the above requirement which evaluates the available papers regarding distribution planning for identifying their methodologies, any limitations, strengths and weaknesses. More precisely this literature can be designated as a snap shot of existing research works regarding the referred research area.

The ultimate Goal of planning is considered as fulfilling of demand growth using resources optimally while complying with several technical specifications. Utilities prefer faster and cheaper planning tools to find the best solutions by evaluating different scenarios. In the paper planning problem has been divided to two sub-problems.

i. Optimal dimensioning of electric distribution substations

ii. Optimal dimensioning of feeders

Solving of main problem as a sequence of above two sub problems might not be guaranteed the optimal solution as identified through the paper. So those two problems should be addressed simultaneously in order to find the best solution. Further in this paper, two types of durations of planning has been identified as simple (one step) or as multiple (several steps). Addressing the planning problem for a single year of operation is considered as one step planning. In multiple steps methodology, planning is considered based on the network operation for multiple years.

In [3] multiple years have been considered as the duration of planning. With the consideration of multiple years, the effect of the inflation rate and the demand growth, to the total cost of operation is unavoidable. Here, the function of optimization is the total cost of the network associated with investment and operation. Cost of investment is the cost which is spent to construct the network. It is obvious that, there is a considerable amount of loss which is associated with LV network due to the higher current flows. Further there is an inevitable loss component which is associated with transformers, namely transformer core and copper loss. The cost associated with these components has been added to the function as operational costs. In addition, the reliability worth has also been reflected in the total cost as an operational cost. So the optimization function has been extracted from [3] and shown below (2-1).

$$OF = \sum_{yr=1}^{N_y} \left(\frac{1+Infr}{1+Intr} \right)^{yr} \left(C_{Inv}(yr) + C_{OM}(yr) + C_L(yr) + \xi . C_{Int}(yr) \right) \tag{2-1}$$

Where:

N_y: Number of years in the study timeframe (year)

Infr: Inflation rate

Inrt: Interest rate

ξ: The decision variable for considering interruptions cost.

Here,

C_{inv} - Capital cost of transformers installation and low voltage feeder construction

C_{OM} - O & M cost associated with distribution transformer and low voltage feeders

C_L - Cost of energy loss and cost of peak power

$C_{int,}$ - Reliability cost which is determined using the outage cost

Since the planning process has been performed considering multiple years of operation, inflation rate has been introduced to the algorithm. Main constraints of the algorithm are radial structure of the distribution network, transformer loading and voltage drop limits. Further constant load growth has been considered throughout the planning horizon.

With the revision of above papers number of influential factors were identified as additions and research gaps regarding available distribution planning methodologies.

i. Many models have considered the loss as a constraint. But they have badly treated the voltage drop as a constraint.

ii. Demand growth on the studied period has rarely been considered.

iii. Reliability worth has badly been addresses in the proposed models. However, it is essential to evaluate the role of the reliability in LV distribution network planning.

iv. Many works have only academic interest and very few have been applied to real world problems.

v. If planning is considered for multiple years,

    a. Load growth should be considered
    b. Inflation rate should be included to the algorithm to consider the Net Present Value (NPV) of the total cost.

2.3 OPTIMAL LV NETWORK DESIGN

Most of all the available planning methodologies are evolved with the various kinds of optimization techniques. According the requirement, the method of optimization, number of inputs and the constraints considered have been differed.

In [2] some of the previous research works have been studied and several optimization techniques have been identified which used to solve the optimization problem. Complex mathematical solution techniques like mixed integer linear programming, artificial intelligence, genetic algorithm, etc. have been proposed in various papers as reviewed and summarized in the paper.

A methodology for adding and siting of new distribution transformers in the MV network based on the load growth has been presented in [4]. Objective function was to minimize the power loss and constraint was the capacity of the substation. Substations were located in the pre-determined locations and using the iterative technique as indicated in the Figure 2.1, best solution has been identified which gave the minimum power loss, by changing the locations of substations. The main goal was to minimize the total power losses on the expanded primary network. Economic feasibility of the planning process has not been addressed in the optimization procedure.

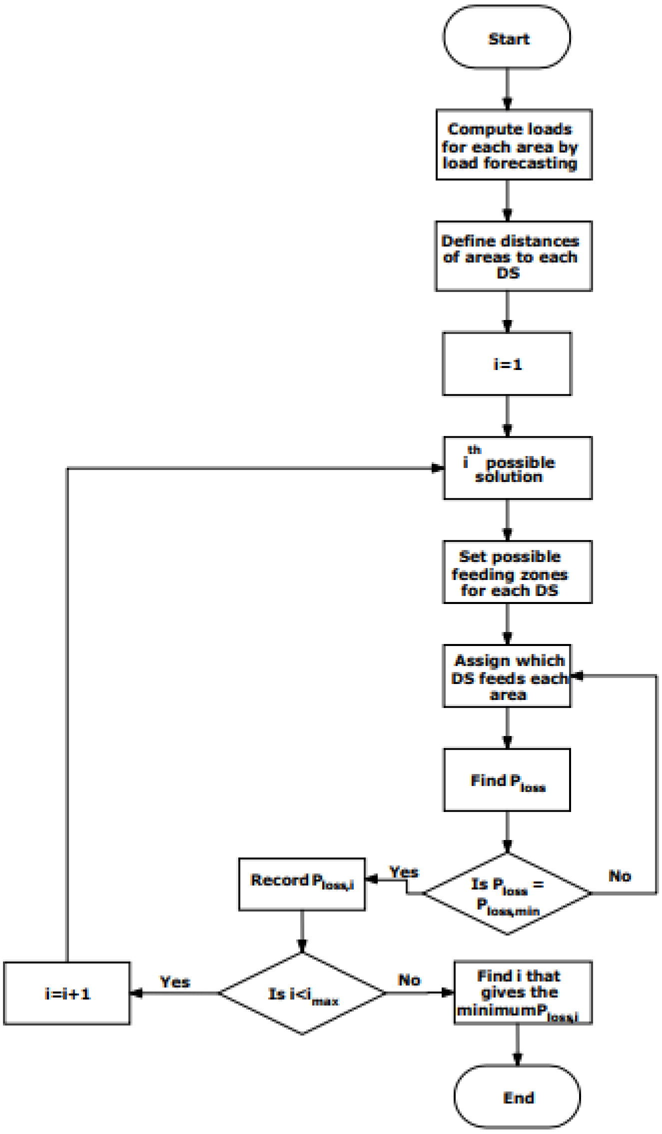


Figure 2.1. Flow Diagram [4]

In this paper, it has been assumed that the minimization of technical losses essentially minimized the voltage drop of the network. This is very important theory since the only parameter that has to be concerned then is the technical losses. Because any measure that is taken to correct the losses of the network will essentially correct the voltage drop of the network as well. So voltage drop is effortlessly bounded by the loss constraint of the algorithm. This theory shall be used and need to verify prior to apply in this research.

A multi-stage decision process where optimum feeder routes with proposed substations are obtained directly based on additional cost of connecting a line, has been presented in [5]. The proposed method requires the network configuration in which the exact location of loads and prospective locations of substations are provided. Initially optimum radial networks are formed with all the candidate substation locations and then substations are eliminated one by one, based upon the value of their costs until the optimum system configuration is obtained.

In [6], it proposes a methodology for distribution network planning using loss reduction approach in which a complicated algorithm is used to determine the optimal solution based on the exact geographical locations of loads and substations. Based on branch exchange technique the optimum LV distribution network is found eliminating the most expensive substation in each step of iterative cost optimization algorithm.

In literatures reviewed above contain very complicated algorithms and lot of modeling is required to find the optimum solution. Some models require the exact geographical locations of loads, substations and their respective capacities. These methods are well suit for performing a detailed design of a distribution network based on the selected transformer capacity and conductor size. In order to compare alternative options for using various sizes of transformers and conductors more time will be required for modeling works. Further for area extended for few square kilometers this type of modeling requires lot of human hours. In addition, for quick decision making purposes this type of methodologies are hard to be used.

There is a necessity of a distribution planning methodology for decision making purposes which requires a lesser number of inputs, minimum time and also a minimum effort. Further the particular methodology should be capable enough to compare the alternatives to identify the best solution. The objective of this research is propose a methodology for planning purposes to fulfill all the aforementioned requirements. For that a simple and precise approach of representing substation and its associated network by means of polygons, which technically called polygon-based panning technique can be used.

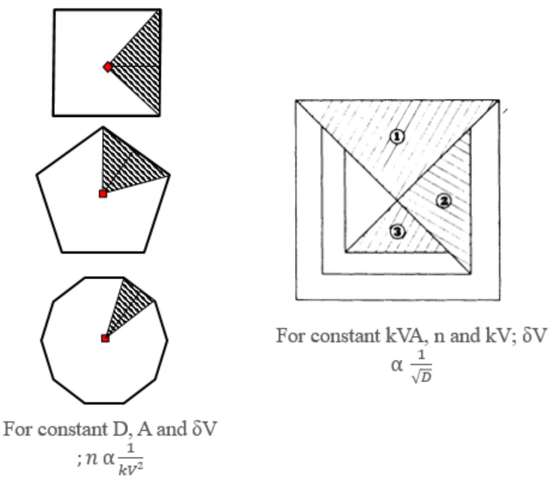
2.4 POLYGON-BASED PLANNING

The Objective of polygon-based planning was to propose a simple method to represent actual distribution system by hypothetical means for quickly analyzing technical compliance and economic considerations of the planning proposals [7]. Here, the feeding area of a distribution substation was assumed to have the shape of regular polygons likes squares, pentagons, hexagons, etc. Then the number of sides of the polygon represent the number of primary feeders radiating from the substation.

This representation greatly simplifies the comparison of alternatives especially for LV networks due to the availability of lot of alternatives. Number of equations have been derived relating voltage, voltage drop, load density, substation area and number of feeders based on polygon shaped networks. Mainly two type of planning possibilities have been discussed in the paper.

i. Constant load-density planning
ii. Increasing load-density planning

Figure 2.2 below indicates the above two concepts clearly.



Where,

D - Load Density

n - Number of main feeders

δV - Voltage Drop

kV - Operating Voltage

A - Main feeder cross sectional area

Figure 2.2. Concepts of polygon - based planning [7]

Using this polygon-based planning technique some useful mathematical relations have been derived which provide swift and convenient information in planning. Following two graphs extracted from the paper indicate such kind of relations.

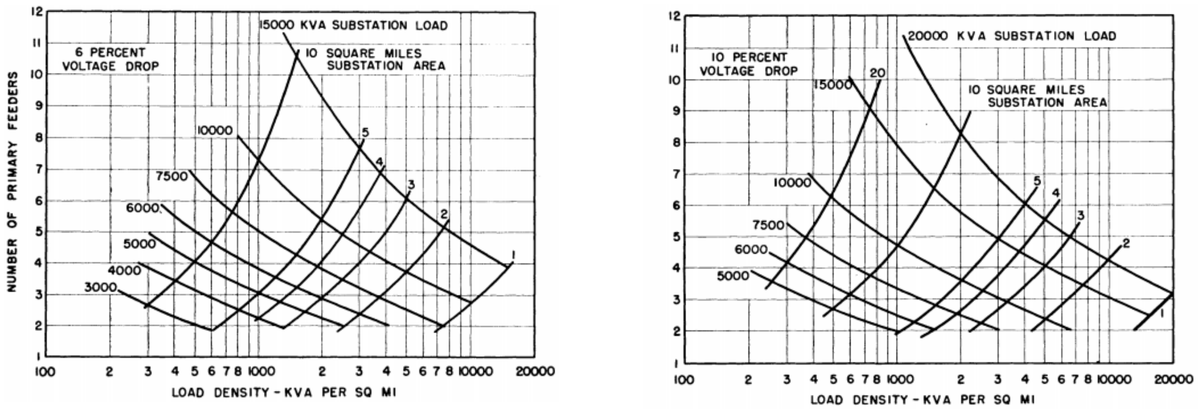


Figure 2.3. The relationships between the system-planning parameters [7]

So the reviewing of this paper can be concluded with observing following key facts which can be directly related to this research as well.

i. Polygon-based planning method can be used to represent actual system to a great extent.
ii. Exact locations of individual loads need not to be considered when planning distribution networks and studying the planning parameters.
iii. The method can be used to provide extensive details for comparison of technical and economic feasibility of planning between alternatives at a glance.

By surfing through the previous research works regarding the particular topic, many important facts including research gaps and supplements were able to gather. Developing a methodology which contains a higher practical aspect rather than contain lot more theoretical approach, is one of the main motivation of this research. So the inputs, technical and other constraints and the procedure of deriving an algorithm to develop a methodology for finding a cost optimized LV distribution network are decided more practically by the aid of the literature review. For particular purpose by deviating from conventional methodologies, polygon-based planning technique is expected to use. Mathematical modeling of the equations based on the polygon-based planning technique and subsequent steps of developing the algorithm will be described in the Chapter 3.

CHAPTER 3

3 THEORICAL APPROACH: POLYGON BASED DISTRIBUTION NETWORK PLANNING

3.1 LV NETWORK DESIGN PARAMETERS

The basic parameters of the network are required to be derived referring the polygon-based planning strategy. In distribution planning voltage drop and loss are the key indices for measuring the performance of the design. So the aforementioned indices were defined using fundamental concepts.

Typical practice of utilities is to take out 4 nos. of feeders from a single substation considering the spacing requirements to draw the lines. So square shaped polygon was assumed here since number of feeders evacuating from the transformer was equal to number sides of the polygon. It was assumed that the load of the area is equally distributed and each feeder serves an area of a right angled-triangular shape as indicated in the Figure 3.1.

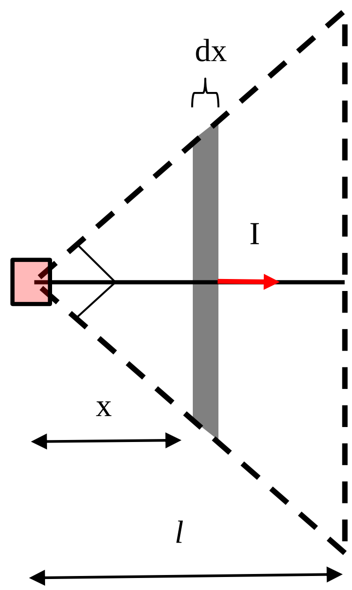


Figure 3.1. Single feeder representation of polygon-based planning

Following notations have their usual meanings as described.

l – length of the feeder in m

ρ – Resistivity of the conductor in Ωm

A – Cross Section of Conductor in mm^2

σ – Load Density in MVA/km^2

V_L – Line-Line Voltage in kV

T - Planning Horizon

Then the current at distance x:

$$I = \frac{\sigma(l^2 - x^2)}{\sqrt{3}V_L} \qquad (3\text{-}1)$$

Then voltage drop δV can be written as:

$$d\delta V = Idr = \frac{\sigma(l^2 - x^2)}{\sqrt{3}V_L}\frac{\rho dx}{A}$$

$$\delta V = \int_0^l \frac{\sigma(l^2 - x^2)}{\sqrt{3}V_L}\frac{\rho dx}{A}$$

$$\delta V = \frac{2\sigma}{3\sqrt{3}V_L}\frac{\rho l^3}{A}$$

$$\delta V\% = \frac{2\sigma}{3\sqrt{3}V_L^2}\frac{\rho l^3}{A} \qquad (3\text{-}2)$$

For the power loss L:

$$dL = 3I^2dr = \frac{\sigma^2(l^2 - x^2)^2}{V_L^2}\frac{\rho dx}{A}$$

$$L = \int_0^l \frac{\sigma^2(l^2 - x^2)^2}{V_L^2}\frac{\rho dx}{A}$$

$$L = \frac{8}{15}\frac{\sigma^2\rho l^5}{V_L^2 A} \qquad (3\text{-}3)$$

Then the percentage loss L% can be written as:

$$L\% = \frac{L}{\text{Feeder kVA} + L}$$

Since Feeder kVA = σl^2 Loss percentage:

$$L\% = \frac{1}{1 + \frac{15}{8}\frac{AV_L^2}{\sigma\rho l^3}} \qquad (3\text{-}4)$$

Using (3-2) and (3-4) derived for percentage voltage drop and percentage loss, a ratio can be defined as indicated in below equation.

$$\frac{\delta V\%}{L\%} = \frac{2\sigma}{3\sqrt{3}V_L^2}\frac{\rho l^3}{A}\left(1 + \frac{15}{8}\frac{AV_L^2}{\sigma\rho l^3}\right)$$

$$\frac{\delta V\%}{L\%} = \delta V\% + 0.72$$

In practice when planning LV distribution network $\delta V\%_{max}$= 6% and $L\%_{max}$= 3%. It denotes that,

$$\frac{\delta V\%}{L\%} < 1$$

This relationship reveals a very important concept in the polygon-based planning methodology. It means that the any measures which takes to correct the loss percentage will automatically correct the voltage drop as well. So in the minimization algorithm only the loss component was considered. For the square shaped polygon indicated in Figure 3.1, following 2 equations can be defined for the demand of the substation and the conductor size based on the length of the feeder and the loss percentage.

$$A = k\left(\frac{1}{\delta L\%} \ - 1\right) l^3 \ ; \text{ where } k = \frac{8}{15}\frac{\sigma\rho}{V_L^2}$$

$$D \ = \frac{4\sigma l^2}{1000}$$

3.2 PLANNING ALGORITHM

The objective of the proposed optimization is to minimize the total cost for delivering the total demand of the selected area. The total cost can be separated as the infrastructure cost and the operational cost. Infrastructure cost is the expenses spend for constructing the LV network to power up the particular area, mainly the cost of transformers and conductors. Operational expenses which can be occurred due to the operation of the network throughout the planning horizon are considered as the operational costs. Power loss of the conductors, transformer core and copper loss are contributed mainly for the operational cost.

In order to describe the proposed planning algorithm quantitatively, a case study has been developed in accordance with realistic network parameters and configurations practiced by distribution utilities. So, power transformers in capacities of 100kVA, 160kVA, 250kVA and 400kVA and bundle conductor sizes of 35mm^2, 50mm^2, 95mm^2, 120mm^2 and 150mm^2 are considered giving rise to 24 numbers of transformer and conductor combinations for designing any LV network. For a given load density and total demand, the best solution of planning is the transformer conductor combination which gives the minimum total cost. Optimum solution for the distribution network was found considering the operation of the network for several years. Since MV networks are planning for 5-year time period [8] in this research also, planning horizon was assumed as 5 years.

When multiple years are considered, it is obvious to consider the demand growth of the network. When costing the infrastructure, the infrastructure should be adequate to fulfill the demand after 5-year time period as well. Further the operational cost should gradually be increased depend on the load growth of the network. In order to take the NPV, inflation rate has to be included to the algorithm. So in the optimization algorithm all the costs components were derived based on the load growth of the network.

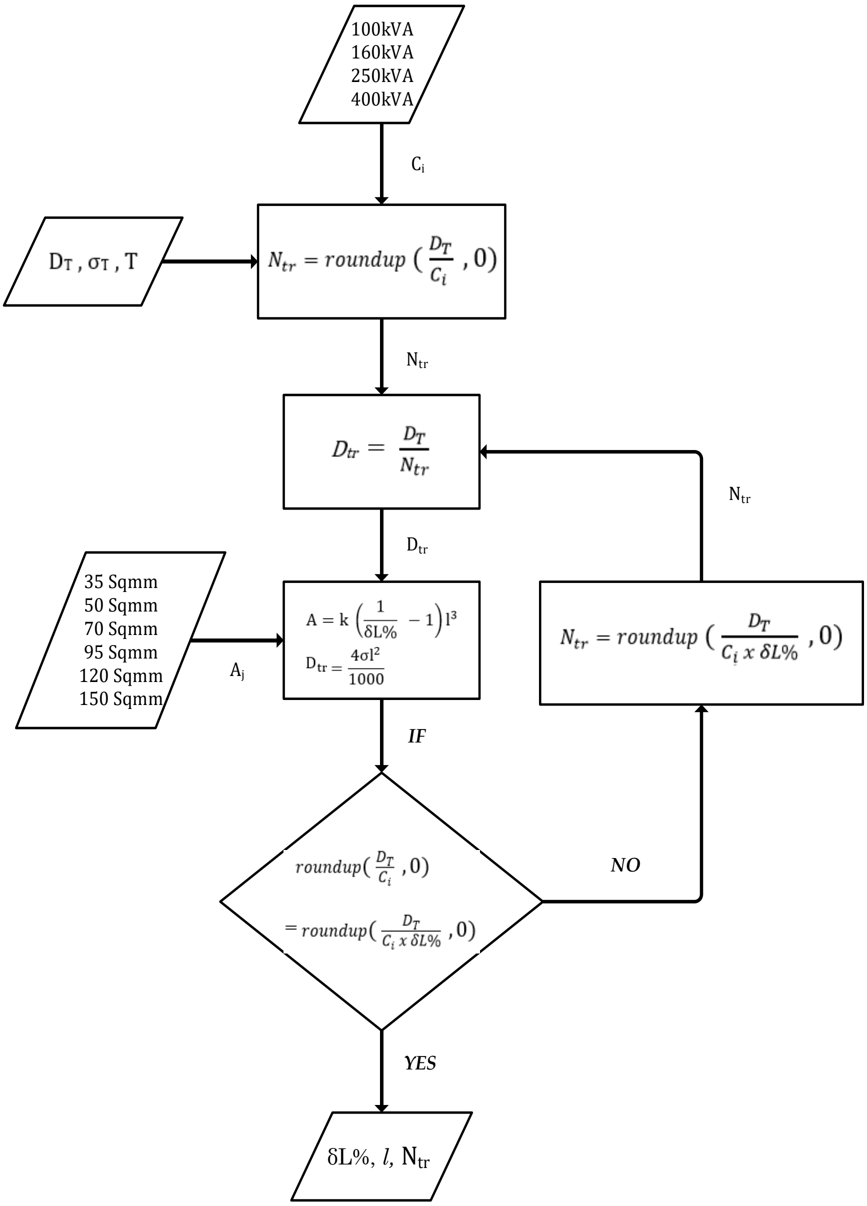


Figure 3.2. Planning Algorithm – Part 1

Basically the algorithm is consisted of two parts and the part 1 is shown in the Figure 3.2 above. 24 combinations which are previously mentioned, are fed to the algorithm and network parameters including number of transformers, feeder length and the power loss level are calculated respective to each combination separately.

Then the observed parameters for each combination are fed to the next part of the algorithm in order to calculate the cost of operation of the network throughout the planning horizon. The combination which offers the minimum cost per kVA, will be selected by the algorithm as the most feasible solution to electrify the particular area. The part 2 of the algorithm have been indicated in the Figure 3.3.

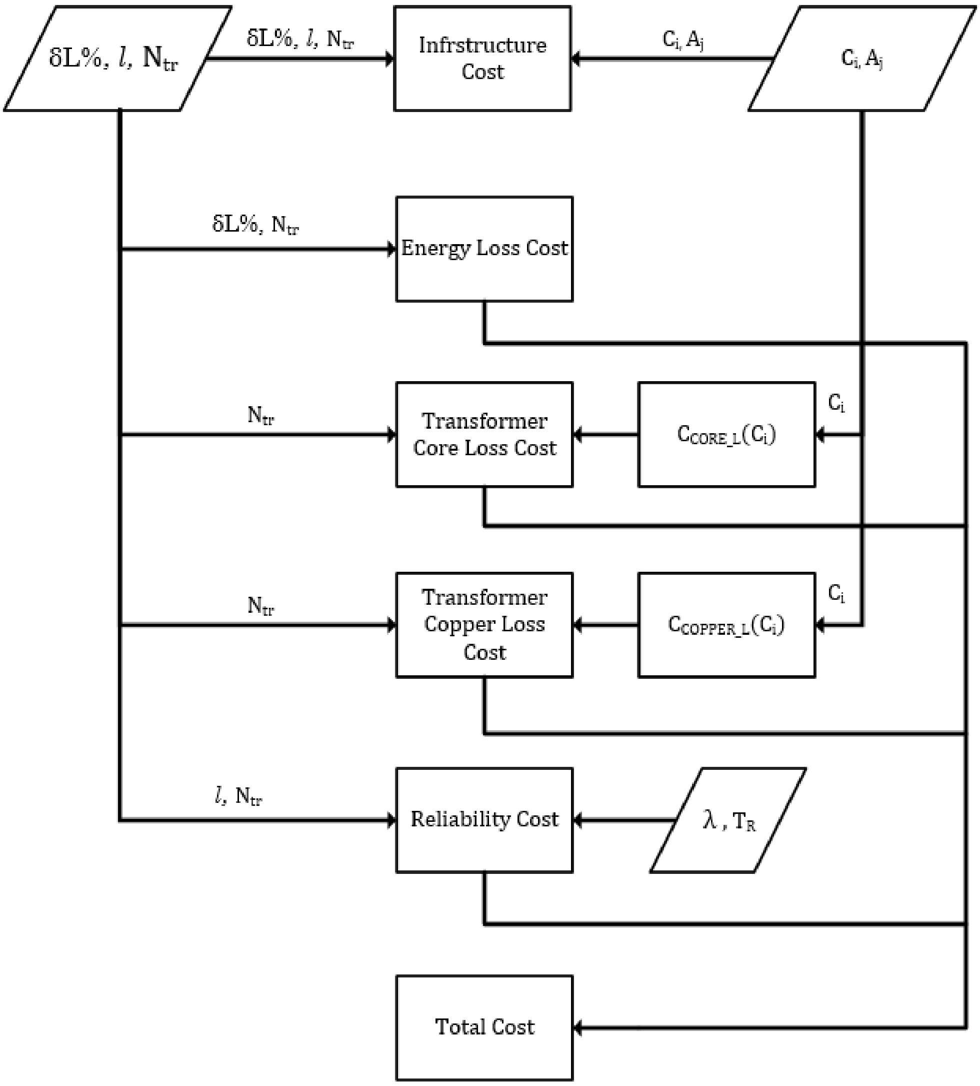


Figure 3.3. Planning Algorithm – Part 2

3.3 FORMULATION OF COST FUNCTIONS

3.3.1 Infrastructure cost

Total cost for installing the transformers and drawing of both MV and LV conductors fall under this category. Not only material but also the labor should be included to the infrastructure cost. All cost functions were derived based on standard costing values used in LECO referring to the Standard Cost Manual(SCM) of LECO. Cost manual is the standard document for costing the daily construction works including new constructions, augmentations and maintenance works. This document is updated yearly depends on the prevailing market prices of the components. Table 3.1 shows the standard construction cost for installing the various sizes of distribution transformers.

Table 3.1. Costs of distribution transformer installations as per SCM

JOB DESCRIPTION		MATERIAL	LABOUR	TOTAL
32.1 50 kVA - SINGLE POLE MOUNTED	Rs	1,425,010	68,350	1,493,360
32.2 100 kVA - SINGLE POLE MOUNTED	Rs	1,056,510	68,350	1,124,860
32.3 160 kVA - SINGLE POLE MOUNTED	Rs	1,201,150	68,350	1,269,500
32.4 250 kVA - SINGLE POLE MOUNTED	Rs	1,466,420	68,350	1,534,770
32.5 400 kVA - DOUBLE POLE MOUNTED	Rs	1,892,910	87,760	1,980,670
32.6 630 kVA - DOUBLE POLE MOUNTED	Rs	2,485,230	87,760	2,572,990

So the total cost of transformers C_{Tra} for given area can be written as,

$$C_{Tra} = n\ x\ C(P_i)$$

n = Number of transformers

$C(P_i)$ = Cost of selected transformer type

Regarding the LV conductors currently LECO uses only the $50mm^2$ and $70mm^2$ ABC for LV feeder wiring. Table 3.2 indicates the cost of drawing 1km line using aforementioned conductor types as indicated in the SCM of LECO.

Table 3.2. Costs of conductor drawing as per SCM

JOB DESCRIPTION		MATERIAL	LABOUR	TOTAL
11.1 70 B/C	Rs	1,895,900	588,430	2,484,330
11.2 50 B/C	Rs	1,675,130	588,430	2,263,560

However, the possibility of using the conductors with bigger cross sectional areas like $95mm^2$, $120mm^2$ and $150mm^2$, as the main feeders was also checked in the research. So per km cabling prices of above conductor sizes were derived from the available conductor sizes in the cost manual. Including the derived prices, per km wiring of the nominated conductor types are tabulated in the Table 3.3.

Table 3.3. Derived costs for installing conductors

Description		**Material**	**Labor**	**Total**
35 B/C	Rs	1,472,353.00	456,974.00	1,929,327.00
50 B/C	Rs	1,675,130.00	588,430.00	2,263,560.00
70 B/C	Rs	1,895,900.00	588,430.00	2,484,330.00
95 B/C	Rs	2,323,857.00	721,255.00	3,045,112.00
120 B/C	Rs	3,262,146.00	1,113,718.00	4,375,864.00
150 B/C	Rs	3,577,211.00	1,221,284.00	4,798,495.00

Based on the polygon-based planning technique total cost of the LV main feeders required for the design network, C_{LV} can be written as,

$$C_{LV} = n \, x \, C(A_i) \, x \, 4l$$

where;

$C(A_i)$ = Cost of per km for selected conductor type

l = length of the feeder for selected transformer, conductor combination

It is essential to include the cost of MV network also to the infrastructure cost and hence to the algorithm. Because in order power up the LV transformers MV cables should be drawn from Primary Substation(PS). If multiple number of small capacity transformers are used, then the cost of MV network might be higher due to the usage of adequate length of MV conductors to connect all transformers to the PS. MV conductor cost can be reduced by introducing transformers with bigger capacities since the required transformer count is less. So the function of MV conductor cost was also included to the algorithm based on the Polygon-based planning technique.

The required length of the MV conductor was considered as the total length required to draw through the square pattern consumer island and connect a transformer as shown in the Figure 3.4.

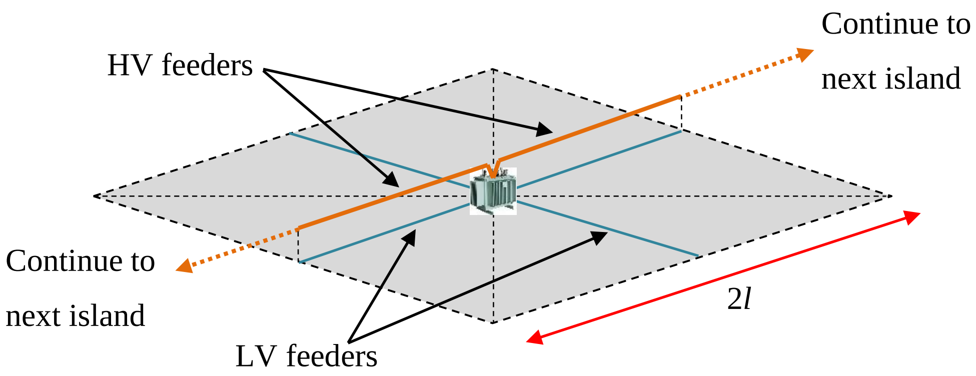


Figure 3.4. HV & LV Feeder Arrangement of Square Shaped Polygon

When considering 24 combinations the length of the maximum feeder and hence the dimension of the square pattern changes. Per km cost of constructing the MV network was observed from standard cost manual. Currently LECO uses 3 types of bare MV conductors, 150mm^2, 100mm^2 and 60mm^2. Considering the expansion of the network cost of 150mm^2 conductor was considered for the optimization algorithm.

Per km cost of 150mm^2 conductor was shown in the Table 3.4 below as declared in the SCM.

Table 3.4. Derived costs for drawing HV Conductors

JOB DESCRIPTION		MATERIAL	LABOUR	TOTAL
14.1 150 AAC	Rs	3,790,160	1,149,810	4,939,970

So the total cost for installing MV network can be defined as,

$$C_{MV} = n \times 2 \times l \times \text{per km MV conductor cost}$$

3.3.2 Operational cost

Cost of infrastructure is occurred in the 0^{th} year of the planning horizon and the transformer size, count of transformers, conductor type and the length of the main feeders will be fixed for planning horizon. However, demand of the transformer, loading of the feeders and hence the feeder power loss levels will be increased due to the demand growth of the network which is depicted in the figure below.

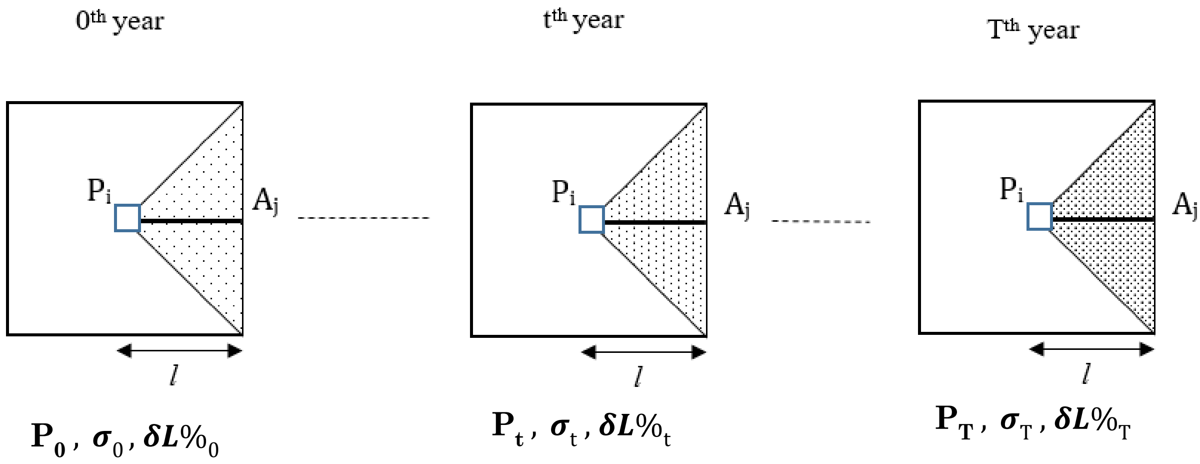


Figure 3.5. Variation of parameters of square polygon with demand growth

Type of operational costs considered here were the energy loss of the conductors, transformer copper loss, transformer core loss and reliability cost. Due to the demand growth, in the upcoming years the aforementioned operational cost types are increased gradually. In the algorithm for comparison over the alternatives the NPV of the total cost of operation is considered applying the inflation rate yearly.

3.3.2.1 Energy loss

Due to the resistance of the conductors, useful electrical energy will be lost as heat. Financially this is a cost to the utility. Equation of the power loss of the conductor can be defined based on the polygon based planning assuming square shape.

$$L = \frac{8}{15}\frac{\sigma^2 \rho l^5}{V_L^2 A}$$

Since designed LV the network should be operated for all the loading conditions, Maximum demands of the consumers were considered for calculating the load density and total demand of the area. So the observed value above is the peak power loss and this should be converted to a cost. In order to represent the power loss as a cost, it is required to be converted to the form of energy. So “Jung’s formula”[9] was referred for this conversion and stated below.

$$\mathrm{UTL} = \frac{\mathrm{LF}^2(2+\mathrm{LF}^2)}{(1+2\mathrm{LF})}$$

Where;

UTL = Utilization Time of Losses,

LF = Load Factor

So if the peak power loss is known, energy loss of the t^{th} year $L_{EL,t}$,

$$\mathrm{L}_{\mathrm{EL,t}} = \frac{\mathrm{D_t}}{1-\delta\mathrm{L\%_t}}\ \delta\mathrm{L\%_t}\ x\ \mathrm{UTL} \tag{3-5}$$

Where;

D_t = Total Demand at t^{th} year

$\delta L\%_t$ = Loss percentage of the particular year

If the optimization algorithm is carefully observed it can be seen that the algorithm is solved and outputs, loss level and the feeder lengths are given for the status of the consumer island after 5 year-time period. From the 0^{th} year onwards until the end of the planning horizon, designed network will be loaded gradually. So the output of the algorithm gives the ultimate power loss level of the network, $\delta L\%_T$. So it is essential to derive any intermediate year power loss level, $\delta L\%_t$ using the loss level of the final year, T of the planning horizon.

Following basic mathematical concepts based on the polygon-based planning technique peak power loss in any intermediate year was able to be defined relating the final year loss level as indicated in (3-6)

$$\delta\mathrm{L\%_t} = \frac{1}{1+\left(\frac{1}{\delta\mathrm{L\%_T}}-1\right)\frac{\sigma_\mathrm{T}}{\sigma_\mathrm{t}}} \tag{3-6}$$

Substituting the above relation in (3-5), energy loss in any year during planning horizon can be written as,

$$\mathrm{L}_{\mathrm{EL,t}} = \frac{\mathrm{D_T}}{\mathrm{GF}^{2(\mathrm{T-t})}}\ \frac{\delta\mathrm{L\%_T}}{1-\delta\mathrm{L\%_T}}$$

where;

D_T = Total Demand at T^{th} year

GF = Growth factor

Ultimately the cost of energy losses during the planning horizon C_{EL} can be written as,

$$C_{EL} = \sum_{t=0}^{T} \text{Cost of } t^{th} \text{ year Losses } (L_{EL,t})$$

$$C_{EL} = n \text{ x} \sum_{t=0}^{T} \frac{L_{EL,t} \text{ x UTL x Unit Cost}}{(1+IR)^t}$$

Where;

IR = Inflation rate

3.3.2.2 Transformer Losses

Basically there are two type of transformer loss, namely core loss and copper loss. Core loss is occurred due to the magnetization of the core of the transformer. Core loss is a constant for a kVA rating of the transformer and just after the loading of the transformer core loss is started to occur. Copper loss is basically a I^2R loss occurred due to the current flow through the winding of the transformer. Despite the core loss, copper loss is varying according to the loading of the transformer.

In order to model the above costs, transformer core and copper loss data were collected form Lanka Transformers Limited(LTL) and those data are attached in ANNEXURE 2. Summary of the core loss and full load copper losses based on the capacity of transformer are revealed in the below Table 3.5.

Table 3.5. Core and copper losses of various transformers

kVA	No load losses (W)	Load losses (W)
100	254	2,079
160	358	2,427
250	438	3,440
400	606	4,909
630	818	6,669

These data directly use in the algorithm respective to the transformer capacity which is going to be selected.

3.3.2.2.1 Core Loss

Core loss is a constant value for selected transformer capacity. Throughout the year, each and every second this much of power is constantly lost from the transformer. So the cost of energy due to the core loss, C_{Cr_L} throughout the planning horizon,

$$C_{Cr\_L} = n \text{ x } \sum_{t=0}^{T} \frac{L_{Cr\_L}(P_i) \text{x } 8760 \text{ x Unit Cost}}{(1 + IR)^t}$$

Where;

$L_{Cr\_L}(P_i)$ = Core loss of the selected transformer capacity

n = number of transformers

3.3.2.2.2 Copper Loss

Copper loss depends on the loading of the transformer. Copper loss of various transformer capacities when they loaded to their maximum capacity are presented in Table 3.5. Since the optimization algorithm considers the operation of the network for multiple years, transformer demand gradually increases yearly according to the demand growth. Hence, copper loss of the transformer also differs yearly with the demand growth. In order to find the cost of copper loss, copper loss at each year of the selected transformer type should be derived by means of each year transformer demand and the copper loss at full load of the selected transformer type.

Copper loss is proportional to square of the current and hence to the square of the demand of the transformer. Also in the polygon based planning method loading of the transformer, P can be written as,

$$P \propto \frac{\sigma}{(1 - \delta L\%)}$$

Copper loss at year t of the transformer in which the capacity is P_i, is $Cppr\_L_t(P_i)$ and it can be written as,

$$L_{Cppr,t}(P_i) \propto {P_t}^2$$

$$L_{Cppr,t}(P_i) \propto [\frac{\sigma_t}{(1 - \delta L\%_t)}]^2 \qquad (3\text{-}7)$$

Similarly, for the end year of the planning horizon Cppr_$L_T(P_i)$,

$$L_{Cppr,T}(P_i) \propto [\frac{\sigma_T}{(1-\delta L\%_T)}]^2 \tag{3-8}$$

Using (3-7) and (3-8) copper loss in any year t,

$$L_{Cppr,t}(P_i) = [\frac{\sigma_t(1-\delta L\%_T)}{\sigma_T(1-\delta L\%_t)}]^2 L_{Cppr,T}(P_i) \tag{3-9}$$

Substituting (3-6) in (3-6) above and performing of series of mathematical equations copper loss at any year within the planning horizon can be written as,

$$L_{Cppr,t}(P_i) = \frac{{\sigma_t}^4}{{\sigma_T}^4}[\delta L\%_T + (1 - \delta L\%_T)\frac{\sigma_T}{\sigma_t}]^2 \text{x } L_{Cppr,T}(P_i)$$

But,

$$L_{Cppr,T}(P_i) = (\frac{P_T}{n} \Big/ P_i)^2 \text{ x } L_{Cppr}(P_i)$$

Where;

P_T = Total load of the network

n = number of transformers of the network

$L_{Cppr}(P_i)$ = Full load copper loss of the transformer capacity P_i

So the total cost of copper losses can be written as follows where all denoted parameters have their usual meaning as depicted above.

$$C_{Cppr\_L} = n \text{ x} \sum_{t=0}^{T} \frac{L_{Cppr,t}(P_i) \text{ x UTL x Unit Cost}}{(1+IR)^t}$$

Here also UTL factor was considered in order to convert the power loss to an energy lost.

3.3.2.3 Cost of reliability

Cost of reliability is also defined based on the characteristics of the network of the polygon-based planning technique. The widely used reliability index which is very easy to assess in cost terms is the ENS (Energy Not Served). ENS is the expected amount of energy not being served to consumers by the system due to an outage occurred in the network. This is measured using the units of kWh. Various researches have been done for quantifying the cost of ENS in Sri Lanka and for this research cost of ENS was considered as 0.663 USD[10].

Failures can be occurred in any component in the network. Here, in order to avoid the complexity of the optimization function only the failure rate of the LV conductor was considered. An equation had to be derived for the ENS of the square pattern. Figure 3.6 was used for the purpose.

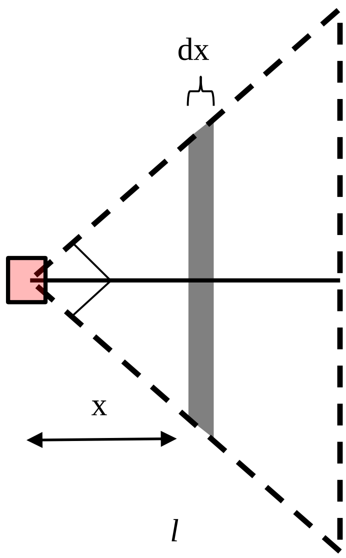


Figure 3.6. Single feeder representation of polygon-based planning for reliability

If the failure rate of all types of conductors is λ/year/km and restoration time is TR hrs, ENS at distance x due to failure of line section dx of a single transformer,

$$\mathrm{dENS} = \lambda\ \mathrm{dx}\ x\ \sigma_t (\mathrm{l}^2 - \mathrm{x}^2)\ \mathrm{x}\ \mathrm{T_R}$$

$$\mathrm{ENS} = 4\int_0^{\mathrm{l}} \lambda\ \mathrm{dx}\ x\ \sigma_t (\mathrm{l}^2 - \mathrm{x}^2)\ \mathrm{x\ TR}$$

$$\mathrm{ENS} = \frac{8\lambda\ \sigma_t l^3\ \mathrm{TR}}{3}$$

So considering the planning horizon cost of reliability can be written as,

$$C_{Rel} = \text{n x} \sum_{t=0}^{T} \frac{8}{3} \frac{\lambda \sigma_t l^3 \, T_R \, x \, UC_{ENS}}{1000 x (1+IR)^t}$$

Where; UC_{ENS} = Cost of ENS

3.3.3 Total Cost

The total cost for the operation of the network throughout the planning horizon is the addition of both infrastructure and operational cost which can be represented according to the equation given below. So it is required to calculate the total cost for each transformer and conductor combination and the option which offered the minimum total cost for the given density is the optimum solution. The parameters of the polygon which represents the optimum combination can be used to plan the LV distribution network.

$$C_T = C_{Tra} + C_{LV} + C_{MV} + C_{EL} + C_{Cr\_L} + C_{Cppr\_L} + C_{Rel}$$

3.3.4 SOLUTION OF THE PROPOSED ALGORITHM

The algorithm which includes all derived mathematical equations and cost functions were modeled in the Matlab software. In order to test the code results were observed for the typical load density values for 1km^2 area running the above algorithm and tabulated in Table 3.6 below.

Table 3.6. Results Observed for Typical Load Densities

Density (MVA/km^2)	Length (m)	Loss (%)	Area (km^2)	Power (kVA)	Number of Transformers	Cost (LKR)
0.1	504.28	1.69%	70	160	1	109,300.00
0.2	505.01	1.97%	120	250	1	77,245.00
0.3	356.77	1.79%	70	250	2	58,705.00
0.4	356.71	1.76%	95	250	2	49,539.00
0.5	291.05	1.62%	70	250	3	46,059.00
0.6	291.54	1.95%	70	250	3	40,454.00
0.7	357.06	1.95%	150	400	2	39,068.00
0.8	291.48	1.92%	95	400	3	35,171.00
0.9	225.14	1.36%	70	250	5	35,995.00
1	225.31	1.51%	70	250	5	33,478.00
1.2	252.37	1.87%	95	400	4	29,375.00
1.5	225.5	1.67%	95	400	5	27,146.00
2	205.88	1.69%	95	400	6	24,058.00

In general, the sizes of the components which are required to build the LV network is gradually increased with the rise of the load density of the selected area agreeing to the observed results through the algorithm. With oversized components, the necessity of the count of the particular component type to fulfill the same requirement is reduced. This will essentially reduce the cost of delivering a single kVA as well with the increment of the load density. Further with increase of load density the length of the main feeder gradually gets reduced resulting a small square polygon. So a careful observation of the results may facilitate the derivation of some basics rules which can be defined as thumb rules for easy reference in planning process.

However, the observed result is required to be justified through a proper validation process. The process of validation including the site selection, application of the methodology and comparison of the results will be described in the next chapter.

CHAPTER 4

4 VERIFICATION OF THE METHODOLOGY

4.1 INTRODUCTION

With the purpose of proceeding the validation through a practical network environment, a consumer island had to be selected and the proposed algorithm had to be applied based on the load density and the total demand of the selected area. The output of the algorithm is the optimum transformer, conductor combination and respective parameters for the selected area. However, algorithm gives the cost for all remaining 23 combinations and their respective parameters. So in the validation process including the optimum solution, 3 lowest combinations were selected and 3 LV distribution networks were designed based on the parameters of 3 combinations. Ultimate goal was to show the combination which gave the lowest cost in the algorithm would also become lowest when applying it in actual consumer island as well.

Thus, several number of LV networks have to be designed based on the locations of the customers. Further in order to check the parameters of the designed networks load flow studies and reliability studies were performed. Commercially available ArcGIS and Neplan Software platforms were used for simulation and load flow studies.

4.2 MODELING OF PRACTICAL NETWORK

4.2.1 Area Selection

A network section at Nugegoda area which falls under the LECO LV distribution was selected for the particular purpose. LECO LV network is merely an overhead network unless for special cases like clearance issues. LV network comprises of 3 phase, four wire radial LV feeder systems. These are approximately 150-200 A rated feeder circuits which are protected by 100A, 125A,160A or 250A fuses according to the current of the circuits. 1 phase 30 A, 3 phase 30 A and 3 phase 60A service connections are furnished through the LV network. Transformers used by LECO are three phase, 11 kV/ 415V, double wound, Dyn11, hermetically sealed type with the capacities of 100 kVA, 160 kVA, 250 kVA, 400 kVA, 630 kVA and 1000kVA. Except 630kVA and 1000kVA transformers which are only used for bulk connections other remaining capacities are used as distribution transformers.

Consumer details of Nugegoda area was collected from billing server of LECO. This data included details of the consumers including name, address, location data and energy usage of last 6 months. Table 4.1 shows the sample of data format of LV consumers.

Table 4.1. Consumer data observed from LECO server

Transformer	Account No.	Name	Address	LAT	LON	Billing Month	Billing
AZ0357	700822903	CHANDRADASA W K	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89006	6.871557	201906	176
AZ0357	700822903	CHANDRADASA W K	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89006	6.871557	201907	210
AZ0357	700822903	CHANDRADASA W K	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89006	6.871557	201908	198
AZ0357	700822903	CHANDRADASA W K	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89006	6.871557	201909	198
AZ0357	700822903	CHANDRADASA W K	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89006	6.871557	201910	211
AZ0357	700822903	CHANDRADASA W K	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89006	6.871557	201911	187
AZ0357	700823002	DAVID H A	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89012	6.87158	201906	4
AZ0357	700823002	DAVID H A	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89012	6.87158	201907	2
AZ0357	700823002	DAVID H A	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89012	6.87158	201908	4
AZ0357	700823002	DAVID H A	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89012	6.87158	201909	0
AZ0357	700823002	DAVID H A	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89012	6.87158	201910	2
AZ0357	700823002	DAVID H A	STANLEY TILAKERATNE ROAD,NUGEGODA,	79.89012	6.87158	201911	0

Using this 6-month energy data, a reasonable value for the maximum demand of each customer was calculated and data sheet with customer details, their location and respective maximum demand were prepared. This data imported directly to GIS software and plotted in the geographical map. Figure 4.1 shows the image of the Nugegoda area with the consumer locations.

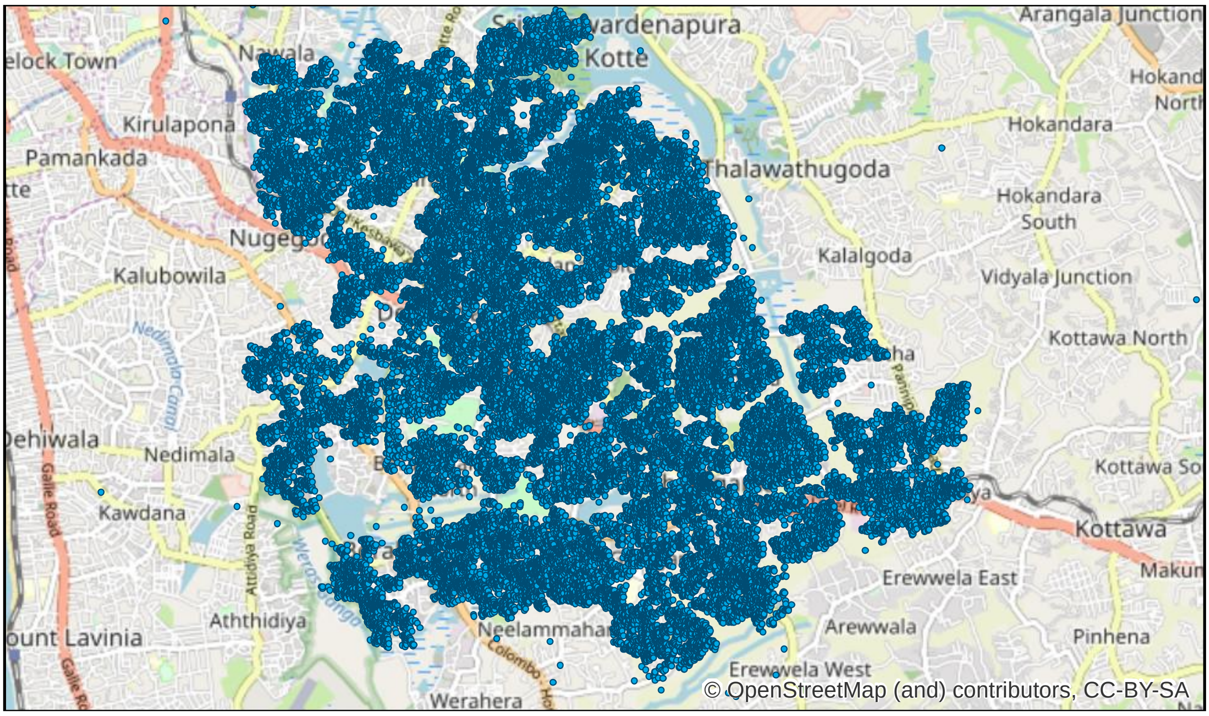


Figure 4.1. Locations of Consumers in Nugegoda Area

After plotting data on map it was observed that some locations of the consumers were not accurate since those are plotted outside the boundary of the Nugegoda area. Further in some locations consumers were unable to find though the map clearly indicated siting of the buildings. So it was required to identify a better consumer island where data is accurate to some extent. So ultimately Pamunuwa area at Maharagama was selected for the study considering the consistency of the available data. Addition of maximum demands of the selected area was 1013kVA. Area was around 0.972km^2 in size, hence the density was 1042.2kVA/km^2.

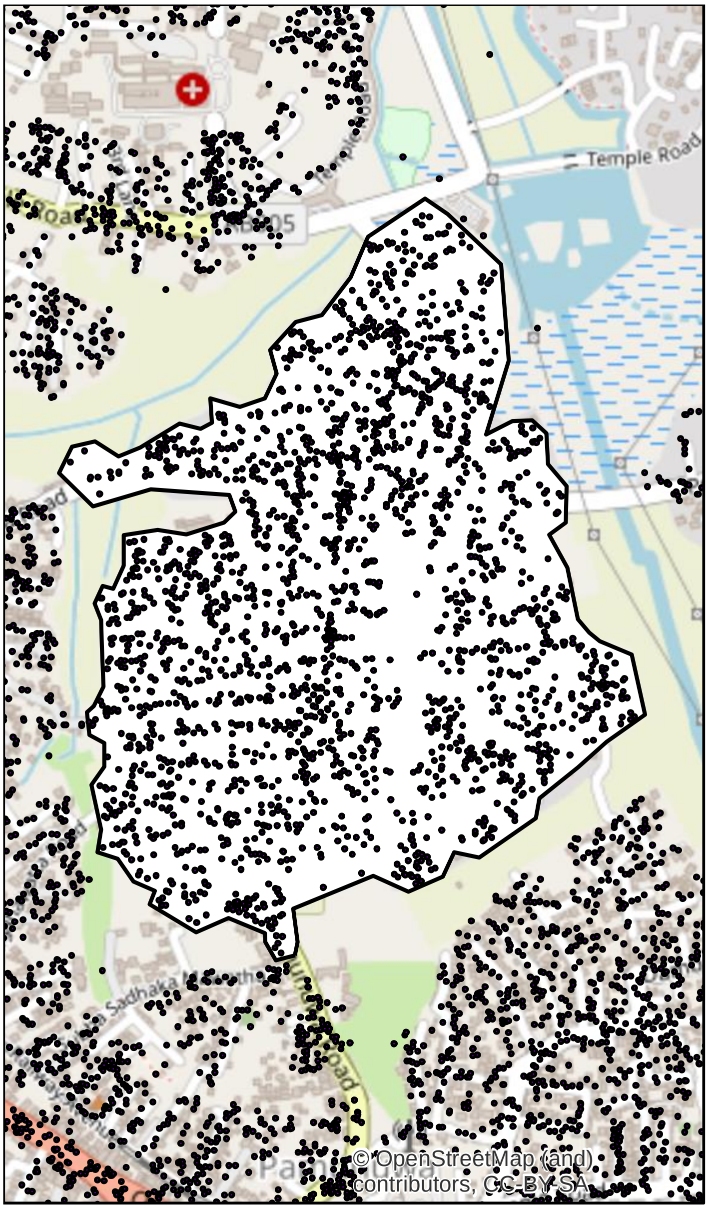


Figure 4.2. Selected area for verification

4.3 COST OPTIMISED PLANNING SOLUTION FOR SELECTED AREA

Derived algorithm was run for Pamunuwa area. Planning horizon was assumed as 5 years. Load growth of the area was taken as 2% according to the load forecasting prepared by LECO for domestic consumers in Nugegoda area. Load Factor (LF) of the LECO was assumed for the study area as well. The current maximum demand of the LECO is 254MW and total sales recorded was 1,522 GWh. So,

$$\mathrm{LF} = \frac{\text{Average Demand}}{\text{Maximum Demand}} = \frac{1522\ x\ 1000 / 8760}{254}$$

$$\mathrm{LF} = 0.68$$

Failure rate and the restoration time for LV conductors were considered as 0.01/km/year and 2hrs referring the outage data of LECO. So based on the above parameters and considering available market prices for energy loss and cost of ENS, algorithm was run and observed result has been presented in Table 4.2.

Table 4.2. Output of the Algorithm for Selected Area

Option	Conductor (mm2)	Transformer (kVA)	Length (m)	Loss (%)	Required Number of Transformers
1	35	100	142.30	0.79%	12
2	35	160	174.28	1.44%	8
3	35	250	220.45	2.87%	5
4	35	400	284.60	5.98%	3
5	50	100	142.30	0.55%	12
6	50	160	174.28	1.01%	8
7	50	250	220.45	2.03%	5
8	50	400	284.60	4.26%	3
9	70	100	142.30	0.40%	12
10	70	160	174.28	0.73%	8
11	70	250	220.45	1.46%	5
12	70	400	284.60	3.08%	3
13	95	100	142.30	0.29%	12
14	95	160	174.28	0.54%	8
15	95	250	220.45	1.08%	5
16	95	400	284.60	2.29%	3
17	120	100	142.30	0.23%	12
18	120	160	174.28	0.42%	8
19	120	250	220.45	0.85%	5
20	120	400	284.60	1.82%	3
21	150	100	142.30	0.19%	12
22	150	160	174.28	0.34%	8
23	150	250	220.45	0.69%	5
24	150	400	284.60	1.46%	3

So for each type of combination when delivering the required power, the maximum length that the main feeder can be drawn and the loss occurred were observed. However, the maximum of the total loss level of a feeder which is allowed according to current practice of LECO is 3%. In this study allowing for 1% loss for spur feeders, maximum loss level allowed for main feeders was considered as 2%. So the combinations in which the loss level exceeded beyond 2% was not considered as a feasible solution. Neglecting those infeasible solutions total cost for delivering a single kVA was calculated for each combination through the algorithm and tabulated in below Table 4.3.

Table 4.3. Cost of each combination for selected area

Option	Transformer Cost (LKR/kVA)	LV Cable Cost (LKR/kVA)	HV Cable Cost (LKR/kVA)	Energy Lost Cost (LKR/kVA)	Core Loss Cost (LKR/kVA)	Copper Loss Cost (LKR/kVA)	Reliability Cost (LKR/kVA)	Total Cost (LKR/kVA)
1	12,164.00	11,876.00	15,204.00	1,485.00	1,243.00	3,928.00	2	45,902.00
2	9,212.00	9,761.00	12,496.00	2,710.00	1,176.00	2,739.00	2	38,096.00
3	7,062.00	7,830.00	10,024.00	5,404.00	913.00	2,654.00	2	NaN
4	5,647.00	6,266.00	8,022.00	11,254.00	783.00	2,710.00	3	NaN
5	12,135.00	13,900.00	15,168.00	1,042.00	1,240.00	3,901.00	2	47,388.00
6	9,172.00	11,402.00	12,442.00	1,905.00	1,171.00	2,705.00	2	38,799.00
7	7,001.00	9,108.00	9,938.00	3,815.00	905.00	2,589.00	2	NaN
8	5,545.00	7,220.00	7,878.00	8,022.00	769.00	2,572.00	3	NaN
9	12,116.00	15,232.00	15,144.00	746.00	1,238.00	3,883.00	2	48,361.00
10	9,146.00	12,478.00	12,406.00	1,365.00	1,167.00	2,682.00	2	39,246.00
11	6,961.00	9,938.00	9,881.00	2,741.00	900.00	2,545.00	2	32,968.00
12	5,478.00	7,827.00	7,782.00	5,801.00	760.00	2,482.00	3	NaN
13	12,103.00	18,650.00	15,128.00	550.00	1,237.00	3,872.00	2	51,542.00
14	9,128.00	15,265.00	12,382.00	1,008.00	1,165.00	2,667.00	2	41,617.00
15	6,934.00	12,134.00	9,843.00	2,028.00	896.00	2,517.00	2	34,354.00
16	5,433.00	9,516.00	7,719.00	4,309.00	754.00	2,424.00	3	NaN
17	12,096.00	26,784.00	15,119.00	436.00	1,236.00	3,865.00	2	59,538.00
18	9,118.00	21,912.00	12,368.00	799.00	1,164.00	2,659.00	2	48,022.00
19	6,919.00	17,398.00	9,821.00	1,609.00	894.00	2,501.00	2	39,144.00
20	5,407.00	13,609.00	7,682.00	3,428.00	750.00	2,390.00	3	33,269.00
21	12,090.00	29,358.00	15,112.00	349.00	1,236.00	3,860.00	2	62,007.00
22	9,110.00	24,008.00	12,358.00	640.00	1,163.00	2,652.00	2	49,933.00
23	6,907.00	19,046.00	9,804.00	1,290.00	893.00	2,489.00	2	40,431.00
24	5,388.00	14,870.00	7,654.00	2,752.00	747.00	2,365.00	3	33,779.00

For unfeasible solutions total cost has been given as “NaN”. Considering other combinations, it can be clearly seen that the minimum cost per kVA is given by the combination 11 in which conductor and transformer sizes are $70mm^2$ and 250kVA respectively. So the final solution has been presented in Table 4.4 below.

Table 4.4. Outcome of the Algorithm

Density (kVA/km^2)	Length (m)	Loss (%)	Area (mm^2)	Capacity (kVA)	Transformer Count	Cost (LKR/kVA)
1.042	220.45	1.46%	70	250	5	32,968.00

Now the validation process was started with optimum solution given above and considering two other combinations which became the next two lowest costs. So these 3 solutions are tabulated in below table in the ascending order, based on the value of total cost per kVA.

Table 4.5. Lowest Combinations for Selected Area

Option	Conductor (mm2)	Transformer (kVA)	Length (m)	Loss (%)	Required Number of Transformers	Total Cost (LKR/kVA)
11	70	250	220.45	1.46%	5	32,968.00
20	120	400	284.60	1.82%	3	33,269.00
24	150	400	284.60	1.46%	3	33,779.00

So the objective of the validation process is to check whether the optimum solution of the algorithm will also become the lowest in real world scenario among the 3 lowest combinations after modeling them in actual consumer island. So it was required to design 3, LV distribution networks using above 3 combinations based on the parameters observed.

4.4 NETWORK DESIGNING

Major part of the design was to locate the transformers and draw the feeders constrained to the feeder length and the transformer count proposed by the algorithm. Despite the polygon-based planning theory, the feeders have to be routed through the roads and possible spacing. When designing it was tried to allocate the total demand of the area equally among the transformers. Further considering a single transformer, loading was tried to fairly distribute among 4 feeders to avoid overloading of feeders. Here, due to the consideration of only the main feeders, loads were aggregated around the main feeder in order to avoid the effect of spur feeders. This became a challenging task since the load was not evenly distributed in real world scenarios.

Design was carried out in the ArcGIS software by locating the transformers and drawing the LV conductors for distributing the power for each consumer. After locating the transformers MV network was drawn connecting all the transformers. Then the network was reduced by aggregating the demand around the main feeders and ultimately observed a network with transformers, main LV feeders and MV network for particular area. Transformers with respective LV network was exported directly to the Neplan software for load flow analysis and reliability analysis.

Load flow analysis was repeated for consecutive 5 years considering the load growth of the network. This was possible with Nepaln Software, since it has an inbuilt capability of modeling the same network under various conditions by defining numerous operational status. So for each year, total peak power loss of the network was calculated using load flow analysis. Following the same procedure, each year ENS was observed through the reliability analysis. Each year transformer loss was calculated considering the increase of transformer loading. So using these data and considering the infrastructure of the network, actual cost for the operation of the network for 5-year planning horizon was assessed.

Following sections describe the analysis of each option and observations received by the algorithm.

4.4.1 Option 1 – 250kVA transformer with 70mm^2 ABC conductor

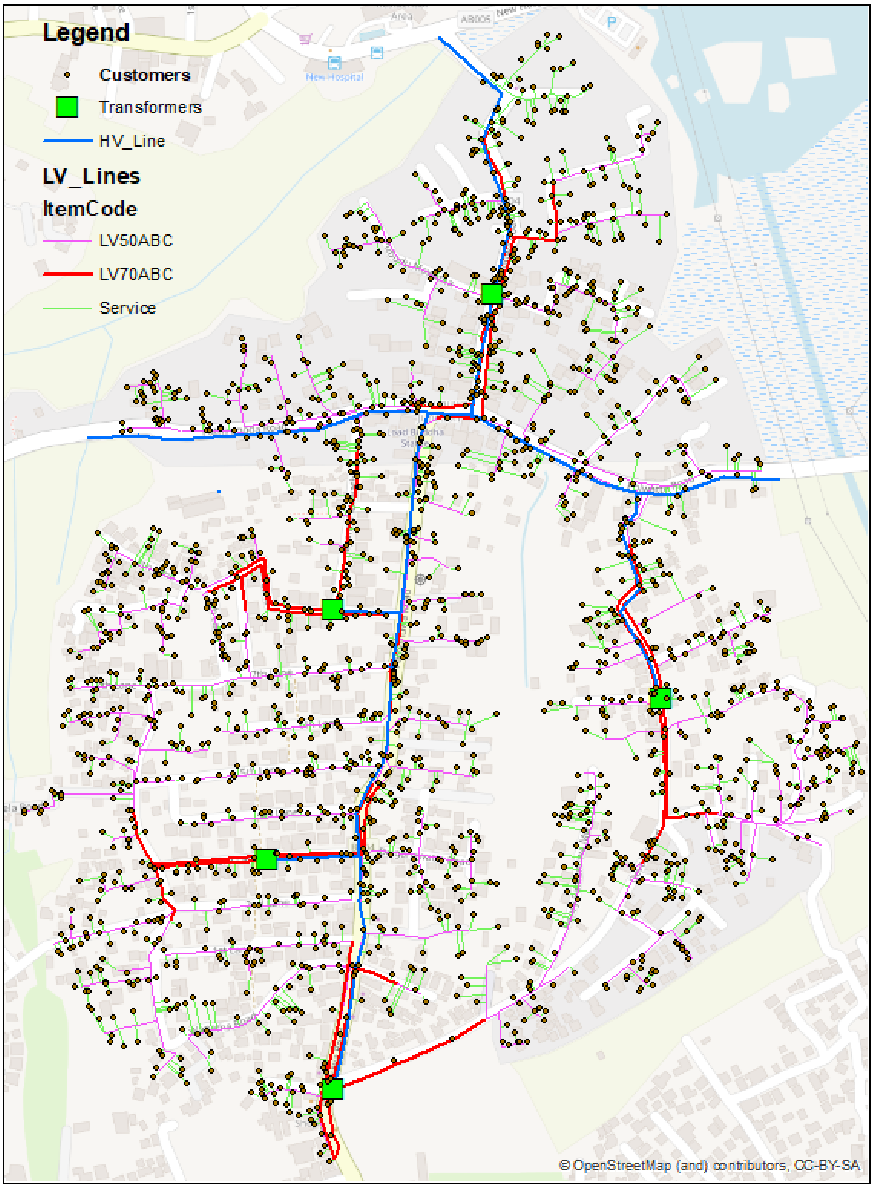


Figure 4.3. LV network design - Option 1

Figure 4.3 shows the complete network designed including main feeders, spur feeders and service connections for 250kVA, 70mm^2 combination. Here maximum main feeder length was considered as 220m which was observed from the algorithm. Further feeders were designed in such a way that the maximum feeder length did not exceed 600m, which is a norm of the LECO in designing LV feeders. However, this network was reduced by aggregating the loads around the main feeders. Figure shows the reduced network which contain only the transformers, main feeders and MV network.

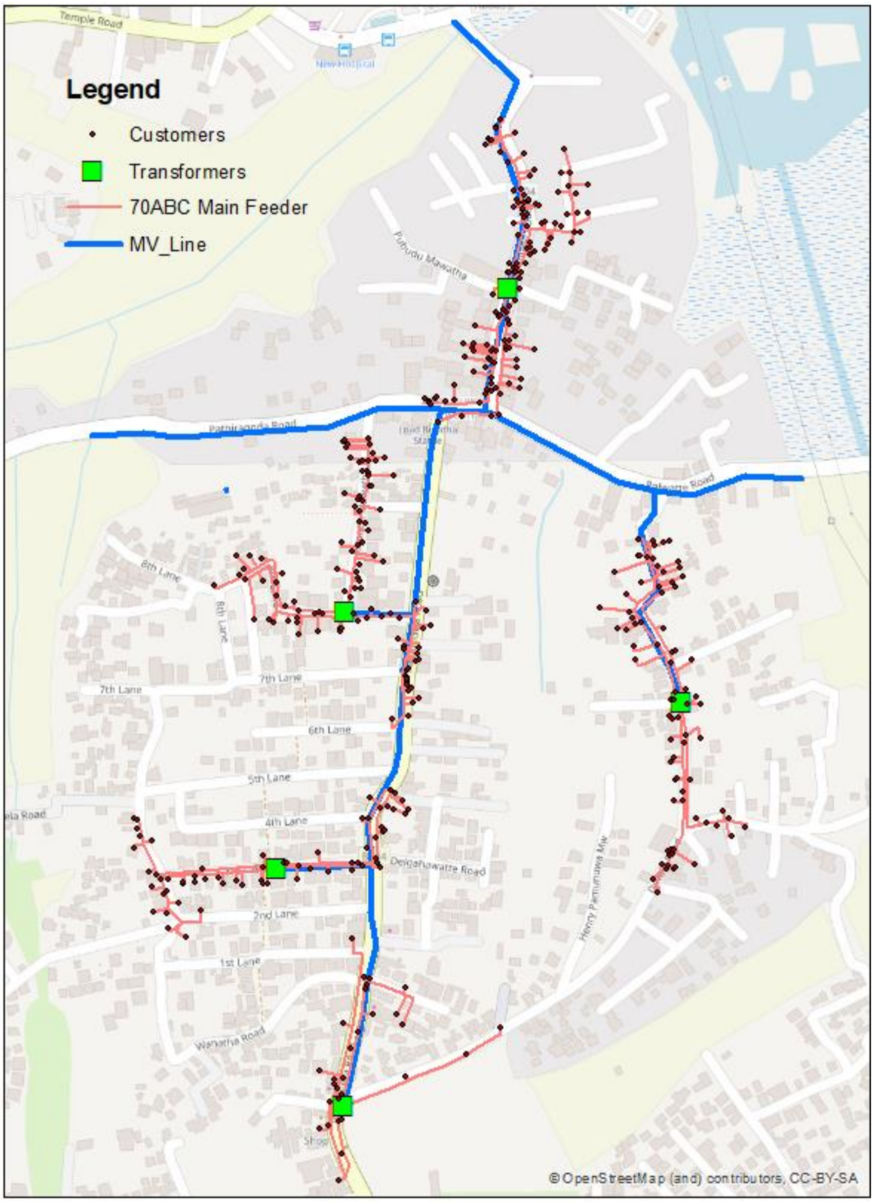


Figure 4.4. Reduced LV network design - Option 1

Only the transformers and LV network were exported to Nepaln and following figure shows the screen shot of the software after the exporting.

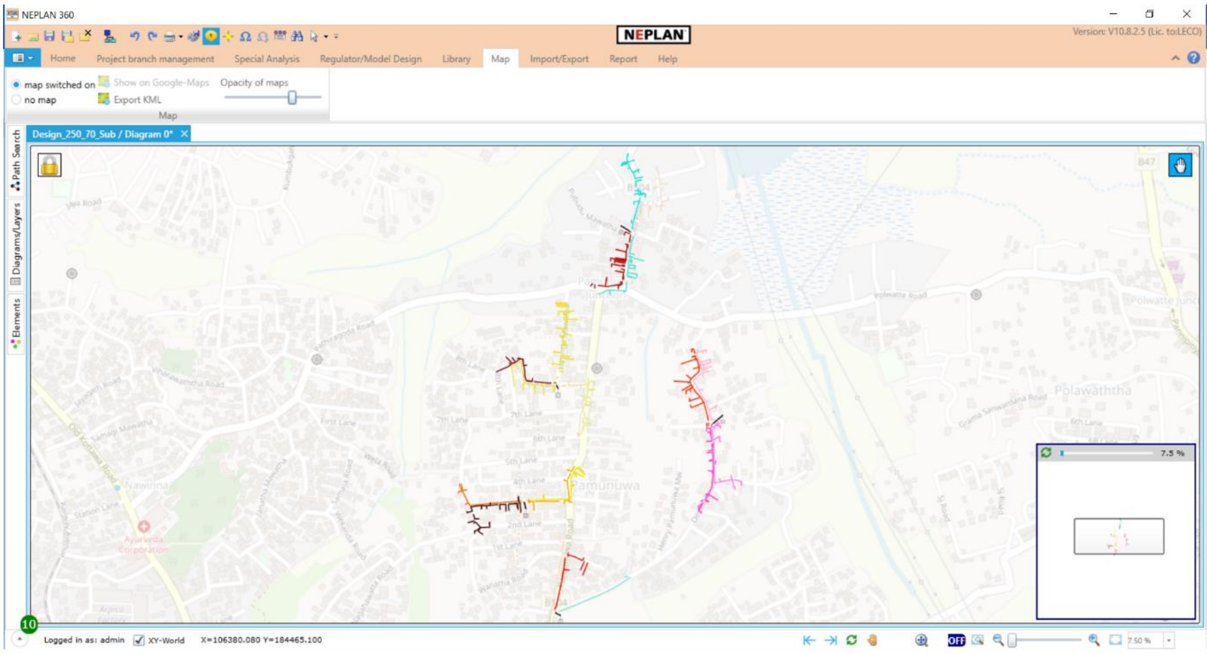


Figure 4.5. LV network design exported to Neplan – Option 1

So results were obtained by running Neplan model for 6 years-time period including the 0th year of operation and considering next 5 years of planning horizon by defining operational status based on the above network. The observed results for average loss percentage, total power loss of the network, transformer copper losses and ENS are shown in Table 4.6 for each year.

Table 4.6. Observed results – Option 1

Year	Percentage Energy Loss	Peak Power Loss (kW)	Transformer Copper Loss (kW)	ENS(kWh)
2020	1.66%	16.65	11.81	6.32
2021	1.69%	17.31	12.28	6.45
2022	1.72%	18.01	12.78	6.58
2023	1.75%	18.74	13.29	6.71
2024	1.79%	19.47	13.83	6.84
2025	1.82%	20.25	14.38	6.98

Detailed calculation of the total operating cost of the network within the planning horizon has been presented in the Table A1.1 and summary of the costs has been given in Table 4.7.

Table 4.7. Cost summary – Option 1

Description		Cost/LKR
i.	Infrastructure Cost	
	Transformers	7,673,850.00
	LV Cable	10,931,052.00
	HV Cable	14,078,914.50
ii.	Energy Lost Cost	4,016,395.96
iii.	Core Loss Cost	990,772.23
iv.	Copper Lost Cost	2,850,372.57
v.	Reliability Cost	3,799.03
	Total Cost	**40,545,156.29**
	Total Cost/kVA	**36,252.00**

4.4.2 Option 2 – 400kVA transformer with 120mm^2 ABC conductor

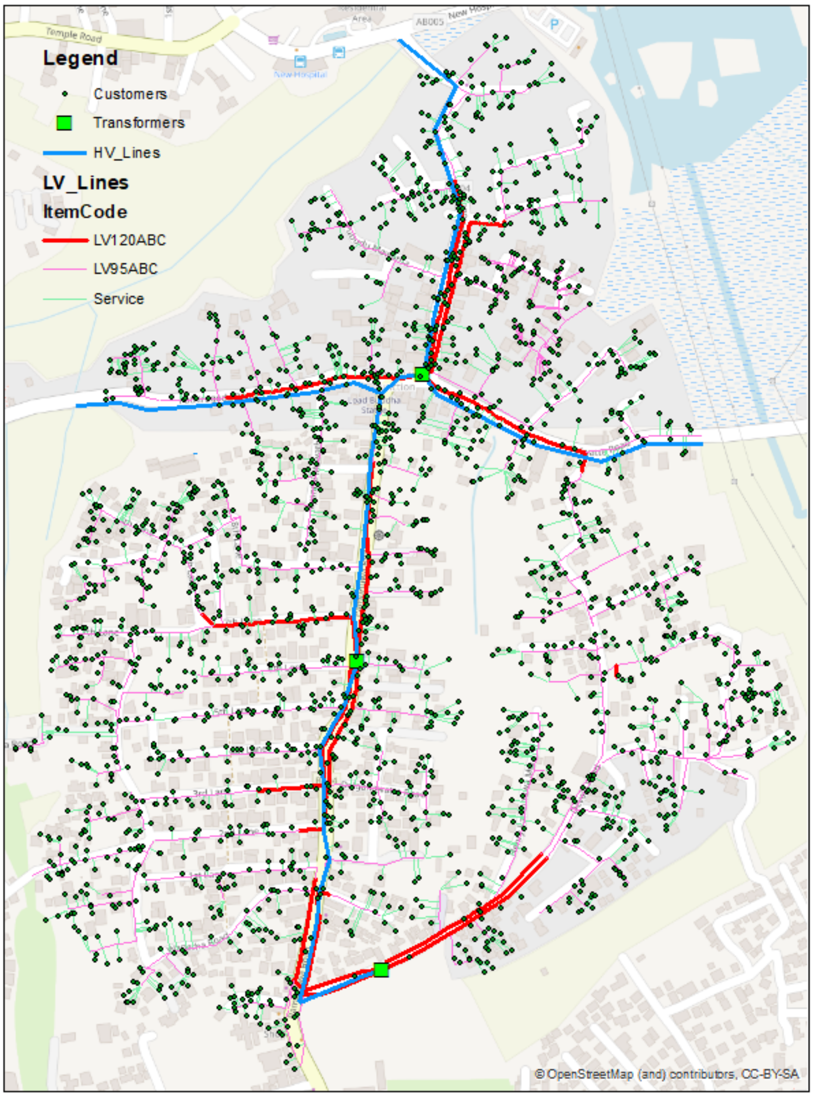


Figure 4.6. LV network design - Option 2

Figure 4.6 shows the total network designed including main feeders, spur feeders and service connections for 400kVA, 120mm^2 combination. In the design maximum main feeder length was considered as 285m, proposed by the algorithm. This network was reduced by aggregating the loads around the main feeders. Figure 4.7 shows the reduced network which contain only the transformers, main feeders and MV network.

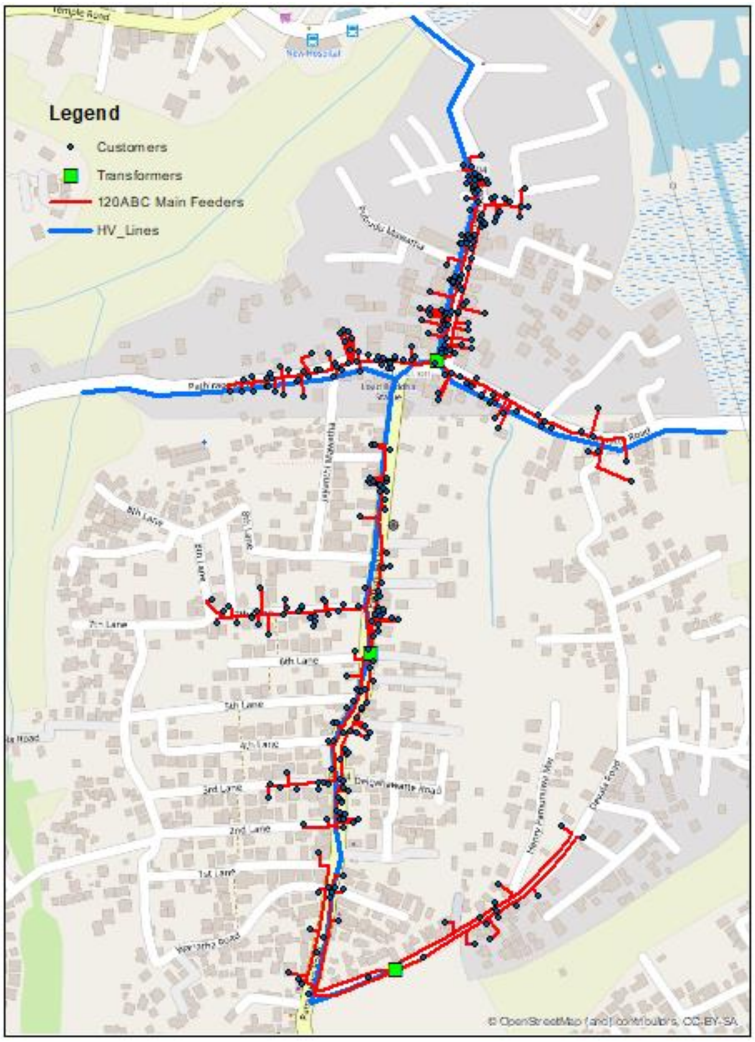


Figure 4.7. Reduced LV network design - Option 2

Except the MV network LV network was exported to Neplan Software and the Figure 4.8 mentioned below indicates a screen shot of the software.

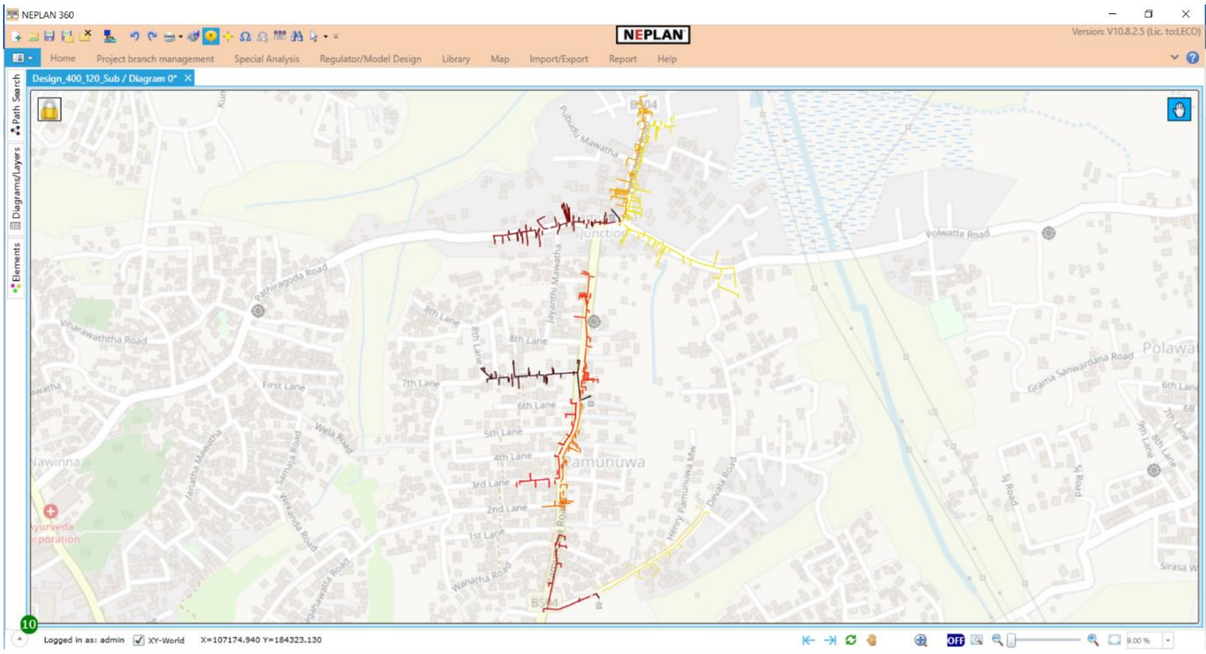


Figure 4.8. LV network design exported to Neplan – Option 2

Observed results for average percentage power loss, total power loss of the network, transformer copper losses and ENS are given in the Table 4.8 below for each year.

Table 4.8. Observed results – Option 2

Year	Percentage Energy Loss	Peak Power Loss (kW)	Transformer Copper Loss (kW)	ENS(kWh)
2020	1.90%	18.69	11.01	7.94
2021	1.94%	19.46	11.45	8.10
2022	1.98%	20.23	11.90	8.26
2023	2.02%	21.04	12.37	8.43
2024	2.05%	21.87	12.86	8.59
2025	2.09%	22.71	13.38	8.77

So detailed calculation of the total cost of the network for operating within the planning horizon has been presented in Table A1.2 and summary of the costs has been given in Table 4.9 below.

Table 4.9. Cost Summary – Option 2

Description		Cost/LKR
i.	Infrastructure Cost	
	Transformers	5,942,010.00
	LV Cable	14,965,454.88
	HV Cable	12,177,026.05
ii.	Energy Lost Cost	4,510,212.11
iii.	Core Loss Cost	822,476.67
iv.	Copper Lost Cost	2,654,231.01
v.	Reliability Cost	4,772.83
	Total Cost	**41,076,183.56**
	Total Cost/kVA	**36,727.00**

4.4.3 Option3 – 400kVA transformer with 150mm^2 ABC conductor

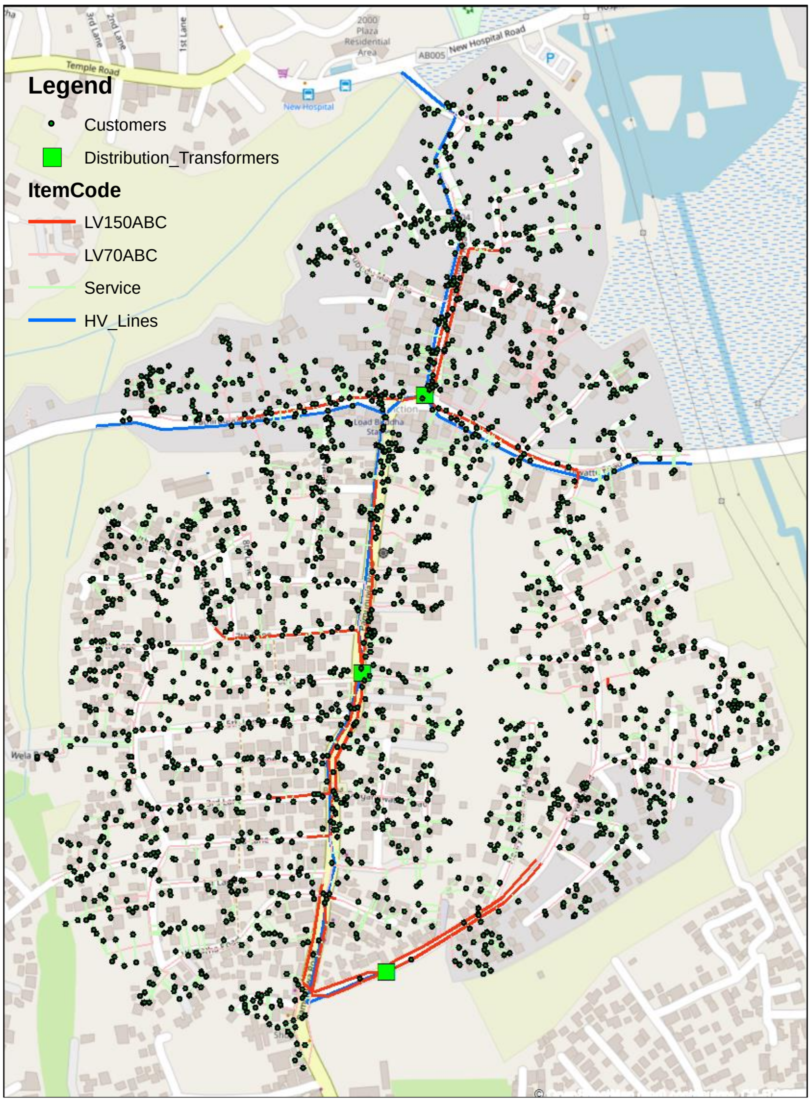


Figure 4.9. LV network design - Option 3

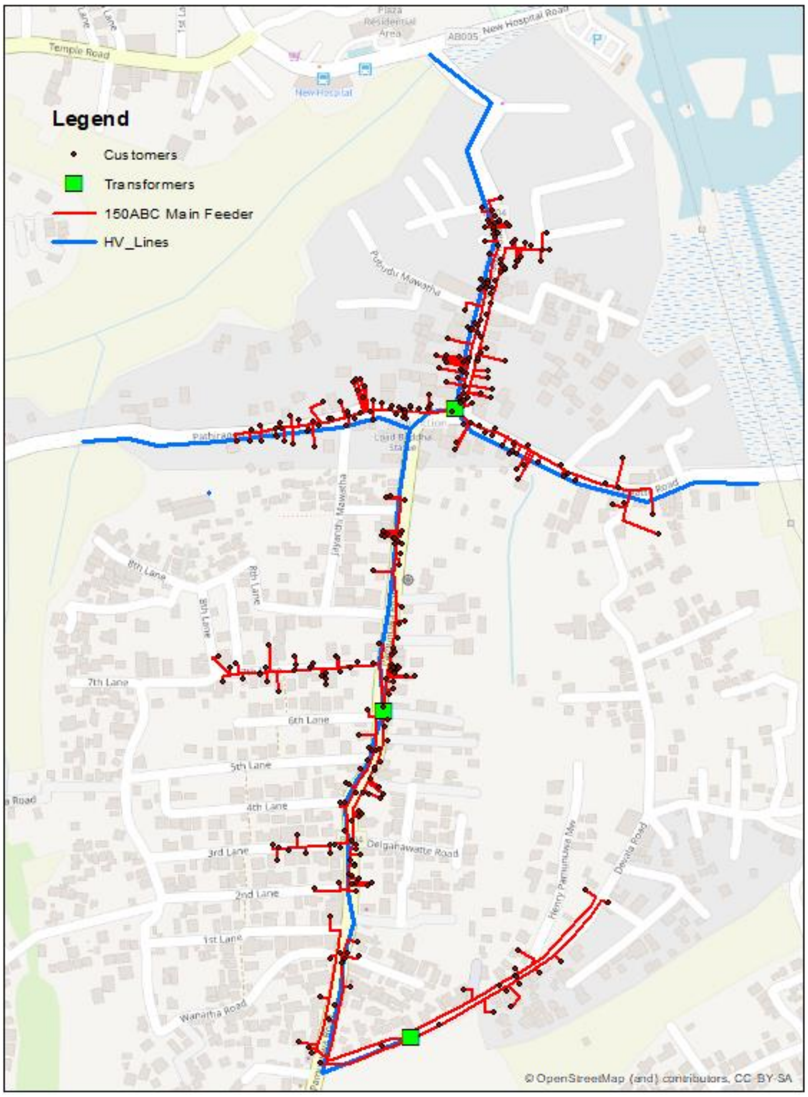


Figure 4.10. Reduced LV network design - Option 3

The design is same as the design of the Option 2- 400kVA transformer with 120mm^2 conductor combination. Maximum feeder length also considered around 285m according to the output of the algorithm. Figure 4.10 shows the geographical representation of the design. Then the LV network was exported directly to the Neplan as previous and observed results for average percentage power loss, total power loss of the network, transformer copper losses and ENS which are given in the following Table 4.10.

Table 4.10. Observed results – Option 3

Year	Percentage Energy Loss	Peak Power Loss (kW)	Transformer Copper Loss (kW)	ENS(kWh)
2020	1.90%	14.84	10.92	6.69
2021	1.94%	15.44	11.37	6.82
2022	1.98%	16.08	11.84	6.96
2023	2.02%	16.77	12.33	7.10
2024	2.05%	17.44	12.83	7.24
2025	2.09%	18.17	13.36	7.39

So detailed calculation of the total cost of the option 3 has been presented in the Table A1.3 and summary of the costs has been shown in below Table 4.11.

Table 4.11. Cost summary – Option 3

Description		Cost/LKR
i.	Infrastructure Cost	
	Transformers	5,942,010.00
	LV Cable	16,410,850.55
	HV Cable	12,177,026.05
ii.	Energy Lost Cost	3,589,847.14
iii.	Core Loss Cost	822,476.67
iv.	Copper Lost Cost	2,641,763.97
v.	Reliability Cost	4,021.44
	Total Cost	**41,587,995.82**
	Total Cost/kVA	**37,185.00**

4.5 COMPARISON OF THE RESULTS

Observed total cost for aforementioned 3 options are compared with each other and also with the respective costs observed from the algorithm and presented in the Table 4.12 below.

Table 4.12. Cost Comparison of 3 Alternatives

	Conductor (mm^2)	Transformer (kVA)	Transformer Count	Total Cost (LKR/kVA)	
				Algorithm	Validation
Option 1	70	250	5	32,968.00	36,252.00
Option 2	120	400	3	33,269.00	36,727.00
Option 3	150	400	3	33,779.00	37,185.00

According to the above Table 4.12, it can be clearly seen that there is a slight difference between the cost values obtained through the algorithm and from simulated network model. However, still the option which gave the minimum total cost per kVA value through the algorithm, has become the lowest in the actual model as well. Not only the minimum cost, but the order of the costs of selected three options has also been received in the order produced through the algorithm.

It can be observed that the output of the algorithm has been validated through the actual model. Consequently, the defined algorithm is proposed the optimum transformer conductor combination and can be used for designing the distribution network based on the load density and the total maximum demand for a given area.

4.6 POLYGON BASED PLANNING CRITERIA – STRATEGIES OF USING THE METHODOLOGY

So the above algorithm in which the derivation begins with polygon-based planning method, can be directly used for planning and designing LV distribution networks for a given area based on the load density. However, according to the outcome of the algorithm, few key points are noted during the research and these can be referred as the guidelines which should be followed for having an optimum distribution network.

i. Number of feeders taken out from a single transformer shall be four in order to utilize the spacing requirements around the transformer.

ii. If bigger transformer capacities are preferred, better to use conductors with large cross sectional areas for feeder wiring rather than using conductors with smaller cross sectional areas. Otherwise the total capacity of the transformer cannot be delivered. If small conductor size is used with the bigger transformer capacity, in order to deliver the power, number of feeders has to be increased which may lead to increase the loss of the network and hence the cost of operation.

iii. Cost of the infrastructure plays a vital role in the total cost in LV planning. For all 24 nos. of combinations considered for 5 year planning horizon more than 80% of the total cost represents the infrastructure. This share can be varied according to the planning horizon considered. Since LV networks are planning for short time periods, accurate cost of the transformers, LV cables and HV cables should be considered.

iv. For areas with lower load densities, small size transformers with small conductor sizes might be suitable and vice a versa. However, this should be confirmed through the algorithm.

v. As far as LV planning is considered cost of reliability does not have a big impact on the total cost. Because unlikely HV and MV network, LV networks does not have alternative ways to restore power after failing a transformer.

vi. For an infinite area based on the load density optimum transformer conductor combinations have been presented in Table 4.13 which can be used in easy decision making in planning. Planning horizon considered is 5 years.

Table 4.13. Optimum Combination for Typical Load Densities

Density (MVA/km^2)	Conductor (mm^2)	Transformer (kVA)	Length (m)	Loss (%)	Cost (LKR)
0.1	50	100	471.17	1.90%	113,500.00
0.2	70	160	421.33	1.94%	70,388.00
0.4	95	250	372.35	1.97%	47,978.00
0.8	70	250	263.4	1.90%	35,312.00
1	70	250	235.83	1.71%	32,562.00
1.5	70	250	192.87	1.40%	28,306.00
2	95	400	210.83	1.80%	23,802.00
4	95	400	149.49	1.29%	19,159.00

5 CONCLUSION

With the arising of the new trends in the distribution systems around the world, the utilities should adapt and update their systems for sustainability. They should adapt new technologies and follow new methodologies for their planning, construction, operation and maintenance works. Utilities have given high priority for planning works, especially for planning HV and MV networks. LV networks are fairly complex to plan and also utilities have less attention towards LV level planning. However, planning of LV networks should also be considered as critical since it also contributes to performance of the utility. The study has developed a low cost and fairly easy methodology for serving this purpose.

The proposed novel methodology which is based on the polygon-based planning technique has been developed in this research, which can be specially used for LV network distribution planning to identify optimal LV network configurations for a given load density and the total kVA demand of the area. The solution which makes the minimum cost, includes number of transformers and capacity, size of conductors, number of feeders and feeder lengths. The proposed methodology has been validated using a consumer island on a LV distribution network of LECO by the aid of GIS and Neplan Software. Distribution network for electrifying the selected consumer island was designed following the parameters observed through the algorithm. Then the actual cost was compared and it was observed that though there was a difference between the actual cost with the output of the algorithm, the optimum combination proposed by the algorithm was became the lowest in actual scenario as well.

The proposed planning criteria can be applicable for LV network classifications based on any geographical conditions; rural, urban or metropolitan areas. Further, the polygon based planning concept can be easily adapted successfully for both high rise buildings consist of multiple stories, or small housing units which are spreaded through a land which is same as plotted land concept. These systems are well planned areas and also unlike the conversional distribution systems, load is distributed in proper manner which enables easy application of the proposed criteria.

As an example if a high rise apartment building is considered, the luxury and the cost of housing units might be got higher with the height of the building. Increasing of luxury level also denotes the high usage of the power through the energy. This simply means with the increase of the height the amount of loading added from a single floor to the distribution conductor gradually increases. This is the basic concept of the polygon based planning concept. So the proposed algorithm can easily be adapted for modern distribution concepts.

Further in the areas where distribution networks are already available this concept still can be used. Because if an area is considered, there is a point where the demand of the area gets saturated due to the unavailability of adequate spaces to add new loads. Then the load growth of the network will be negligible and on this stage considering the load density and the total demand optimum network can be designed.

Thus, the polygon-based planning method based criteria is successful in using for long term and short term network planning.

5.1 LIMITATIONS OF THE STUDY AND RECOMMENDATIONS FOR FUTURE WORK

The main focus of this research is to develop a methodology and criteria for LV planning based on polygon-based planning technique. Since this is a theoretical approach certain approximations and assumptions have to be considered to fulfill the above purpose. Identified limitations of this study are listed below with the proposals for future work.

- In order to calculate the load density and the total maximum demand of the area 6-month energy consumption and the defined LF were used. With the introduction of the smart energy meters to the utility consumption data for each 15-minute time interval can be recorded and to calculate more accurate figure for maximum demand and load density, these loading data can be used.
- The effect of the spur feeders was eliminated in this research. If the selection of spur feeders is also allowed, there may be more combinations than 24 and algorithm might get more complicated. However, if polygon based planning technique can be defined and algorithm can be extended introducing the selection of spur feeder, accurate sizing of spur feeder also can be done.
- If more accurate pricing data is available for components and other operational status same methodology can be used for MV network planning. Further developing the algorithm to cater with different voltage levels, tool can be used for identifying the best fit voltage level for a given area based on the load density.

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ANNEXURE 1

Table A1.1. Detailed Cost Calculation – Option 1

UTL	H	4271.6
Loss Cost	LKR/kWh	10.78
Cost of ENS	LKR/kWh	120
Demand	kVA	1013.1

Option 1 - 250kVA transformer with 70Sqmm Cable

Infrastructure Cost

	Unts.	Qty.	Unit Rate/LKR	Total (LKR)
Transformers	Nos.	5	1,534,770.00	**7,673,850.00**
LV Cable	Km	4.40	2,484,330.00	**10,931,052.00**
HV Cable	Km	2.85	4,939,970.00	**14,078,914.50**

Energy Lost Cost

Year	Loss(kW)	IR	Loss Cost (LKR)
2020	16.65	1.00	766,696.67
2021	17.31	1.10	724,625.68
2022	18.01	1.21	685,389.87
2023	18.74	1.33	648,337.09
2024	19.47	1.46	612,356.81
2025	20.25	1.61	578,989.84
Total			**4,016,395.96**

Core Loss Cost

Year	Loss(kW)	IR	Loss Cost (LKR)
2020	2.19	1.00	206,807.83
2021	2.19	1.10	188,007.12
2022	2.19	1.21	170,915.56
2023	2.19	1.33	155,377.79
2024	2.19	1.46	141,252.53
2025	2.19	1.61	128,411.39
Total			**990,772.23**

Copper Loss Cost

	Loss(kW)	IR	Loss Cost (LKR)
2020	11.81	1.00	543,824.42
2021	12.28	1.10	514,229.12
2022	12.78	1.21	486,286.69
2023	13.29	1.33	459,868.38
2024	13.83	1.46	434,882.64
2025	14.38	1.61	411,281.34
Total			**2,850,372.57**

Reliability Cost

	ENS(kWh)	IR	Loss Cost (LKR)
2020	6.32	1.00	632.00
2021	6.45	1.10	586.04
2022	6.58	1.21	543.42
2023	6.71	1.33	503.89
2024	6.84	1.46	467.25
2025	6.98	1.61	433.27
Total			**3,799.03**

Total Cost for 5 years/LKR	**40,545,156.29**
Total Cost per kVA/kVA	**36,251.72**

Table A1.2. Detailed Cost Calculation – Option 2

Option 2 - 400kVA transformer with 120Sqmm Cable

Infrastructure Cost

	Unts.	**Qty.**	Unit Rate/LKR	**Total (LKR)**
Transformers	Nos.	3	1,980,670.00	**5,942,010.00**
LV Cable	km	3.42	4,375,864.00	**14,965,454.88**
HV Cable	km	2.47	4,939,970.00	**12,177,026.05**

Energy Lost Cost

Year	**Loss(kW)**	**IR**	**Loss Cost (LKR)**
2020	18.69	1.00	860,634.28
2021	19.46	1.10	814,628.29
2022	20.23	1.21	769,874.35
2023	21.04	1.33	727,908.88
2024	21.87	1.46	687,839.93
2025	22.71	1.61	649,326.38
Total			**4,510,212.11**

Core Loss Cost

Year	**Loss(kW)**	**IR**	**Loss Cost (LKR)**
2020	1.818	1.00	171,678.83
2021	1.818	1.10	156,071.66
2022	1.818	1.21	141,883.33
2023	1.818	1.33	128,984.85
2024	1.818	1.46	117,258.95
2025	1.818	1.61	106,599.05
Total			**822,476.67**

Copper Loss Cost

	Loss(kW)	**IR**	**Loss Cost (LKR)**
2020	11.01	1.00	506,979.36
2021	11.45	1.10	479,185.39
2022	11.90	1.21	452,905.95
2023	12.37	1.33	428,075.08
2024	12.86	1.46	404,620.84
2025	13.38	1.61	382,464.39
Total			**2,654,231.01**

Reliability Cost

	ENS(kWh)	**IR**	**Loss Cost (LKR)**
2020	7.94	1.00	794.00
2021	8.10	1.10	736.25
2022	8.26	1.21	682.71
2023	8.43	1.33	633.06
2024	8.59	1.46	587.02
2025	8.77	1.61	544.32
Total			**4,772.83**
Total Cost for 5 years/LKR			**41,076,183.56**
Total Cost per kVA/kVA			**36,726.52**

Table A1.3. Detailed Cost Calculation – Option 3

Option 3 - 400kVA transformer with 150Sqmm Cable
Infrastructure Cost

	Unts.	**Qty.**	Unit Rate/LKR	**Total (LKR)**
Transformers	Nos.	3	1,980,670.00	**5,942,010.00**
LV Cable	km	3.42	4,798,494.31	**16,410,850.55**
HV Cable	km	2.47	4,939,970.00	**12,177,026.05**

Energy Lost Cost

Year	**Loss(kW)**	**IR**	**Loss Cost (LKR)**
2020	14.84	1.00	683,350.06
2021	15.44	1.10	646,344.34
2022	16.08	1.21	611,941.65
2023	16.77	1.33	580,182.13
2024	17.44	1.46	548,510.67
2025	18.17	1.61	519,518.29
Total			**3,589,847.14**

Core Loss Cost

Year	**Loss(kW)**	**IR**	**Loss Cost (LKR)**
2020	1.818	1.00	171,678.83
2021	1.818	1.10	156,071.66
2022	1.818	1.21	141,883.33
2023	1.818	1.33	128,984.85
2024	1.818	1.46	117,258.95
2025	1.818	1.61	106,599.05
Total			**822,476.67**

Copper Loss Cost

	Loss(kW)	**IR**	**Loss Cost (LKR)**
2020	10.92	1.00	503,046.59
2021	11.37	1.10	476,086.22
2022	11.84	1.21	450,579.53
2023	12.33	1.33	426,460.88
2024	12.83	1.46	403,592.38
2025	13.36	1.61	381,998.37
Total			**2,641,763.97**

Reliability Cost

	ENS(kWh)	**IR**	**Loss Cost (LKR)**
2020	6.69	1.00	669.00
2021	6.82	1.10	620.35
2022	6.96	1.21	575.23
2023	7.10	1.33	533.39
2024	7.24	1.46	494.60
2025	7.39	1.61	458.63
Total			**4,021.44**

Total Cost for 5 years/LKR	**41,587,995.82**
Total Cost per kVA/kVA	**37,184.14**

ANNEXURE 2

<u>Role of LECO</u>

Lanka Electricity Company (Private) Limited (LECO) founded in 1983, is an electricity distribution utility. Its major shareholder is the Ceylon Electricity Board (CEB) and other shareholders are Government Treasury, Urban Development Authority (UDA) and few Local Authorities in Sri Lanka. At the inception, the company was registered under the Companies Act No 17 of 1982 and re registered under Sri Lanka Companies Act No 7 of 2007 as a private limited Liability Company. LECO operational area includes the urban areas along the Western costal belt from Negombo to Galle, excepting the Colombo and Dehiwela Mount Lavainia municipalities and few small pockets operated by CEB distribution licensees. LECO operational area is shown in Figure A2.1.

Figure A2.1. Operational Area of LECO

LECO’s main source supply is from CEB owned 37nos. of 33kV/11kV Primary Substations at 11kV. Its distribution network comprises of 1,013km of 11kV distribution lines, 3,725km of low voltage lines and 4850 numbers of 11kV/400V distribution transformers. The current maximum demand of the system is 254MW. Total sales recorded was 1,522 GWh.

Software Used in Verification

ArcGIS Software

ArcGIS is a Geographic Information System (GIS) platform developed by Esri. Software contains a range of applications which can be used by the aid of maps and geographic information. It facilitates to create maps with a geographical reference, compile geographic data, share mapped information and manage geographic information in a database. Inbuilt tools that the software comprises of can be used in map based data analysis. Moreover, ArcGIS allows the users to develop customized tools using Python programming language. Currently ArcGIS is the asset management software of LECO in which all network assets are recorded including installation, maintenance and customer service data.

So in this study required asset data was received from the ArcGIS software with their respective geographical information. Further the designing of the LV networks also carried out in the ArcGIS.

Neplan Software

NEPLAN is a software tool to analyze, plan, optimize and simulate electrical networks. The software contains a user-friendly graphical interface with the extensive libraries for the network elements, protection devices and control circuits, which allows the user to perform study cases very efficiently. The software has a modular concept which is based on international standards, such as IEC, ANSI, IEEE, etc. Software can be used in transmission, distribution, generation and industrial networks for planning purposes, investment analysis, power quality, multi-period optimization, protection setting and assessment, dynamic simulation (RMS/EMT), etc. Software can handle a network above 500,000 bus bars easily with the aid of new IT-techniques and algorithm. LECO currently uses this software for planning of the MV network. In this study Neplan was used for Load flow analysis and the reliability analysis for the designed network during the validation process.

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TRANSFORMER TEST CERTIFICATE

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Customer	LECO						
Standards	IEC : 60076						
Application	DISTRIBUTION TRANSFORMER						
Serial No	T/15/U010010045	Cooling	ONAN	Phase	Three	Date	7/18/2015
			Ratings				
HV Voltage (V)	11000	LV Voltage (V)	415	Capacity (kVA)	100	Duty	Continuous
Vector Group	Dyn11	Frequency (Hz)	50	Type of Unit	Hermetically Sealed		
Tapping (HV)				Guaranteed temperature rise (°C)			
Step% 2.5	Range	+ 2.5 % to -7.5 %		Top Oil	55	Winding	60

TESTS CONDUCTED

1. RATIO AND VECTOR GROUP TEST

HV/LV (11/0.415 kV)

TAP NO.	VOLTAGES (kV)		CAL. RATIO	MEASURED RATIO		
	HV	LV		A - B a - n	B - C b - n	C - A c - n
1	11.275	0.4150	47.056	47.058	47.058	47.060
2(Nor)	11.000	0.4150	45.908	45.924	45.922	45.924
3	10.725	0.4150	44.761	44.782	44.778	44.778
4	10.450	0.4150	43.613	43.622	43.622	43.624
5	10.175	0.4150	42.465	42.476	42.480	42.480

Detected Vector Group : Dyn11

2. DC RESISTANCE TEST (at 30.70 °C)

HV (11 kV) - WINDING RESISTANCE (in Ohms)

TAP NO.	A - B	B - C	C - A	Avg. Resistance
2(Nor)	24.2660	24.1940	24.1600	24.2067

LV (0.415 kV) - WINDING RESISTANCE (in milliOhms)

TAP NO.	a - b	b - c	c - a	Avg. Resistance
-	25.015000	25.290000	24.715000	25.0067

3. NO LOAD TEST

Measured No Load Loss (W)	254	Measured No Load Current (%)	1.51

4. LOAD TEST

Measured Tap position		Principal Tap	
Measured Load loss at 75 °C (W)	2079	Impedance Voltage at 75 °C (%)	3.93
Efficiency at 1.0 p.f. at full load (%)	97.72	Efficiency at 0.8 p.f. at full load (%)	97.17

5. SEPARATE - SOURCE VOLTAGE WITHSTAND TEST

HV to LV wdgs and Earth 28 kV for 60 Sec : Passed
LV to HV wdgs and Earth 3 kV for 60 Sec : Passed

6. INDUCED OVER VOLTAGE WITHSTAND TEST

At 2 X Rated Voltage at 120 Hz for 50 Sec : Passed

7. INSULATION RESISTANCE TEST (at 30.00 °C) in Giga Ohm

HV to LV	HV to Earth	LV to Earth
>2	>2	>2

8. OIL DIELECTRIC STRENGTH TEST (Mineral oil free of PCB)

Across 2.5 mm gap : 60kV

9. TANK PRESSURE TEST

Oil leaks : Not Detected

Manager Testing : For LTL Transformers (Pvt) Limited 9/7/2015

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Figure A2.2. Test report for 100kVA Transformer

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TRANSFORMER TEST CERTIFICATE

Customer	LECO						
Standards	IEC : 60076						
Application	DISTRIBUTION TRANSFORMER						
Serial No	T/15/U016010045	Cooling	ONAN	Phase	Three	Date	9/3/2015
Ratings							
HV Voltage (V)	11000	LV Voltage (V)	415	Capacity (kVA)	160	Duty	Continuous
Vector Group	Dyn11	Frequency (Hz)	50	Type of Unit	Hermetically Sealed		
Tapping (HV)				Guaranteed temperature rise (°C)			
Step% 2.5	Range	+ 2.5 % to -7.5 %		Top Oil	55	Winding	60

TESTS CONDUCTED

1. RATIO AND VECTOR GROUP TEST

HV/LV (11/0.415 kV)

TAP NO.	VOLTAGES (kV) HV	VOLTAGES (kV) LV	CAL. RATIO	MEASURED RATIO A - B (a - n)	MEASURED RATIO B - C (b - n)	MEASURED RATIO C - A (c - n)
1	11.275	0.4150	47.056	47.084	47.082	47.088
2(Nor)	11.000	0.4150	45.908	45.928	45.928	45.926
3	10.725	0.4150	44.761	44.760	44.760	44.762
4	10.450	0.4150	43.613	43.598	43.598	43.598
5	10.175	0.4150	42.465	42.436	42.438	42.444

Detected Vector Group : Dyn11

2. DC RESISTANCE TEST (at 27.00 °C)

HV (11 kV) - WINDING RESISTANCE (in Ohms)

TAP NO.	A - B	B - C	C - A	Avg. Resistance
2(Nor)	10.6770	10.6810	10.6810	10.6797

LV (0.415 kV) - WINDING RESISTANCE (in milliOhms)

TAP NO.	a - b	b - c	c - a	Avg. Resistance
-	10.315000	10.327000	10.394000	10.3453

3. NO LOAD TEST

Measured No Load Loss (W)	358	Measured No Load Current (%)	1.57

4. LOAD TEST

Measured Tap position		Principal Tap	
Measured Load loss at 75 °C (W)	2427	Impedance Voltage at 75 °C (%)	4.00
Efficiency at 1.0 p.f. at full load (%)	98.29	Efficiency at 0.8 p.f. at full load (%)	97.87

5. SEPARATE - SOURCE VOLTAGE WITHSTAND TEST

HV to LV wdgs and Earth 28 kV for 60 Sec : Passed
LV to HV wdgs and Earth 3 kV for 60 Sec : Passed

6. INDUCED OVER VOLTAGE WITHSTAND TEST

At 2 X Rated Voltage at 120 Hz for 50 Sec : Passed

7. INSULATION RESISTANCE TEST (at 29.00 °C) in Giga Ohm

HV to LV	HV to Earth	LV to Earth
>2	>2	>2

8. OIL DIELECTRIC STRENGTH TEST (Mineral oil free of PCB)

Across 2.5 mm gap : 60kV

9. TANK PRESSURE TEST

Oil leaks : Not Detected

Manager Testing : **For LTL Transformers (Pvt) Limited** 9/7/2015

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Internet	:	www.ltl.lk

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Figure A2.3. Test report for 160kVA Transformer

LTL Transformers (Pvt) Limited
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Telephone: (+94 11) 260 5101-3 Fax : (+94 11) 260 7312 E-mail : transformer@ltl.lk

TRANSFORMER TEST CERTIFICATE Page 1 of 1

Customer	**LECO**						
Standards	**IEC : 60076**						
Application	**DISTRIBUTION TRANSFORMER**						
Serial No	**T/15/U025010048**	**Cooling**	**ONAN**	**Phase**	**Three**	**Date**	**7/2/2015**
		Ratings					
HV Voltage (V)	**11000**	**LV Voltage (V)**	**415**	**Capacity (kVA)**	**250**	**Duty**	**Continuous**
Vector Group	**Dyn11**	**Frequency (Hz)**	**50**	**Type of Unit**	**Hermetically Sealed**		
Tapping (HV)				**Guaranteed temperature rise (°C)**			
Step% 2.5	**Range**	**+ 2.5 % to -7.5 %**		**Top Oil**	**55**	**Winding**	**60**

TESTS CONDUCTED

1. RATIO AND VECTOR GROUP TEST

HV/LV (11/0.415 kV)

TAP NO.	VOLTAGES (kV)		CAL. RATIO	MEASURED RATIO		
	HV	LV		A - B	B - C	C - A
				a - n	b - n	c - n
1	11.275	0.4150	47.056	47.060	47.062	47.062
2(Nor)	11.000	0.4150	45.908	45.920	45.920	45.920
3	10.725	0.4150	44.761	44.782	44.782	44.780
4	10.450	0.4150	43.613	43.642	43.640	43.642
5	10.175	0.4150	42.465	42.504	42.506	42.508

Detected Vector Group : Dyn11

2. DC RESISTANCE TEST (at 28.80 °C)

HV (11 kV) - WINDING RESISTANCE (in Ohms)				
TAP NO.	A - B	B - C	C - A	Avg. Resistance
2(Nor)	6.5320	6.5565	6.5180	6.5355

LV (0.415 kV) - WINDING RESISTANCE (in milliOhms)				
TAP NO.	a - b	b - c	c - a	Avg. Resistance
-	6.016000	6.008000	6.024000	6.0160

3. NO LOAD TEST

Measured No Load Loss (W)	438	Measured No Load Current (%)	0.35

4. LOAD TEST

Measured Tap position		Principal Tap	
Measured Load loss at 75 °C (W)	3440	Impedance Voltage at 75 °C (%)	3.82
Efficiency at 1.0 p.f. at full load (%)	98.47	Efficiency at 0.8 p.f. at full load (%)	98.10

5. SEPARATE - SOURCE VOLTAGE WITHSTAND TEST

HV to LV wdgs and Earth 28 kV for 60 Sec : Passed
LV to HV wdgs and Earth 3 kV for 60 Sec : Passed

6. INDUCED OVER VOLTAGE WITHSTAND TEST

At 2 X Rated Voltage at 120 Hz for 50 Sec : Passed

7. INSULATION RESISTANCE TEST (at 28.00 °C) in Giga Ohm

HV to LV	HV to Earth	LV to Earth
>2	>2	>2

8. OIL DIELECTRIC STRENGTH TEST (Mineral oil free of PCB)

Across 2.5 mm gap : 60kV

9. TANK PRESSURE TEST

Oil leaks : Not Detected

Manager Testing : For LTL Transformers (Pvt) Limited 9/7/2015

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Figure A2.4. Test report for 250kVA Transformer

LTL Transformers (Pvt) Limited

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TRANSFORMER TEST CERTIFICATE Page 1 of 1

Customer	LECO						
Standards	IEC : 60076						
Application	DISTRIBUTION TRANSFORMER						
Serial No	T/15/U040010004	Cooling	ONAN	Phase	Three	Date	6/3/2015
		Ratings					
HV Voltage (V)	11000	LV Voltage (V)	415	Capacity (kVA)	400	Duty	Continuous
Vector Group	Dyn11	Frequency (Hz)	50	Type of Unit	Hermetically Sealed		
Tapping (HV)				Guaranteed temperature rise (°C)			
Step% 2.5	Range	+ 2.5 % to	-7.5 %	Top Oil	55	Winding	60

TESTS CONDUCTED

1. RATIO AND VECTOR GROUP TEST

HV/LV (11/0.415 kV)

TAP NO.	VOLTAGES (kV)		CAL. RATIO	MEASURED RATIO		
	HV	LV		A - B / a - n	B - C / b - n	C - A / c - n
1	11.275	0.4150	47.056	47.074	47.074	47.078
2(Nor)	11.000	0.4150	45.908	45.932	45.932	45.928
3	10.725	0.4150	44.761	44.792	44.790	44.792
4	10.450	0.4150	43.613	43.652	43.654	43.652
5	10.175	0.4150	42.465	42.482	42.484	42.486

Detected Vector Group : Dyn11

2. DC RESISTANCE TEST (at 29.20 ° C)

HV (11 kV) - WINDING RESISTANCE (in Ohms)

TAP NO.	A - B	B - C	C - A	Avg. Resistance
2(Nor)	3.6800	3.6766	3.6644	3.6737

LV (0.415 kV) - WINDING RESISTANCE (in milliOhms)

TAP NO.	a - b	b - c	c - a	Avg. Resistance
-	3.214000	3.223000	3.262000	3.2330

3. NO LOAD TEST

Measured No Load Loss (W)	606	Measured No Load Current (%)	0.32

4. LOAD TEST

Measured Tap position		Principal Tap	
Measured Load loss at 75 ° C (W)	4909	Impedance Voltage at 75 ° C (%)	4.25
Efficiency at 1.0 p.f. at full load (%)	98.64	Efficiency at 0.8 p.f. at full load (%)	98.31

5. SEPARATE - SOURCE VOLTAGE WITHSTAND TEST

HV to LV wdgs and Earth 28 kV for 60 Sec : Passed

LV to HV wdgs and Earth 3 kV for 60 Sec : Passed

6. INDUCED OVER VOLTAGE WITHSTAND TEST

At 2 X Rated Voltage at 120 Hz for 50 Sec : Passed

7. INSULATION RESISTANCE TEST (at 29.00 ° C) in Giga Ohm

HV to LV	HV to Earth	LV to Earth
>2	>2	>2

8. OIL DIELECTRIC STRENGTH TEST (Mineral oil free of PCB)

Across 2.5 mm gap : 60kV

9. TANK PRESSURE TEST

Oil leaks : Not Detected

Manager Testing : **For LTL Transformers (Pvt) Limited** 9/7/2015

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Figure A2.5. Test report for 400kVA Transformer

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TRANSFORMER TEST CERTIFICATE

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Customer	LECO						
Standards	IEC : 60076						
Application	DISTRIBUTION TRANSFORMER						
Serial No	T/15/U063010006	Cooling	ONAN	Phase	Three	Date	7/3/2015
		Ratings					
HV Voltage (V)	11000	LV Voltage (V)	415	Capacity (kVA)	630	Duty	Continuous
Vector Group	Dyn11	Frequency (Hz)	50	Type of Unit	Hermetically Sealed		
Tapping (HV)				Guaranteed temperature rise (°C)			
Step% 2.5	Range	+ 2.5 % to	-7.5 %	Top Oil	55	Winding	60

TESTS CONDUCTED

1. RATIO AND VECTOR GROUP TEST

HV/LV (11/0.415 kV)

TAP NO.	VOLTAGES (kV)		CAL. RATIO	MEASURED RATIO		
	HV	LV		A - B a - n	B - C b - n	C - A c - n
1	11.275	0.4150	47.056	47.050	47.044	47.044
2(Nor)	11.000	0.4150	45.908	45.924	45.918	45.918
3	10.725	0.4150	44.761	44.790	44.792	44.794
4	10.450	0.4150	43.613	43.654	43.658	43.656
5	10.175	0.4150	42.465	42.530	42.530	42.532

Detected Vector Group : Dyn11

2. DC RESISTANCE TEST (at 31.40 °C)

HV (11 kV) - WINDING RESISTANCE (in Ohms)				
TAP NO.	A - B	B - C	C - A	Avg. Resistance
2(Nor)	1.9174	1.9271	1.9081	1.9175

LV (0.415 kV) - WINDING RESISTANCE (in milliOhms)				
TAP NO.	a - b	b - c	c - a	Avg. Resistance
-	2.003500	2.022000	2.053500	2.0263

3. NO LOAD TEST

Measured No Load Loss (W)	818	Measured No Load Current (%)	0.23

4. LOAD TEST

Measured Tap position		Principal Tap	
Measured Load loss at 75 °C (W)	6669	Impedance Voltage at 75 °C (%)	4.16
Efficiency at 1.0 p.f. at full load (%)	98.83	Efficiency at 0.8 p.f. at full load (%)	98.54

5. SEPARATE - SOURCE VOLTAGE WITHSTAND TEST

HV to LV wdgs and Earth 28 kV for 60 Sec : Passed

LV to HV wdgs and Earth 3 kV for 60 Sec : Passed

6. INDUCED OVER VOLTAGE WITHSTAND TEST

At 2 X Rated Voltage at 120 Hz for 50 Sec : Passed

7. INSULATION RESISTANCE TEST (at 28.00 °C) in Giga Ohm

HV to LV	HV to Earth	LV to Earth
>2	>2	>2

8. OIL DIELECTRIC STRENGTH TEST (Mineral oil free of PCB)

Across 2.5 mm gap : 60kV

9. TANK PRESSURE TEST

Oil leaks : Not Detected

Manager Testing : For LTL Transformers (Pvt) Limited 9/7/2015

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Figure A2.6. Test report for 630kVA Transformer

LTL Transformers (Pvt) Limited
(A Subsidiary of LTL Holdings (Pvt) Ltd)
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TRANSFORMER TEST CERTIFICATE

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Customer	LECO						
Standards	IEC : 60076						
Application	DISTRIBUTION TRANSFORMER						
Serial No	T/15/U100010012	Cooling	ONAN	Phase	Three	Date	5/14/2015
			Ratings				
HV Voltage (V)	11000	LV Voltage (V)	415	Capacity (kVA)	1000	Duty	Continuous
Vector Group	Dyn11	Frequency (Hz)	50	Type of Unit	Hermetically Sealed		
Tapping (HV)				Guaranteed temperature rise (°C)			
Step% 2.5	Range	+ 2.5 % to -7.5 %		Top Oil	55	Winding	60

TESTS CONDUCTED

1. RATIO AND VECTOR GROUP TEST

HV/LV (11/0.415 kV)

TAP NO.	VOLTAGES (kV)		CAL. RATIO	MEASURED RATIO		
	HV	LV		A - B / a - n	B - C / b - n	C - A / c - n
1	11.275	0.4150	47.056	47.036	47.036	47.042
2(Nor)	11.000	0.4150	45.908	45.882	45.880	45.880
3	10.725	0.4150	44.761	44.748	44.750	44.744
4	10.450	0.4150	43.613	43.606	43.606	43.606
5	10.175	0.4150	42.465	42.446	42.450	42.450

Detected Vector Group : Dyn11

2. DC RESISTANCE TEST (at 29.00 °C)

HV (11 kV) - WINDING RESISTANCE (in Ohms)

TAP NO.	A - B	B - C	C - A	Avg. Resistance
2(Nor)	1.1976	1.2215	1.2003	1.2065

LV (0.415 kV) - WINDING RESISTANCE (in milliOhms)

TAP NO.	a - b	b - c	c - a	Avg. Resistance
-	1.183000	1.183000	1.195500	1.1872

3. NO LOAD TEST

Measured No Load Loss (W)	1070	Measured No Load Current (%)	0.23

4. LOAD TEST

Measured Tap position		Principal Tap	
Measured Load loss at 75 °C (W)	10445	Impedance Voltage at 75 °C (%)	4.85
Efficiency at 1.0 p.f. at full load (%)	98.86	Efficiency at 0.8 p.f. at full load (%)	98.58

5. SEPARATE - SOURCE VOLTAGE WITHSTAND TEST

HV to LV wdgs and Earth 28 kV for 60 Sec : Passed
LV to HV wdgs and Earth 3 kV for 60 Sec : Passed

6. INDUCED OVER VOLTAGE WITHSTAND TEST

At 2 X Rated Voltage at 120 Hz for 50 Sec : Passed

7. INSULATION RESISTANCE TEST (at 29.00 °C) in Giga Ohm

HV to LV	HV to Earth	LV to Earth
>2	>2	>2

8. OIL DIELECTRIC STRENGTH TEST (Mineral oil free of PCB)

Across 2.5 mm gap : 60kV

9. TANK PRESSURE TEST

Oil leaks : Not Detected

Manager Testing : For LTL Transformers (Pvt) Limited 9/7/2015

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Figure A2.7. Test report for 1000kVA Transformer