CONSIDERATION OF LOSSES IN DETERMINING SOLAR PV PENETRATION LEVEL IN DISTRIBUTION NETWORKS

R. M. M. P. Nishshanka

(168623G)

Degree of Master of Science in Electrical Installations

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

May 2020

CONSIDERATION OF LOSSES IN DETERMINING SOLAR PV PENETRATION LEVEL IN DISTRIBUTION NETWORKS

R. M. M. P. Nishshanka

(168623G)

Dissertation submitted in partial fulfillment of the requirements for the Degree Master of Science in Electrical Installations

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

May 2020

DECLARATION OF THE CANDIDATE & SUPERVISOR

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date:

(R. M. M. P. Nishshanka)

The above candidate has carried out research for the Masters Dissertation under our supervision.

Signature of the supervisor: Date:

(Dr. J.V.U.P Jayatunga)

Signature of the supervisor: Date:

(Dr. P. S. N De Silva)

Abstract

When it was realized that the conventional energy sources which powered up the industrial revolution are on depletion, a sudden awakening occurred in the field of renewable energy, during the latter part of the last century. As a result, a salient technological development is progressive in the solar PV industry. There are certain benefits including zero emissions, free availability of solar power and economic benefits, turning rooftop solar into an attractive method of investment for domestic electricity consumers. The same global trend has moved towards Sri Lanka during the last five years, due to the government initiative “Surya Bala Sangramaya” on promoting rooftop solar generation. Along with that, loan schemes were introduced to encourage customers to install rooftop solar PV systems. As a result, in urban highly populated areas, distribution transformers are now available with the addition of more than 75% of installed solar rooftop capacities compared to the connected transformer capacity.

Rooftop solar PV systems add clean energy to the network, while enabling the customers to get financial benefits from their investment. However, continues addition of distributed renewable generation into the network creates several issues in the system, such as power quality issues, issues associated with reverse power flow etc.

Under this situation, now is the high time for utilities to identify the impact to the network with solar PV addition and take remedial action to mitigate the issues immediately. As a preliminary action, introducing maximum solar penetration level is recommended.

This research addresses the aforementioned issue and provides a methodology on identifying the maximum allowable solar penetration level, focusing on the power loss. It was observed that the power loss of the network decreases with solar PV addition but after some level, it increases. Though many researches are available for the common issues associated with rooftop solar systems, this is an aspect which has less attention. Thus, it is believed that this research would lay the foundation for certain practical implementations and many novel studies in this discipline.

In this study, a practical network was modeled and analyzed to identify the behavior of power loss of a distribution transformer with the increment of solar penetration level. Initial case study confirms that power losses increase with high solar penetration level. Therefore, to identify common behavior, generalized model was developed, which could provide platform to define limits for solar penetration.

Monte Carlo study was carried out for different cases, and as a result, maximum allowable solar penetration level for a transformer, which can be defined without any conditions was identified. Further, maximum allowable limit which can be defined with conditions also was identified with the applicable constraints. As the ultimate finding of the research, solar PV approval criteria were developed, which can be easily adopted by distribution utilities to add rooftop solar power to the network, in a mutual beneficial mode for both the customer and the utility.

Acknowledgement

I take this opportunity to covey my gratitude to all those who contributed in successfully completing this research.

First, I would like to express my sincere gratitude to my supervisor, Dr. P. S. N. De Silva, for providing me the concept of study and continuous guidance throughout the period.

Also I take this opportunity to extend my gratitude for the internal supervisor of this research, Dr. Upuli Jayatunga, for the guidance and the encouragement, which helped me in completing this task through successfully.

Further, I appreciate the guidance and advices given by the evaluation panel.

My sincere thanks go to my immediate supervisor Mr. S.D.C. Gunawardhana, System Development Manager of LECO, and to all my colleagues at Lanka Electricity Company Private Limited, who helped me in many ways during this period.

Last but not least, I express my heartiest gratitude and love to my husband and my parents, who took a lot of burden and patient, which helped me to complete this work under difficult circumstances.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Description
PUCSL	Public Utilities Commission of Sri Lanka
LECO	Lanka Electricity Company Private Limited
CEB	Ceylon Electricity Board
LV	Low Voltage
MV	Medium Voltage
GIS	Geographic Information System
PV	Photovoltaic

CHAPTER 1

1 INTRODUCTION

1.1 Background

1.1.1 Revolution of the Rooftop Solar PV Systems

The technological advancement of Rooftop Solar Photovoltaic Systems began to accelerate globally in mid-1990s, with the rapid increment of scarcity in non-renewable resources, such as oil and natural gas. Concerns on the impact of global warming and continuous improvement of economic position of technologies further laid foundation for the rapid development of rooftop solar PV systems. The revolution was further supported with the introduction of feed-in tariff policy in early 2000s. It led to an investment security followed by soaring number of PV deployments in Europe. For several years since early 2000s, worldwide growth of solar PV systems was driven by European deployment, since then it gradually shifted to Asia. According to International Energy Agency, worldwide growth of photovoltaic is recorded as 40% in average per year from 2000 to 2013 and total installed capacity has reached 303 GW by the end of year 2016. [1]

With reference to the market analysis done by International Energy Agency [1], distributed solar PV capacity is forecasted to increase over 250% during the period of 2019 to 2024, which would be more than twice the amount recorded in the previous six years period. This would increase the total capacity up to 530 GW by 2024, while the share of distributed applications in total solar PV capacity growth increases from 36% to 45%. [1]

This high growth rate is anticipated for distributed PV due to the expected reduction in associated costs due to the listed reasons and resulting rapid growth of consumer adoption of solar PV.

1. Faster investment cost reductions.
2. Clarification of regulatory and incentive schemes in multiple markets.

3. The reduction of non-economic barriers such as protracted application processing, high connection fees and unjustified deployment caps.
4. Access to affordable financing, especially in emerging economies.
5. Speedy implementation of retail market reforms, enabling more cost-reflective electricity pricing for residential and commercial users.

Initially, Sri Lankan market for rooftop solar PV systems had been saturated with “off grid” solar systems, where customers had to consume their generated energy on daily basis for their electricity requirements. However, the market base hit a sudden increase in demand for PV systems with the introduction of grid connected solar system concept in year 2010.

The integration of the grid connected rooftop solar systems to the Sri Lankan national grid was initiated with the introduction of net metering concept. Net metering is one of the world famous methods that enable customers to connect their own on-site generation system to the utility grid and receive benefit of carry forward excess energy generated on top of their electricity consumption.

In year 2016, The Ministry of Power and Renewable Energy Sri Lanka launched a new solar PV based power generation project named 'Soorya Bala Sangramaya' (Battle for Solar Energy) in collaboration with Sri Lanka Sustainable Energy Authority (SLSEA), Ceylon Electricity Board (CEB) and Lanka Electricity Company (Private) Limited (LECO) to promote rooftop solar PV systems in households, religious places, hotels, commercial establishments and industrial buildings etc. The project intended to add 200 MW of solar electricity to the national grid by year 2020 and 1000 MW by 2025 through this intervention. One of the added advantages initiated under this project was that, the excess generation of energy can be either carried forward or encashed as a monetized benefit. Under that, customer can select a preferred option from the following three schemes, according to the electricity usage:

Net Metering, Net Accounting and Net Plus.

Net metering is a billing mechanism that credits solar energy system owners for the electricity they add to the grid. Under the net accounting scheme, if the generated units of electricity using the solar panels fixed on houses/premises are greater than the amount consumed, the customer will be paid by utility. Net plus mechanism measures energy imports and exports separately and pay accordingly.

1.1.2 Impact of Increasing Solar PV integration on Sri Lankan National Grid

Sri Lankan distribution network consists of 33 kV, 11 kV medium voltage network and 400 V/ 230 V low voltage network. Majority of medium voltage networks are overhead operating networks whereas remaining portion contains underground networks in the highly urbanized areas in Colombo and Kandy districts. The low voltage network is a complete overhead network, in the voltage level of 400V/ 230V.

As the regulator to the Sri Lankan energy sector, Public Utilities Commission of Sri Lanka (PUCSL) has issued five licenses for electricity distribution. Four out of those five licenses are issued to CEB while the remaining license is issued to LECO. Further, PUCSL has provided guidelines and set of regulations to the distribution utilities on maintaining the quality of supply and reducing distribution losses.

As described under section 1.1.1, introduction of the project 'Soorya Bala Sangramaya' and other government relief initiatives on rooftop PV solar systems has led to addition of enormous number of small-scale solar power systems into the national distribution network over the last three years.

Addition of rooftop solar PV systems to the national grid is beneficial not only for the environment, but also for individual customers. However, it also introduces drawbacks to the existing network. High solar PV penetration creates issues in power supply quality, stability and protection perspectives, persuading utilities to carefully analyze and take proper actions to mitigate the issues. Most common issues observed with high solar PV penetration are briefed as follows.

1. **Over voltage** (Local Voltage Rise)– This is the most frequent practical issue observed with high solar PV penetration in a network. When the solar array is placed at a particular location, that location can experience higher voltage than normal, depending on the voltage setting of the equipment. Standard recommendation for low voltage systems in Sri Lanka is within +/- 6% of the

nominal voltage. However, the standard limit is likely to be violated by individual rooftop Solar PV suppliers to enhance their energy generation.

2. **Increase of power loss** - The conventional distribution power grid was designed with the assumption that power should always flow from the source to the load. With the popularization of distributed energy sources, this concept is no longer valid.

   Residential and commercial locations that utilize solar systems can act as either a load or a source, depending on whether they are drawing power from the grid or supplying power to the grid. This denotes the power flow reverses its direction from time to time. This process creates an issue for the utility such as increase of LV power losses.

3. **Voltage Unbalance and transients in solar equipment -** Unbalance in voltage between phases is another problem utility face when single solar systems are used. If the solar array is not connected to the phases, then an unbalanced voltage condition can occur. Higher the number of single phase solar arrays connected to the grid, worse the problem becomes.

   Transients are another issue that can arise when using solar power intermittency. Solar panels respond nearly instantaneously to the changes in solar radiation. The bandwidth of the solar radiation that affects solar panels is wider than our visual range, meaning even on clear days, the solar panels can be changing rapidly due to pollutants we do not see. If the solar system does not have proper voltage conditioning, this can create high-speed transients.

4. **Problems with harmonics** - Inverters convert the DC current to AC current. These non-linear devices can create harmonics. Inverters tend to operate at relatively higher frequencies in order to maximize their efficiency. However, the higher the frequency the inverter functions at, higher the order of the harmonics it creates.

5. **Stability Issues -** Since solar energy relies on the sun, electricity cannot be generated during the night and during bad weather conditions. This means utility has to maintain capacity to cater the demand in the absence of solar generation. This is an extra cost associate with the utility.

6. **Protection Coordination Issues** – Protection system of present distribution networks are based on radial, unidirectional power flow. Protection coordination issues arise when there is a dynamic scenario.

1.2 Problem Statement and Motivation

Integration of distributed solar PV systems to utilities demonstrates a rapid increasing trend globally as well as locally. Continuous technological development in solar PV sector reduces financial barriers and hence enables individual customers in investing for rooftop solar PV systems. Moreover, national energy policies are willing to increase the renewable energy contribution and hence encourage individual customers with attractive tariff schemes and loan schemes.

However, it is clear that the maximum allowable rooftop solar installations have upper limits due to technical restrictions in power quality, stability and protection constraints. There are no defined upper limits for the rooftop solar as a national policy. This has resulted issues with high penetration loss of solar, which can be seen when studying distribution transformers containing decent number of net metering customers.

In the present scenario, individual customer can install rooftop solar PV system up to their contracted demand. That distributed generation will be connected to the distribution transformer of that individual customer. In LECO, capacity of a distribution transformer is determined by considering a coincident factor of 0.8 and an utilization factor of 0.2. Thus, total summation of contract demands of a transformer will be 6.25 times of its rated capacity.

Actual data of highly residential areas like Kotte, Maharagama and Nugegoda, where LECO is the distribution utility, was studied and observed some transformers have more than 50% solar installed capacity with reference to rated capacity of the transformer.

At present, allowable solar PV installation limits are not defined by authorities and hence there is no control for solar penetration level. While focusing on this, it would be an absolute necessity to assess the effect of high solar penetration. Based on the assessment, adopting pre-defined limits to direct solar penetration is essential. This research intends to propose limits with conditions which are derived by a study based on power loss, which can be used in planning stage.

1.1. Scope of the study

This research is focused on developing a systematic approach for evaluation of maximum solar PV penetration level which is applicable for radial, low voltage distribution network in Sri Lanka. For the analysis, data is taken from LECO distribution network, which operates in highly urbanized areas of the country. Initial study was based on existing transformers in LECO area. Generalized models were developed by considering available transformer categories according to the number of feeders.

For the modeling purpose, an OpenDSS simulation tool, integrated with MATLAB software, has been used. Five LV models were developed for possible cases. Models were designed as three phase four wire networks that allows to analyze the behavior of the power loss with increasing solar penetration. A model has been developed with transformer, feeders, customer loads and solar PV generation and simulation runs with location randomness of solar PV systems.

Monte Carlo study was done by considering location randomness of the solar PV systems and solar penetration level as variable parameters. Load flow result for 500 different samples per each LV model were taken as simulation result. Final limits were determined by considering the normalized curve of the result. Conditions were identified for the limits and further study is carried out to confirm the behavior with different loading levels of the transformer.

1.3 Objective of the study

The objectives of the study are listed below.

- Asses optimum solar penetration capacity for a transformer
- Identify the allowable penetration levels and conditions based on power loss

1.4 Thesis organization

An overview of the thesis is presented in this section. A summary of content of each chapter is provided below. The appendices contain the simulation models and outputs for various investigations done as a part of the research work.

Chapter 1 – This chapter describes the revolution of solar PV systems in global and local context. Description of problem statement & motivation, scope, objective and the methodology of research has been provided in this chapter.

Chapter 2 – As the research work is based on the impact of solar penetration to the network, this chapter provides details of hosting capacity and limiting factor concepts.

Chapter 3 – This chapter captures the research works done on selected test feeder, with the detailed explanation of modeling and features of OpenDSS. The results and observation of the case study has been discussed.

Chapter 4 – Chapter 4 presents an investigative study to understand the impact of high penetration of solar PV systems based on power loss. A generalized model has been developed and used for simulation of five hundred different scenarios.

Chapter 5 – Outcome of the investigation has been presented in this chapter. Solar penetration limits have been defined based on the result and application of the limits with different authorization levels is presented. Case studies have been carried out to understand the impact of network conditions as an additional study.

Chapter 6 – This chapter conclude the result of the research. Recommendations for further studies also discussed.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

The research presented in this thesis is a study carried out to find optimum solar penetration capacity of a distribution transformer based on power loss of the low voltage network.

Behavior of the power loss with increasing solar penetration level was studied as an initiation to the study. It confirms that power losses are decreasing with solar addition but reduces with high solar penetration levels and that emphasize previous study results of similar researches.

Main focus of the study is to develop generalized model to define general limits for solar penetration. The underlying concept of the study is a statistical study carried out on different type of low voltage models. Transformer capacity, number of feeders per transformer and actual usage of each transformer type were considered to define low voltage models.

2.2 Hosting capacity of a transformer

Hosting Capacity approach [8] specify the impacts of increasing distributed energy resources penetration on power systems. The basis of this approach was to gather the technical limitations imposed by both system operators and customers.

Hosting capacity of a transformer is the amount of distributed generation, integrated into the transformer, above which the system performance becomes unacceptable [8]. The Hosting Capacity calculation is not a fixed calculation with a single result. Thus, it should be calculated for various performance indices such as over voltage and, power loss, thermal overload, power quality and protection problems.

Potential power quality impact for Sri Lankan network [8] was discussed with respective of active power flow, feeder voltage rise, voltage unbalance and total network loss. As a result of scenario analysis, optimum solar penetration level identified as 40%. Requirement of further case studies modeled with different platform and generalized modeling is essential to emphasis the result.

2.3 Maximum Solar PV penetration due to over voltage curtailment

Overvoltage is a major practical issue encountered by utilities with distributed solar PV systems. In theoretical context, individual solar PV customer advise to adhere voltage limits given by the Sri Lankan utility [2], that is +/-6%. In that condition, maximum voltage at any point of the feeder should not exceed the maximum defined by the utility as presented in Figure 2-1.

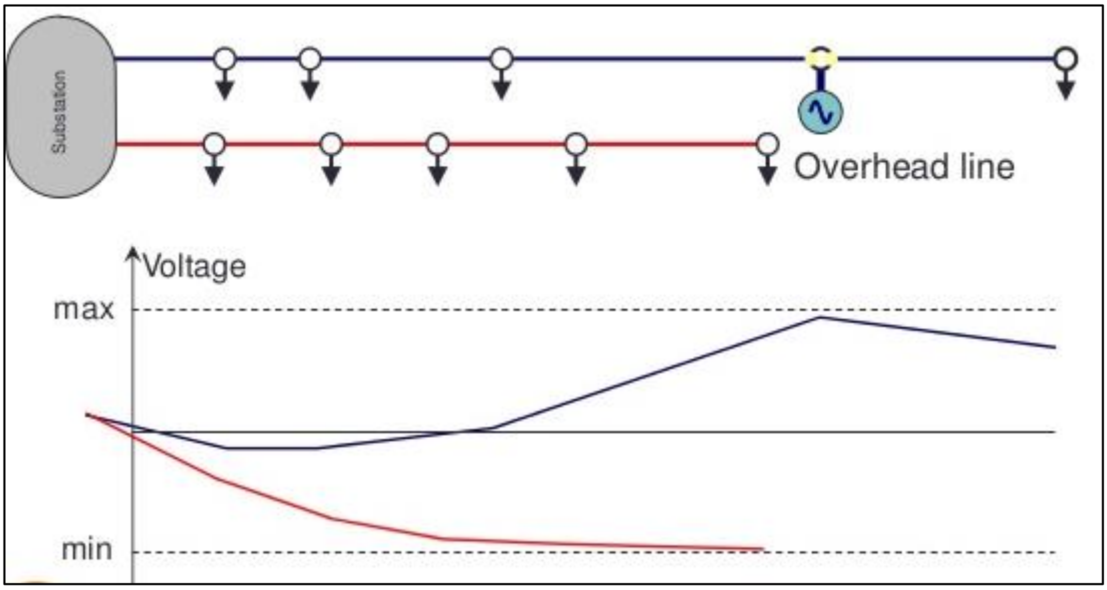

Figure 2-1: Voltage variation along the feeder with solar PV system

However, in the practice the settings are saved at high value to maximize the generation. Specially areas where solar PV density is high, individual customer may experience less generation due to voltage rise of the feeder. Therefore, as a malpractice, voltage limits are violating by the customers. This results, overvoltage problem for nearby customers. Further, due to the intermittence of solar generation, voltage variations may experience by the customers.

Since this is a major practical issue, many researches are attempted on this. As a result of one of study , deterministic approach for overvoltage curtailments was introduced for Sri Lankan network [9].

Watson [7] has been done a comprehensive study on impact of solar Photovoltaics on the low-voltage distribution network in New Zealand. As per the study, importance of introducing mitigation actions for urban networks were highlighted. Adopting upper voltage limit was discussed as a mitigation action.

Continuous power quality monitoring should be conduct by utility as a mitigation action for overvoltage problem. Currently, PUCSL of Sri Lanka has been introduced power quality monitoring project. This was implemented in LECO, by installing network monitoring devices in the field and voltage, current readings are monitoring remotely to identify any violations. It is expected to minimize voltage variations in the network with this facility in near future.

2.4 Limiting factor concept and related findings

The adverse impacts of high distributed generation penetration levels on electrical networks have been investigated in many studies. Limiting factors defined based on performance indices and it’s depend on the features of the network. Therefore, common standard limits were not defined yet for global practice. However, researches are investigating on defining on limits country wise, region wise available which could be used by utilities.

Probabilistic Impact Assessment of Low Carbon Technologies in LV Distribution Systems in UK [3] was conducted and identified that feeders with less number of customers (25 customers for studied feeders) did not present any problem of having low carbon technologies such as solar PVs and electrical vehicles.

Watson [7] has been introduced maximum allowable PV penetration levels for LV distribution network in New Zealand which depends on power factor and secondary voltage of transformer.

Chathurangi [8] found 40% of solar penetration level as the optimum solar penetration level based on scenario analysis carried out for Sri Lankan network.

Above studied and findings highlighting the difficulty of defining standard limit in global. But in practice, case by case study is not convenient for utilities with the large network and customer base. Therefore, reasonably accurate and practical limits to be defined at lease for utility wise to avoid power quality issues in the network. Early identification will help for fair distribution of solar PV rooftop systems within the customer base.

2.5 Hosting capacity enhancement techniques

In recent years, most countries are examining methodologies to enhance hosting capacity of solar PVs and other distributed power generation methods. Connection of large number of distributed generators is required network improvements. However, distributed generator penetration still in the improving level and hence at this stage investing on such network improvement may not be viable. As a solution, researches are introduced hosting capacity improvement techniques.

Network reconfiguration introduced solution and proved that this technique can improve hosting capacity up to 20% depending on the hour and on the case considered [10]. This technique is more viable for automated networks, otherwise cost of automation is necessary.

Another storage is another solution discussed [6],[10] but this solution is costly and the possible enhancement depend on the investment.

2.6 Power loss variation with solar penetration

In the case of the PV penetration, the power losses decrease as the penetration level increases. Then the losses start to increase again due to the higher energy exports to the HV network. This behavior was highlighted in case studies [6] done on LV distribution network of Sri Lanka.

Power loss depend on the magnitude and direction of the current flow in the feeder. If the customer load distribution and solar PV distributions are uniform, it is possible to predict the behavior of the power loss.

However, actual feeder has non uniform distribution for loads and solar PVs and hence the behavior of the power loss is highly volatile. It will be depending on magnitudes and locations of loads and solar PVs. Further the network structure, feeder arrangement and properties also influence the result. With the above condition it's difficult to define standard, universal limits for solar penetration based on power loss.

Therefore, to study the behavior for particular network, exact conditions have to be identified. This research focused on the above discussed gap on power loss behavior study for Sri Lankan network.

CHAPTER 3

3 MODELING AND DEVELOPMENT

3.1 Overview

This study uses two types of network models,

- Modeling of a practical feeder – Actual low voltage network selected from LECO network was modeled by using actual data. Main objective is to observe the behavior of power loss under actual scenario and understand the system response with further solar PV addition.
- Generalized model – Hypothetical Low voltage distribution network models were developed considering the parameters of actual LV networks available in Sri Lanka. Objective of this development is to analyze the overall behavior and identify general limits.

The Open Distribution System Simulator (OpenDSS) is been used for the modeling. It is a comprehensive electrical system simulation tool for electric utility distribution systems. OpenDSS can drive with MATLAB program and was used in developing generalized model.

3.2 Modeling of the 400V practical Feeder

This part of the research study required a test feeder with high solar penetration level. Area with the highest solar PV density in LECO was identified as the Green Zone which lies under the Kotte Branch; Pitakotte Customer Service Center.

It consists of 65 transformers spread in 3.4 km^2 area. Transformer data with existing solar PV installed capacity were extracted from LECO system data base and thereafter transformers having more than 50% solar PV installed capacity against transformer capacity is tabulated in Table 3-1.

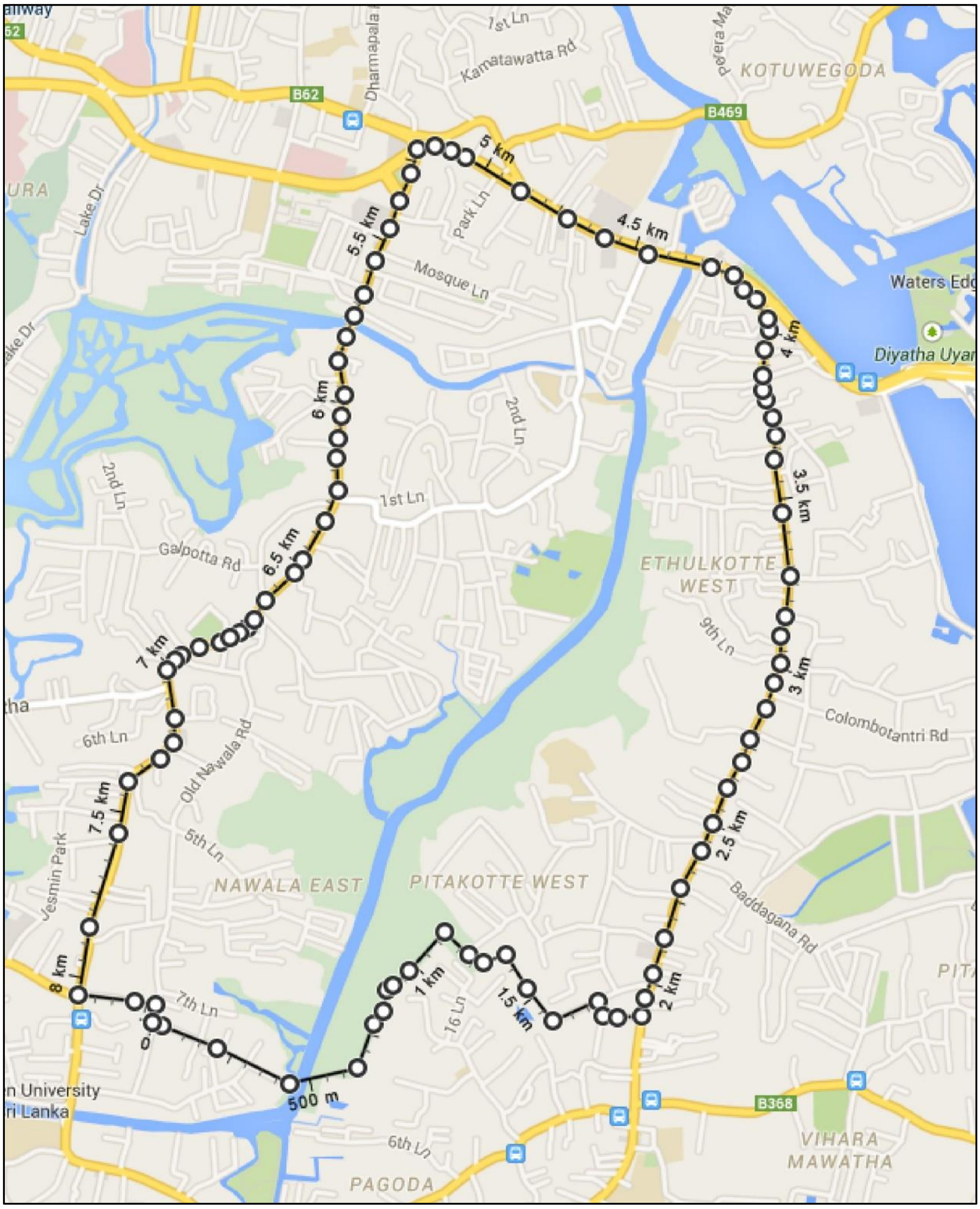

Figure 3-1: GIS Map of Green Zone Area

Table 3-1:Transformer Data

Transformer Code	Transformer Capacity(kVA)	Solar Consumers count	Installed total solar capacity(kW)	Installed solar capacity as a percentage of Transformer capacity
AZ0204	160	19	133	83%
AZ8251	100	1	60	60%
AZ0518	100	9	56	56%
AZ0512	160	15	87	55%
AZ0531	100	8	53	53%
AZ0184	250	26	132	53%
AZ0228	250	27	124	50%

Out of the above transformers, AZ0204 was selected for the purpose of further analysis considering following facts.

a. Highest solar installed capacity recorded
b. Diversified network architecture with extended branches.
c. Availability of customer data and solar PV data

Basic feeder data are shown in Table 3-2.

Table 3-2: Test Feeder Details

Transformer Name	AZ0204
Source	Ethulkotte Primary Substation
Branch	Kotte Branch
Customer Service Center	Pitakotte CSC
Transformer Capacity	160kVA
Location	Lat:6°53'41.369, Lon:9°53'35.308 (School Lane, Kotte)
Total Number of Customers	291
Number of feeders	3
Maximum demand recorded in 2019	162kVA

Total number of customers served by AZ0204 was 291 and among them 19 customers have solar PV rooftop systems. Details of the customer base latched to AZ0204 are shown in Table 3-3.

Table 3-3: Customer details of AZ0204

Customer category	Number of customers
Domestic - SP	160
Domestic - TP	72
Domestic – TP Net Accounting	2
Domestic – SP Net Metering	1
Domestic – TP Net Metering	19
General Purpose 1 - SP	20
General Purpose 1 - TP	4
General Purpose 2 - TP	13
Total	291

Feeder distribution of the LV network extracted from Geographical Information system shown in Figure 3-2.

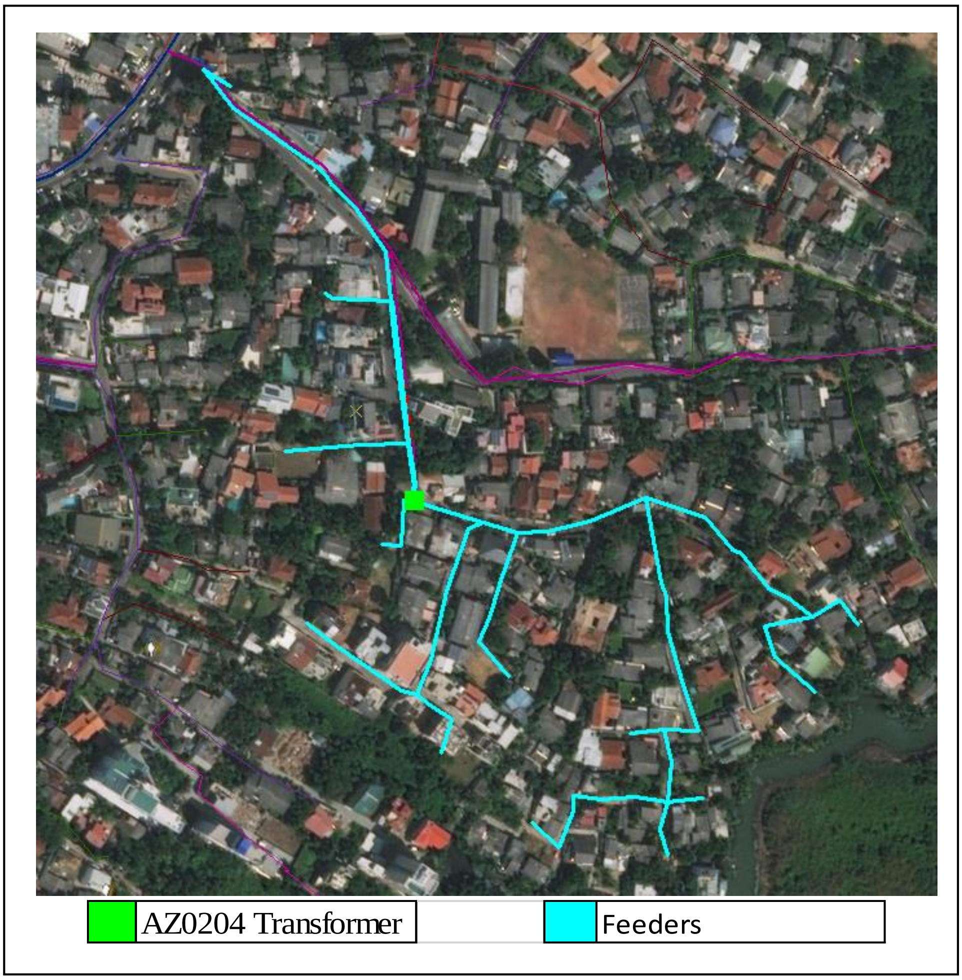

Figure 3-2: GIS map of AZ0204

Model of the test feeder was developed using OpenDSS codes according to the actual data of the Transformer, Lines, Loads, and Solar PV systems. Steady state analysis was executed for a defined loading level.

3.2.1 Modeling of LV Transformer

The AZ0204 is a 160kVA transformer consisting of two windings in delta-wye connection. This was modeled using Transformer object in OpenDSS library. Properties in order are,

- Wdg = Integer representing the winding which will become the active winding for subsequent data.
- Bus = Definition for the connection of this winding (each winding is connected to one terminal of the transformer and, hence, to one bus).
- Conn = Connection of this winding. One of {wye | ln} for wye connected banks or {delta | ll} for delta (line-line) connected banks. Default is wye.
- kV = Rated voltage of this winding, kV. For transformers designated 2- or 3-phase, enter phase-to-phase kV. For all other designations, enter actual winding kV rating. Two-phase transformers are assumed to be employed in a 3-phase system. Default is 12.47 kV.
- kVa= Base kVA rating (OA rating) of this winding.
- Tap = Per unit tap on which this winding is set.
- %R = Percent resistance of this winding on the rated kVA base. (Reactance is between two windings and is specified separately)
- %Loadloss = Percent Losses at rated load. Causes the %r values to be set for windings 1 and 2.
- %Noloadloss = Percent No load losses at nominal voltage. Default is 0. Causes a resistive branch to be added in parallel with the magnetizing inductance.

Sample code

```
! Transformers
new transformer.AZ0204 windings=2 buses=(Sourcebus, loadbus) conns=(delta, wye)
kvs=(11, 0.4) kvas=(160, 160) %Rs=(1.41, 1.03) %loadloss=1.516 %Noloadloss=0.2237
```

3.2.2 Modeling of LV Feeders

Arial Bundled Conductors (ABC) with four core aluminum twisted conductors, including neutral conductor as messenger cable are used in LECO for LV feeders. Each core is insulated with extruded cross-linked thermosetting polyethylene (XLPE) and the cores are twisted together with a right hand lay. Conductor data for the ABC conductors used are tabulated in Table 3-4.

Table 3-4:Arial Bundled Cable details

	Conductor		3x70 +1x50 mm2	3x50 +1x35 mm2	3x70 +1x50 +16 mm2	3x50 +1x35 +16 mm2
	LECO Code		B241	B243	B244	B245
1	Phase conductor size	mm²	70	50	70	50
2	Neutral / messenger conductor	mm²	50	35	50	35
3	Conductor Resistance (20^0C)					
	a. Phase conductor	Ohm/km	0.443	0.641	0.443	0.641
	b. neutral / messenger conductor	Ohm/km	0.0868	0.0868	0.0868	0.0868
4	Conductor Reactance for 50Hz (20^0C)					
	a. Phase conductor	Ohm/km	0.630	0.0848	0.630	0.0848
	b. neutral / messenger conductor	Ohm/km	0.0868	0.0879	0.0868	0.0879
5	Stranding					
	a. Phase conductor	No / mm	19/2.14	19/1.78	19/2.14	19/1.78
	b. neutral / messenger conductor	No / mm	7/3.00	7/2.52	7/3.00	7/2.52
	c. street lighting conductor	No / mm	-	-	7/1.70	7/1.70
6	Voltage rating	V	600/1000			600/1000
7	Insulation Thickness					
	a. Phase conductor	mm	1.8	1.6	1.8	1.6
	b. neutral / messenger conductor	mm	1.6	1.6	1.6	1.6
	c. street lighting conductor	mm	-	-	1.2	1.2
8	Insulation Material		XLPE	XLPE	XLPE	XLPE
9	Conductor material					
	a. Phase conductor and street lighting		AAC	AAC	AAC	AAC

	b. Neutral / messenger		AAAC	AAAC	AAAC	AAAC
10	Maximum permissible temperature of cores	Deg C	90	90	90	90
11	Maximum current rating phase and neutral	Amps	213	168	213	168

Selected test feeder has all four type of ABC cables, lengths and feeder distribution represented in Figure 3-3.

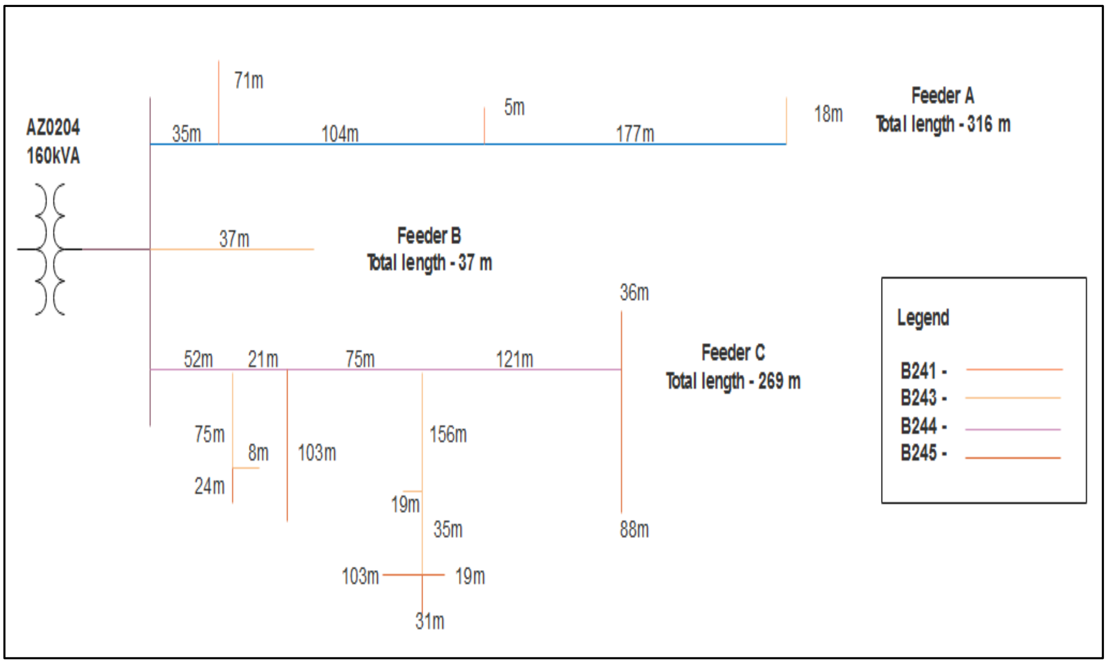

Figure 3-3: Single Line Diagram of AZ0204

When modeling the LV feeder, Line code object from the OpenDSS general library was used. The line code properties are as follows.

- Nphases= Number of phases. Default = 3.
- Rmatrix= Series resistance matrix, ohms per unit length.
- Xmatrix= Series reactance matrix, ohms per unit length.
- Cmatrix= Shunt nodal capacitance matrix, nanofarads per unit length.
- BaseFreq= Base Frequency at which the impedance values are specified. Default = 60.0 Hz.

- Units= {mi |km | kft | m| ft | ine | cm} Length units. If not specified, it is assumed that the units correspond to the length being used in the Line models.

Sample code for LECO feeders

```
!Linecodes
New Linecode.LVB245 rmatrix="0.76788 | 0.049345 0.76788 | 0.049345 0.049345 0.76788 | 0.049345 0.049345 0.049345 1.02234"
~ xmatrix="0.79595 | 0.67998 0.79595 | 0.67998 0.67998 0.79595 | 0.71450 0.71450 0.71450 0.80512"
~ cmatrix="71.14052 | -12.69738 71.14052 | -12.69738 -12.69738 71.14052 | -39.65467 -39.65467 -39.65467 118.29947"
~ Units=km BaseFreq=50 nphases=4

New Linecode.LVB244 rmatrix="0.54593 | 0.049345 0.54593 | 0.049345 0.049345 0.54593 | 0.049345 0.049345 0.049345 0.75555"
~ xmatrix="0.780639 | 0.667566 0.780639 | 0.667566 0.667566 0.780639 | 0.70208 0.70208 0.70208 0.78594"
~ cmatrix="72.79872 | -11.20242 72.79872 | -11.20242 -11.20242 72.79872 | -44.09965 -44.09965 -44.09965 131.52099"
~ Units=km BaseFreq=50 nphases=4

New Linecode.LVB243 rmatrix="0.76788 | 0.049345 0.76788 | 0.049345 0.049345 0.76788 | 0.049345 0.049345 0.049345 1.02234"
~ xmatrix="0.79595 | 0.67998 0.79595 | 0.67998 0.67998 0.79595 | 0.71450 0.71450 0.71450 0.80512"
~ cmatrix="71.14052 | -12.69738 71.14052 | -12.69738 -12.69738 71.14052 | -39.65467 -39.65467 -39.65467 118.29947"
~ Units=km BaseFreq=50 nphases=4

New Linecode.LVB241 rmatrix="0.54593 | 0.049345 0.54593 | 0.049345 0.049345 0.54593 | 0.049345 0.049345 0.049345 0.75555"
~ xmatrix="0.780639 | 0.667566 0.780639 | 0.667566 0.667566 0.780639 | 0.70208 0.70208 0.70208 0.78594"
~ cmatrix="72.79872 | -11.20242 72.79872 | -11.20242 -11.20242 72.79872 | -44.09965 -44.09965 -44.09965 131.52099"
~ Units=km BaseFreq=50 nphases=4
```

Line segments were identified as the span between two poles. Then the two ends of the line were considered as nodes. Each line segment was named by the bounded pole names. Following properties were defined for line segment.

- Bus1/Bus2 = Start and end of the segment.
- Length = Length of the line segment
- Phases = Number of phases
- Line code = Pre-defined line code which should be referred

Sample code for line segment in Feeder A

```
!AZ0204 Feeder A Lines
new line.LB_83/5/3-1        bus1=loadbus    bus2=83/5/3-1   length=0.010 phases=4 units=km linecode=LVB244
new line.83/5/3-1_83/5/3    bus1=83/5/3-1   bus2=83/5/3     length=0.025 phases=4 units=km linecode=LVB244
new line.83/5/3_83/5/2      bus1=83/5/3     bus2=83/5/2     length=0.033 phases=4 units=km linecode=LVB244
new line.83/5/2_83/5/1      bus1=83/5/2     bus2=83/5/1     length=0.037 phases=4 units=km linecode=LVB244
new line.83/5/1_83/5-1      bus1=83/5/1     bus2=83/5-1     length=0.034 phases=4 units=km linecode=LVB244
new line.83/5-1_83/5        bus1=83/5-1     bus2=83/5       length=0.028 phases=4 units=km linecode=LVB244
new line.83/5_83/4          bus1=83/5       bus2=83/4       length=0.032 phases=4 units=km linecode=LVB244
new line.83/4_83/3-2        bus1=83/4       bus2=83/3-2     length=0.018 phases=4 units=km linecode=LVB244
new line.83/3-2_83/3-1      bus1=83/3-2     bus2=83/3-1     length=0.006 phases=4 units=km linecode=LVB244
new line.83/3-1_83/3        bus1=83/3-1     bus2=83/3       length=0.005 phases=4 units=km linecode=LVB244
new line.83/3_83/2          bus1=83/3       bus2=83/2       length=0.060 phases=4 units=km linecode=LVB244
new line.83/2_83/1          bus1=83/2       bus2=83/1       length=0.028 phases=4 units=km linecode=LVB244
new line.83/1_83/1A         bus1=83/1       bus2=83/1A      length=0.018 phases=4 units=km linecode=LVB243

new line.83/5/3_83/5/3/1    bus1=83/5/3     bus2=83/5/3/1  length=0.028 phases=4 units=km linecode=LVB241
new line.83/5/3/1_83/5/3/2  bus1=83/5/3/1   bus2=83/5/3/2  length=0.043 phases=4 units=km linecode=LVB241

new line.83/5-1_83/5-1/1    bus1=83/5-1     bus2=83/5-1/1  length=0.005 phases=4 units=km linecode=LVB241
```

3.2.3 Modeling of Loads

In a LV distribution feeder, loads are the customers connected to that feeder at each pole. Therefore, pole can be defined as a node and total number of nodes in this model is 67. The loads can be either single phase or three phase. The total load visible to the LV feeder at the point of connected node is the sum of all customer loads connected to that node.

In a single pole node, there may be a combination of single phase customers and three phase customers in a mix. However, the final load in a pole node can be represented as a three phase balance load considering the addition of all loads.

Actual energy consumptions of the customers were extracted from the LECO system database to calculate the loads at each node. Diversity factor was defined for each tariff category to distribute the loads for nodes.

$$D_n = \frac{\sum Monthy\ consumtion\ of\ Dn}{(\sum Xn) * (Total\ montly\ consumption\ of\ the\ transfomer)}$$

Dn – Diversity factor of each category

Xn – Number of customers of each category

Load per node,

Load per node = $\Sigma\ (D_n X_n)$ x Demand to be modeled

As per the above calculation, following diversity factors were calculated.

Table 3-5: Diversity Factors of Load Categories

Category	Diversity Factor (D)
D1 (Domestic 0-60)	0.02
D2 (Domestic 61-90)	0.08
D3 (Domestic 91-120)	0.12
D4 (Domestic 121-180)	0.15
D5 (Domestic Above 180)	0.25
GP 1	0.19
GP 2	0.21

Load object in OpenDSS library was used to develop the load models. It is basically defined by its nominal kW and PF or its kW and kVar. Loads are assumed to be balanced three phase. The properties of load object are as follows.

- bus1= Name of bus to which the load is connected
- Phases = Number of phases
- kV = Base voltage for load
- kW = Nominal active power, kW for the load, Total of all phases
- pf = nominal power factor for load

Sample code for Feeder A loads

```
!AZ0204 Feeder A Loads
new load.83/5/3-1   bus1=83/5/3-1   phases=3 kV=0.4 kW=1.66 pf=0.95
new load.83/5/3     bus1=83/5/3     phases=3 kV=0.4 kW=1.66 pf=0.95
new load.83/5/3/1   bus1=83/5/3/1   phases=3 kV=0.4 kW=2.39 pf=0.95
new load.83/5/3/2   bus1=83/5/3/2   phases=3 kV=0.4 kW=3.82 pf=0.95
new load.83/5/2     bus1=83/5/2     phases=3 kV=0.4 kW=3.24 pf=0.95
new load.83/5/1     bus1=83/5/1     phases=3 kV=0.4 kW=2.59 pf=0.95
new load.83/5-1     bus1=83/5-1     phases=3 kV=0.4 kW=1.82 pf=0.95
new load.83/5-1/1   bus1=83/5-1/1   phases=3 kV=0.4 kW=4.73 pf=0.95
new load.83/5       bus1=83/5       phases=3 kV=0.4 kW=1.33 pf=0.95
new load.83/4       bus1=83/4       phases=3 kV=0.4 kW=3.54 pf=0.95
new load.83/3-2     bus1=83/3-2     phases=3 kV=0.4 kW=0.83 pf=0.95
new load.83/3-1     bus1=83/3-1     phases=3 kV=0.4 kW=1.66 pf=0.95
new load.83/3       bus1=83/3       phases=3 kV=0.4 kW=2.12 pf=0.95
new load.83/2       bus1=83/2       phases=3 kV=0.4 kW=9.26 pf=0.95
new load.83/1       bus1=83/1       phases=3 kV=0.4 kW=1.62 pf=0.95
new load.83/1A      bus1=83/1A      phases=3 kV=0.4 kW=3.28 pf=0.95
```

3.2.4 Modeling of Solar PV

Total solar additions on each pole were denoted using the PVSystem object in OpenDSS library. Following properties were used.

- phases= Number of phase of the system
- bus1= connected bus
- kV= voltage level
- kVA= Installed solar PV capacity
- irrad= Expected irradiation level at the installed location
- Pmpp= Maximum power point
- PF= Power Factor
- effcurve= Efficiency curve of the invertor
- P-TCurve= Per unit curve of rated Pmpp vs temperature

Sample code of Solar PV

```
New PVSystem.83/2  phases=3 bus1=83/2 kV=0.4 kVA=30 irrad=0.8 Pmpp=1 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/3-2  phases=3 bus1=83/3-2 kV=0.4 kVA=50 irrad=0.8 Pmpp=16 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/4  phases=3 bus1=83/4 kV=0.4 kVA=3 irrad=0.8 Pmpp=1 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5  phases=3 bus1=83/5 kV=0.4 kVA=12 irrad=0.8 Pmpp=4 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/10  phases=3 bus1=83/5/10 kV=0.4 kVA=24 irrad=0.8 Pmpp=8 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/13  phases=3 bus1=83/5/13 kV=0.4 kVA=10 irrad=0.8 Pmpp=3 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/14  phases=3 bus1=83/5/14 kV=0.4 kVA=18 irrad=0.8 Pmpp=6 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/16  phases=3 bus1=83/5/16 kV=0.4 kVA=18 irrad=0.8 Pmpp=6 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/16/1  phases=3 bus1=83/5/16/1 kV=0.4 kVA=39 irrad=0.8 Pmpp=3 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/3  phases=3 bus1=83/5/3 kV=0.4 kVA=30 irrad=0.8 Pmpp=10 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/3/2  phases=3 bus1=83/5/3/2 kV=0.4 kVA=64 irrad=0.8 Pmpp=21 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/5  phases=3 bus1=83/5/5 kV=0.4 kVA=26 irrad=0.8 Pmpp=9 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/5/1  phases=3 bus1=83/5/5/1 kV=0.4 kVA=30 irrad=0.8 Pmpp=10 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/5/2  phases=3 bus1=83/5/5/2 kV=0.4 kVA=25 irrad=0.8 Pmpp=5 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/5/7  phases=3 bus1=83/5/5/7 kV=0.4 kVA=44 irrad=0.8 Pmpp=15 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/6/2  phases=3 bus1=83/5/6/2 kV=0.4 kVA=20 irrad=0.8 Pmpp=7 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5-1/2  phases=3 bus1=83/5-1/2 kV=0.4 kVA=10 irrad=0.8 Pmpp=3 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
New PVSystem.83/5/5/6  phases=3 bus1=83/5/5/6 kV=0.4 kVA=10 irrad=0.8 Pmpp=4 PF=1 effcurve=Efficiency P-TCurve=JAP_PvsT
```

3.3 Case Study Results

Four case studies have been carried out on above modeled AZ0204 transformer by simulating base case without solar PV systems and increasing solar PV penetration in the network. The case studies are as listed below.

1. Scenario 1 : Simulation for system without rooftop solar PV : base case
2. Scenario 2 : Simulation for actual rooftop solar PV installed capacity 124kW (75%)
3. Scenario 3 : Simulation for rooftop solar additions of 155kW (95%)
4. Scenario 4 : Simulation for rooftop solar additions of 253kW (155%)

Simulation for each and above case required solar PV installed capacity and transformer load as inputs. LV loss and recorded minimum voltage was taken from the simulations as outputs. Summary of the load flow result for the above four cases are shown in Table 3-6.

Table 3-6: Case study results

Scenario	**Load (kW)**	**Transformer power (kW)**	**Solar PV generation (kW)**	**Total loss %**	**Minimum voltage recorded**	**Node with Min. Voltage**
1	150	153	0	2.28%	219.37	Feeder end
2	150	34	124 (83%)	0.57%	223.30	Feeder end
3	150	-4	155 (95%)	0.69%	223.99	Feeder end
4	150	-101	253 (155%)	0.86%	226.06	Feeder end

Scenario 1 is the base case where no solar PV systems connected to the transformer. In that case power loss of the transformer indicates 2.28% loss with 219.37V minimum voltage. Scenario 2 is the possible maximum solar PV penetration of the AZ0204 transformer, which is 83%. In that case total loss are reduced and minimum voltage recorded is improved. Hypothetical case was simulated as scenario 3 to understand the behavior of power loss and minimum voltage with further addition of solar PV systems. At this point reverse power flow started, and power losses are increasing. To confirm the above behavior, further hypothetical case was simulated as scenario 4 and it confirms that power losses are getting increase with higher solar penetration.

From the above results, it is certain that power loss is decreasing up to some level with solar penetration. However, after some level, again power loss is getting increased. Therefore, further studies were required in order to understand the behavior of power loss under different solar penetration levels.

Requirement of developing a generalized model was identified by above case study which is explained in the Chapter 4.

CHAPTER 4

4 EVALUATION OF OPTIMUM SOLAR PV LEVEL SUBJECTED TO POWER LOSS OF THE FEEDER

4.1 Introduction

The purpose of generalized model development is to analyze the variation of power loss under different solar penetration levels. Main challenge in development of generalized model was to identify the actual LV network systems & integrate them to the simulation. The actual LV network system includes different transformer capacities, different number of feeders per transformers, different feeder lengths etc. Considering the LECO network distribution system, five LV models were identified to represent the entire LV network system.

Under that, number of distribution transformers installed in LECO area was analyzed and it was found out that the most common type of capacities used as distribution transformers are 100kVA & 160kVA. Five LV feeder models were developed upon the thorough consideration of existing LV feeder topologies. Loading level of the transformer was derived by considering the normalized curve of distribution transformers. Different solar penetration levels from 0% to 110% were considered for the simulations.

4.2 Development of generalized LV distribution model

Generalized model is a hypothetical model developed for LV distribution networks by accommodating structures of actual LV network. Existing network structure of the LECO distribution system was studied to understand the general network topology.

Feeder data and loading data of hundred distribution transformer were extracted from LECO data base as given in Table 4-1.

Table 4-1: Feeder and loading data of distribution transformers

Transformer capacity(kVA)	No of transformers	No of feeders	Feeder count	Feeder count %
100	30	1	3	14%
		2	10	48%
		3	6	29%
		4	2	10%
160	70	1	3	5%
		2	13	23%
		3	28	50%
		4	12	21%

As per the above table, five main categories were identified.

1. 100 kVA Transformer with 2 feeders
2. 100 kVA Transformer with 3 feeders
3. 160 kVA Transformer with 2 feeders
4. 160 kVA Transformer with 3 feeders
5. 160 kVA Transformer with 4 feeders

4.2.1 System parameters

Loading level of the transformer

Loading level of the transformer was taken from normalized load curve of the distribution transformer shown in Figure 4-1 and data extracted on average loading level of distribution transformers in Table 4-2.

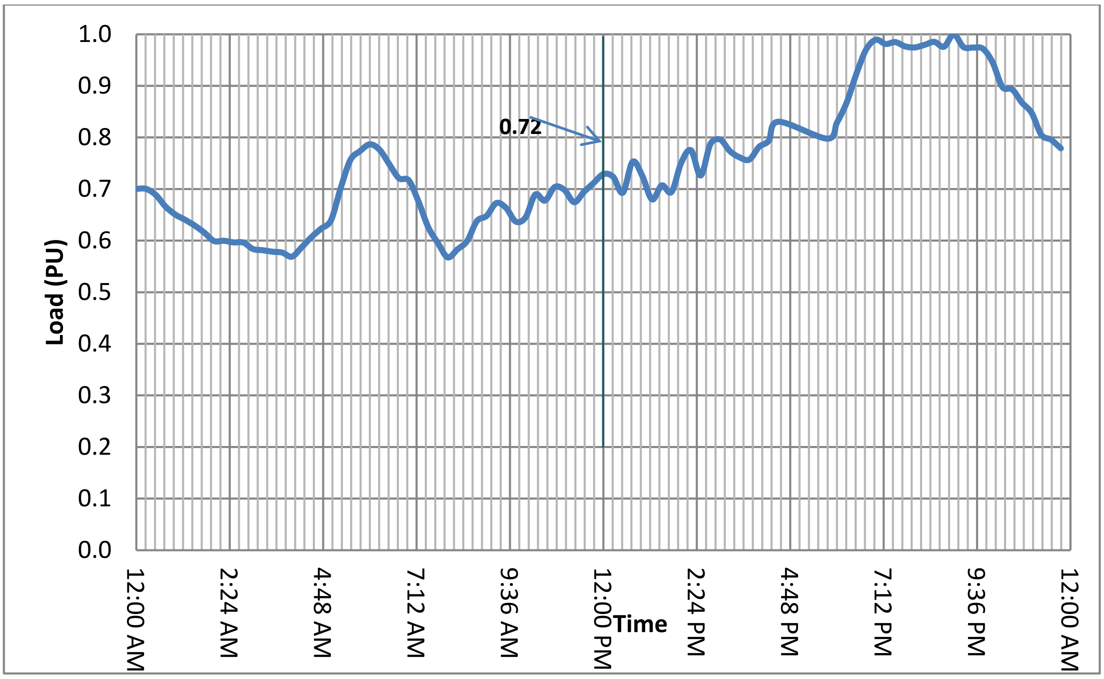

Figure 4-1: Normalized load curve of the distribution transformers

Table 4-2: Average loading of distribution transformers

Capacity of the Transformer	Average Loading
100kVA	82%
160kVA	85%

As per the normalized curve, loading level at 12.00 P.M is 72% from the peak. Transformer loading is defined by following equation.

Transformer loading = Average loading x (Load level at 12 P.M / Peak Load)

Therefore, modeled load levels are,

- 100 kVA - 59%
- 160 kVA – 61%

Solar penetration levels

Solar penetration level is the percentage of solar PV installed capacity compared to the capacity of transformer. Twelve levels were considered in the range of 0-110% with 10% step.

Solar PV systems

Solar PV systems are modeled as balanced 3 phase systems & connected to the nodes randomly in each run. Voltage settings of the investors are kept as ±6% of the nominal value.

4.3 Monte Carlo Analysis

Monte Carlo is a method which use random sampling to obtain numerical results. Random inputs will be generated by considering variables to perform a simulation on each input and results of each will aggregate the final result.

The underlying concept of the Monte Carlo analysis is used to incorporate the randomness of location and solar penetration percentage to solve problems. It gives a range of possible outcomes and probabilities by allowing to consider the likelihood of different scenarios. Monte Carlo methods vary with the application; however basic steps are as follows.

1. Define possible inputs
2. Generate inputs randomly
3. Perform computation on the inputs
4. Aggregate the results

4.3.1 LV models

Possible inputs were defined by introducing five LV models. Following parameters were considered.

- Capacity of the transformer – 100kVA / 160kVA
- Number of feeders – 2 /3 /4

Length of a feeder was considered as 500m and pole span was considered as 35m. With the above assumptions, number of poles per feeder will be 15. Single line diagram of a LV model of 160kVA transformer with 3 feeders is shown in Figure 4-2.

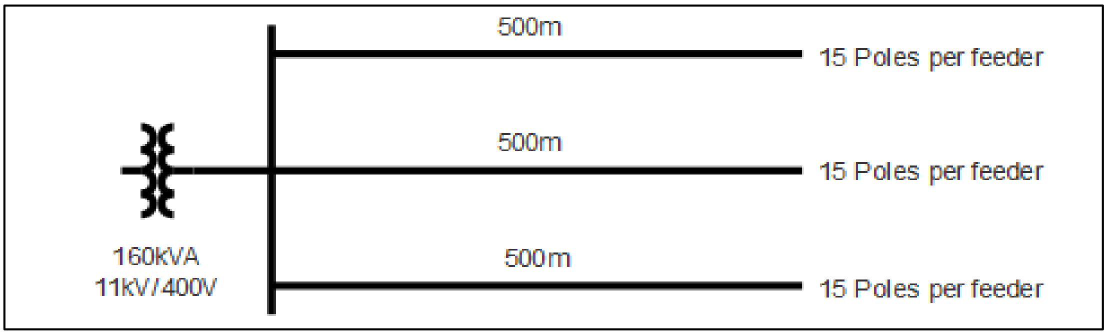

Figure 4-2 : Single line diagram of LV Model (160kVA , 3 feeders)

Similarly, five models were developed and for each LV model, twelve solar penetration levels were considered as shown in Figure 4-3.

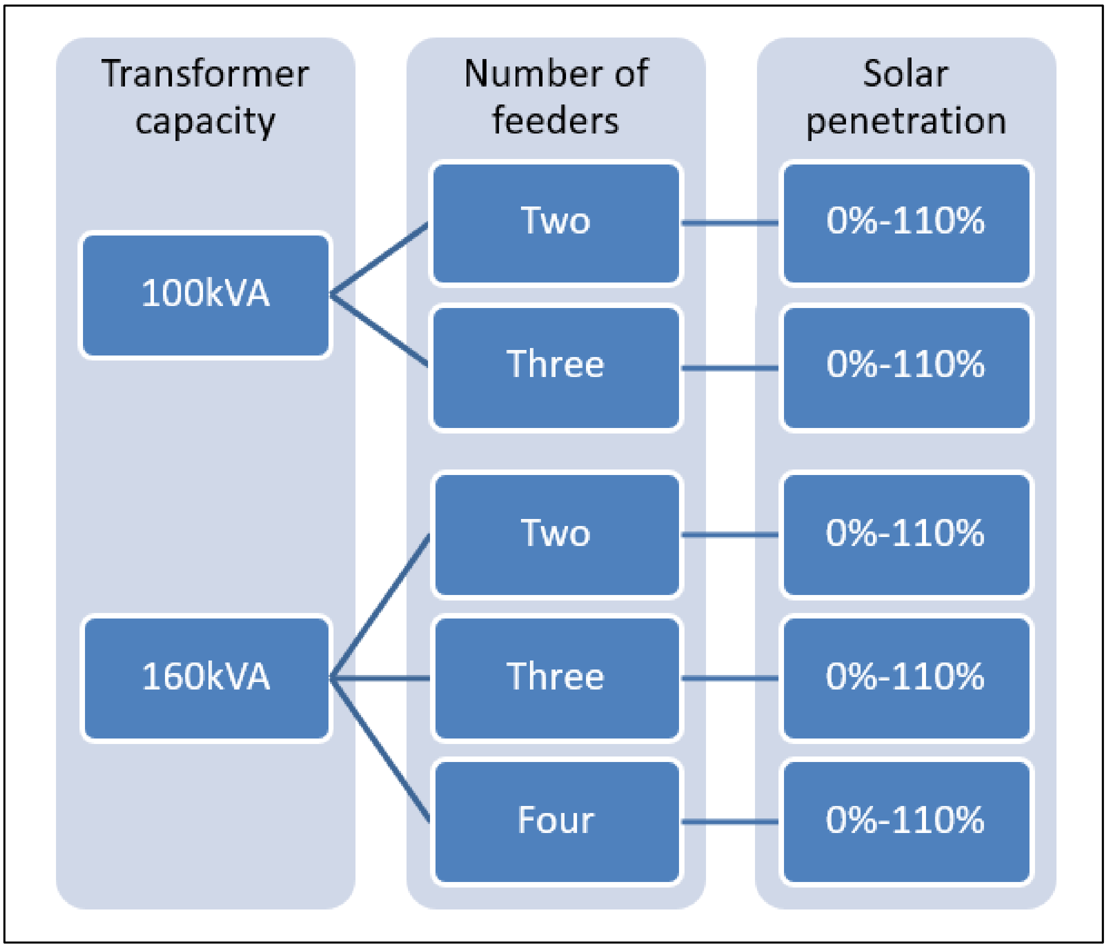

Figure 4-3 : LV models for Monte Carlo study

4.3.2 Modeling different scenarios

In order to generate the inputs, location randomness was considered for solar PV systems. It was done using MATLAB. From each LV model, hundred cases were simulated with location randomness. Therefore, total numbers of simulations are 500.

Table 4-3: Sample cases for simulation

LV Model	Transformer Capacity	Number of feeders	Solar penetration levels	Expected number of samples with location randomness	Total
1	100kVA	2	12	100	100
2	100kVA	3	12	100	100
3	160kVA	2	12	100	100
4	160kVA	3	12	100	100
5	160kVA	4	12	100	100
Total number of samples					500

4.3.3 MATLAB integration

OpenDSS allow MATLAB to drive the simulation and perform custom calculations. This is helpful to simulate different scenarios & to export result for statistical analysis. It is required to Initialize OpenDSS, startup the solver and set up the interface variable in MATLAB for integration as shown in Figure 4-4..

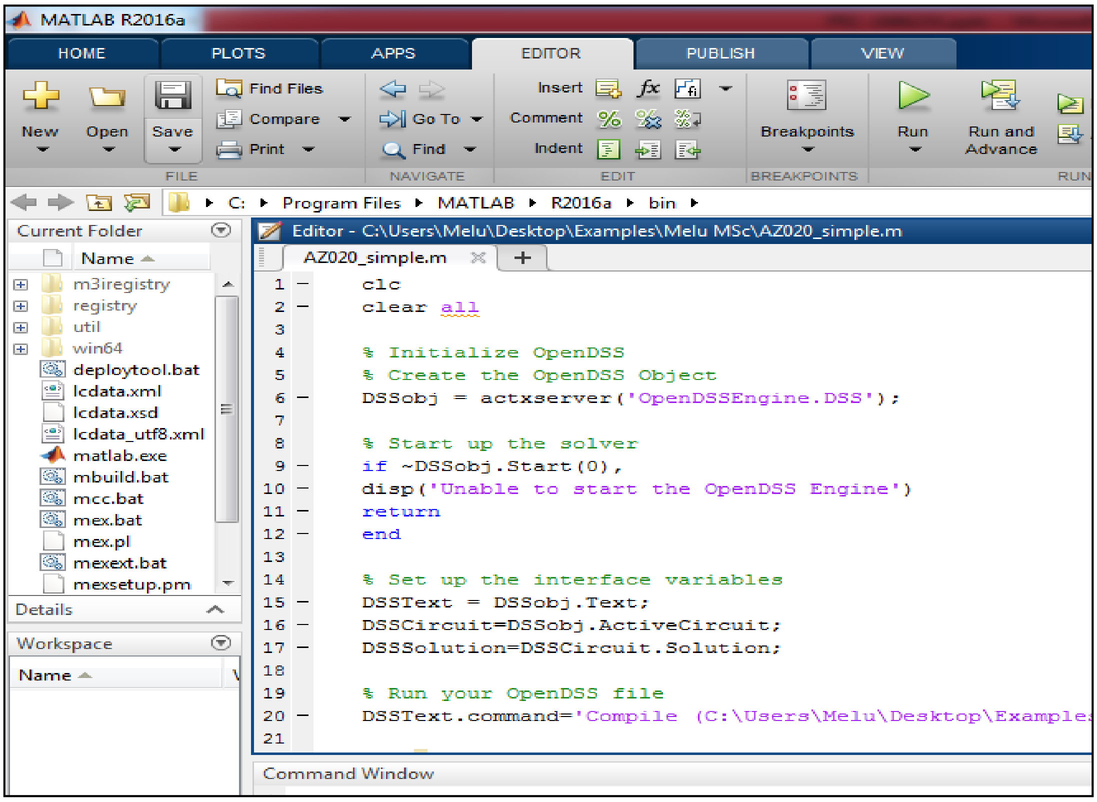

Figure 4-4 : MATLAB interface for OpenDSS integration

CHAPTER 5

5 POWER LOSS BASED CRITERIA FOR OPTIMUM SOLAR PV LEVEL

5.1 Results and analysis

Five case studies have been carried out on the selected 160kVA transformer by simulating the present actual situation, with further expected solar injections. Normalized curve for power loss, which were obtained by simulating 500 cases, are presented in the results. Normalized curve was obtained by considering the maximum of the summation of power losses recorded for all solar penetration level as unity.

The case studies are as presented below. In each of the case, two limits were identified from the curves, as Limit 1 & Limit 2, where the power loss matches to the initial loss level with the increment of the solar penetration respectively.

1. 100 kVA Transformer with 2 feeders

Stacked curves for 100 cases were illustrated in Figure 5-1.

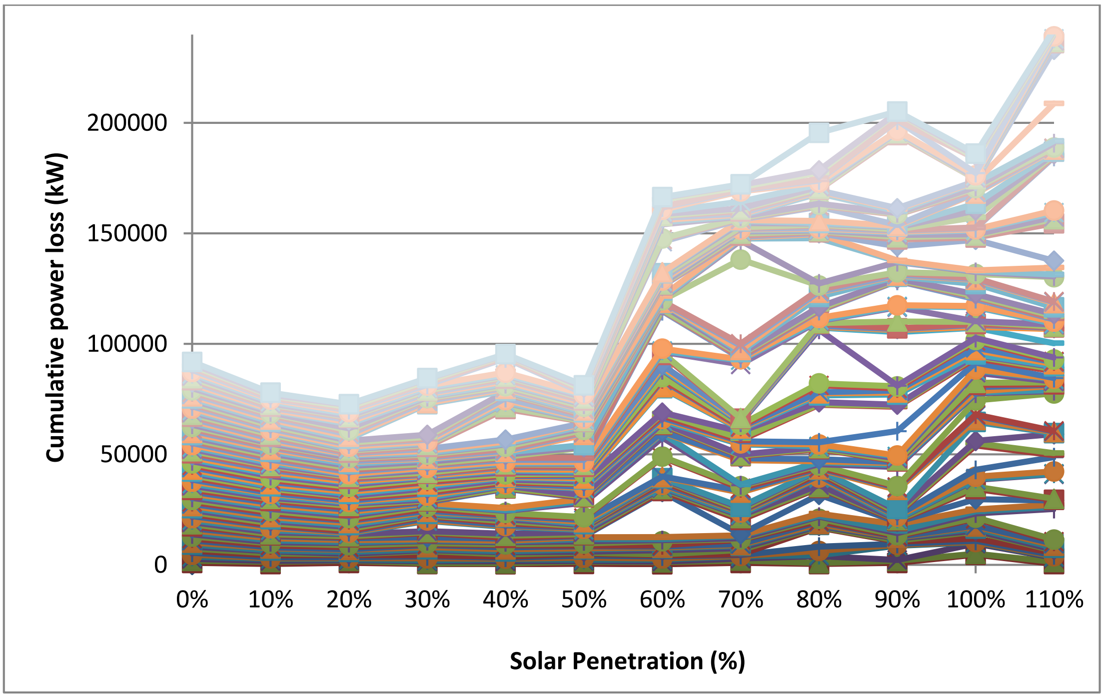

Figure 5-1: Staked curves for 100 cases of 100kVA Transformer with 2 feeders

Normalized plot of the cumulative power loss of 100 cases is shown in Figure 5-2.

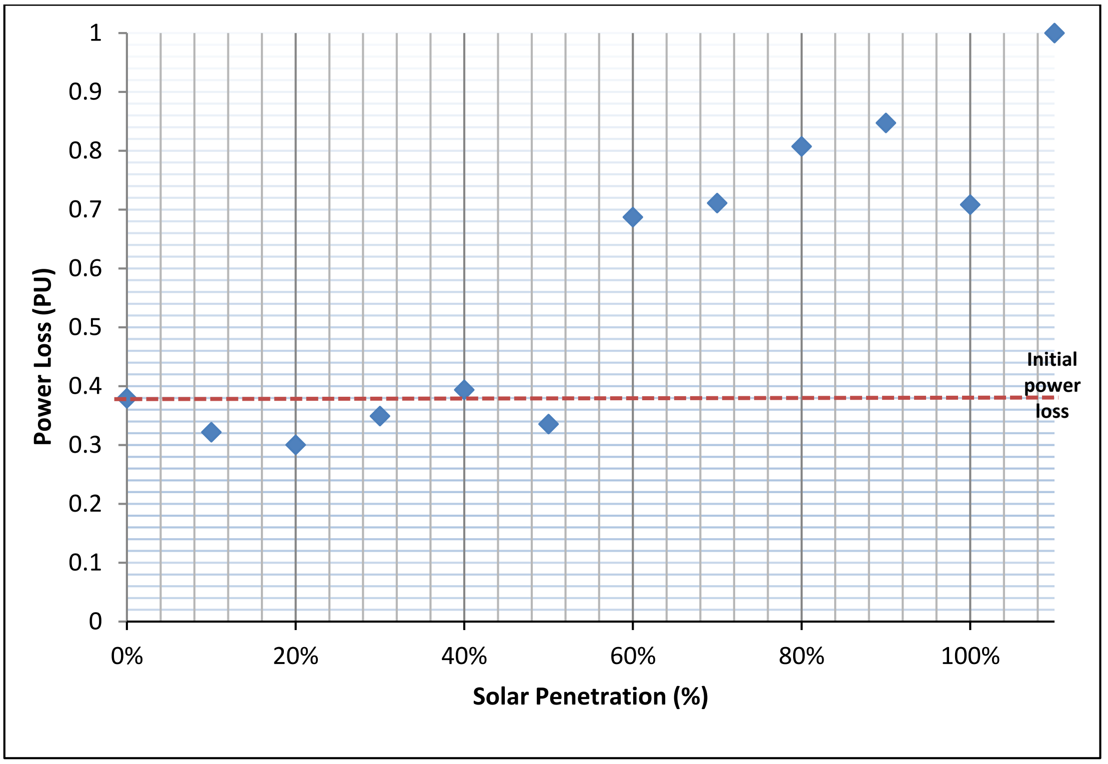

Figure 5-2: Normalized power loss for 100 kVA Transformer with 2 feeders

As per the above scatter plot, initial loss level reaches again in between 30%-40% and 50%-60%. The first point reaches the initial loss level defined as Limit one and second point defined as Limit 2.

Using liner interpolation,

- Limit 1 – 36%
- Limit 2 – 51%

2. 100 kVA Transformer with 3 feeders

Staked curves for cumulative power loss and corresponding normalize plot are shown in Figure 5-3 & Figure 5-4 respectively.

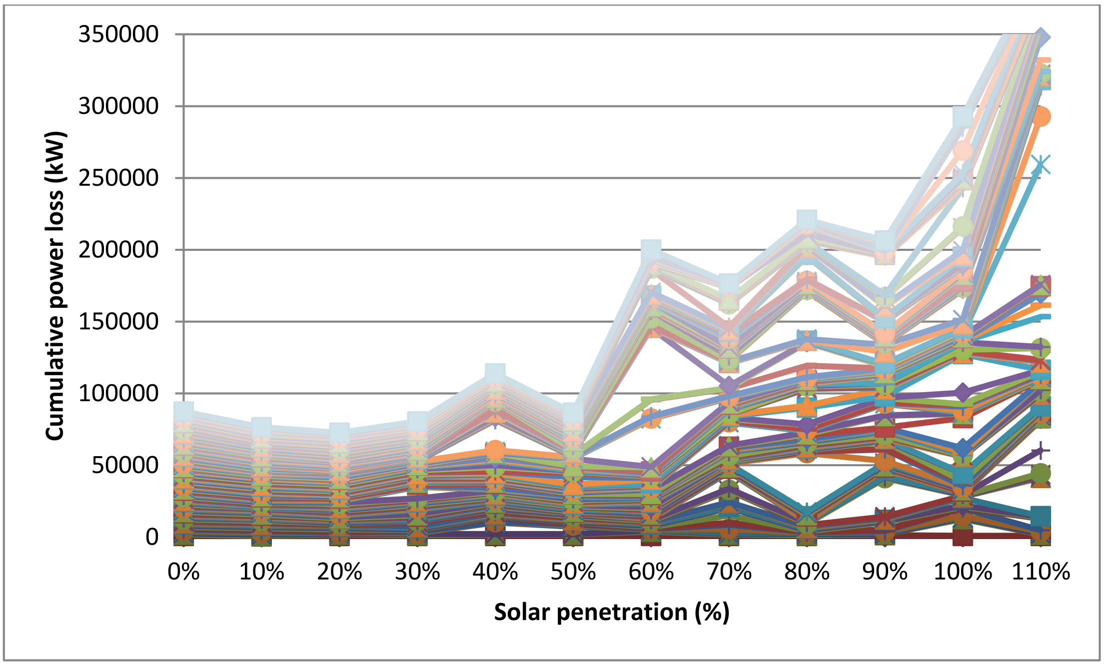

Figure 5-3 : Staked curves for 100 cases of 100kVA Transformer with 3 feeders

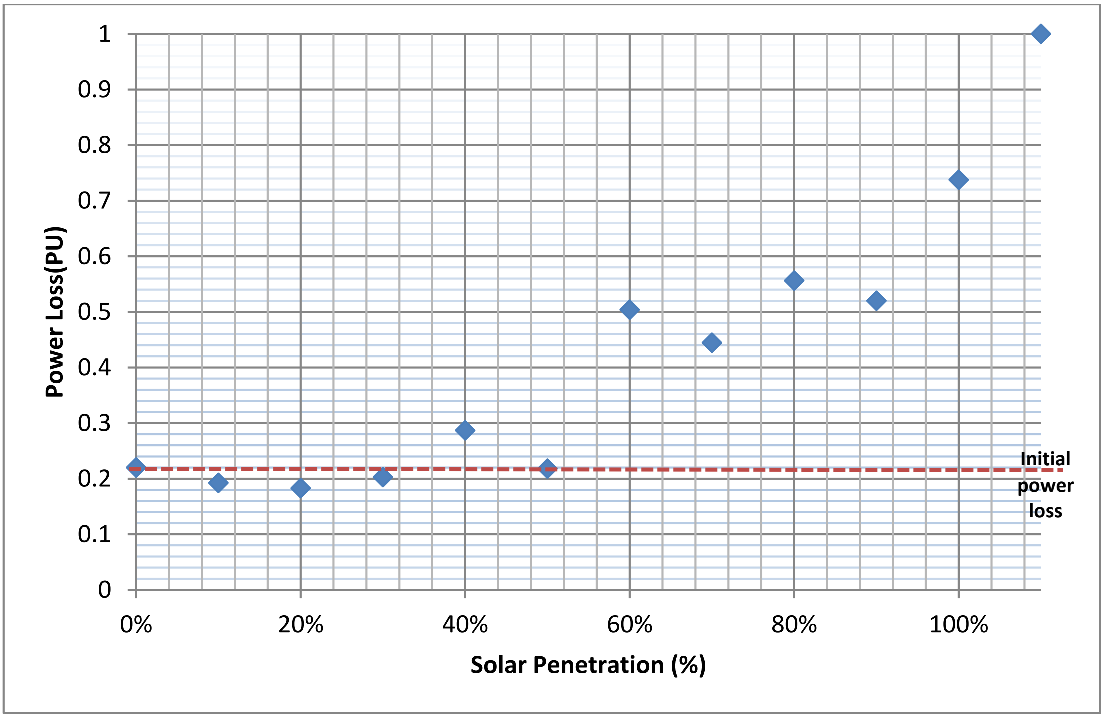

Figure 5-4 : Normalized power loss for 100 kVA Transformer with 3 feeders

Similar to the results of above scenario -1, initial loss level reaches for this scenario in between 30%-40% and 50%-60%. Limits can be defined as follows using liner interpolation.

- Limit 1 – 32%
- Limit 2 – 50%

3. 160 kVA Transformer with 2 feeders

Staked curves for cumulative power loss and corresponding normalize plot are shown in Figure 5-5 & Figure 5-6 respectively.

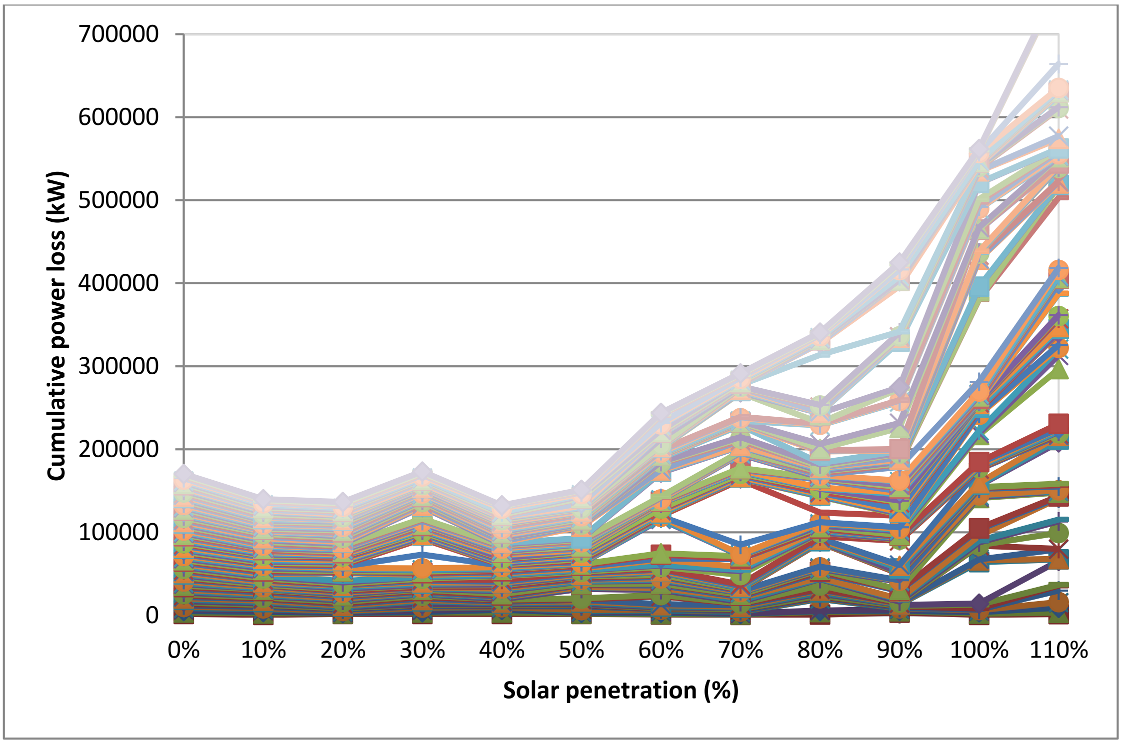

Figure 5-5 : Staked curves for 100 cases of 160kVA Transformer with 2 feeders

Behavior of the power loss for scenario 3 is unchanged, and limits are laid between 30%-40% and 50%-60%. Followings are limits found from liner interpolation.

- Limit 1 – 30%
- Limit 2 – 52%

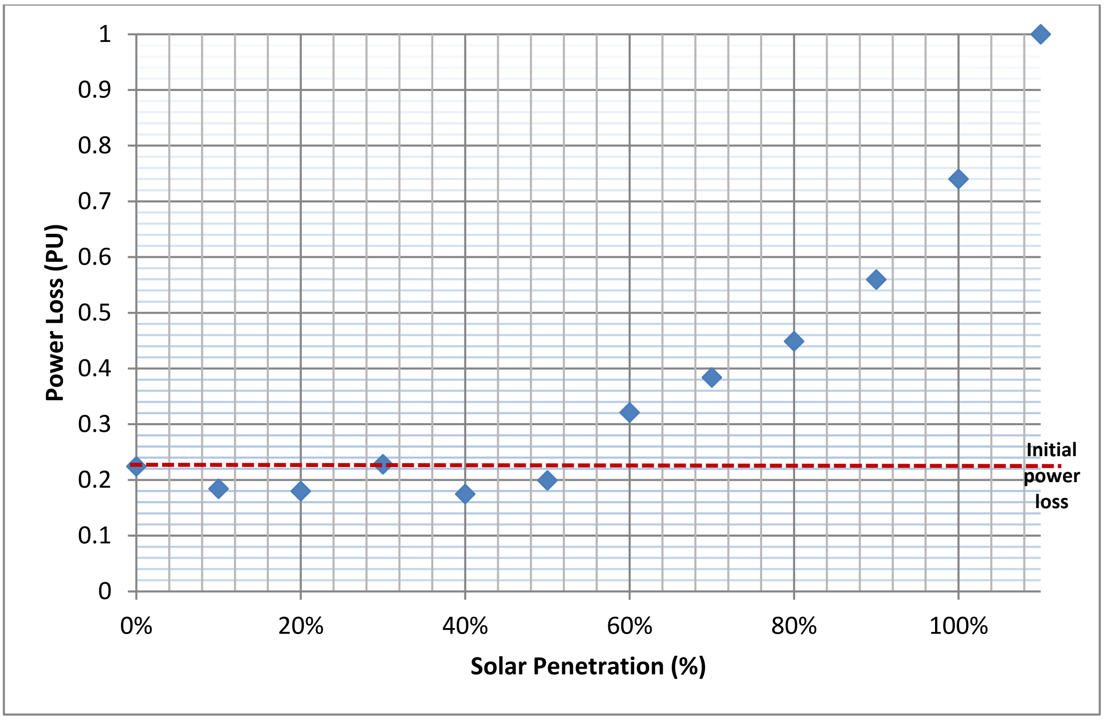

Figure 5-6 : Normalized power loss for 160 kVA Transformer with 2 feeders

4. 160 kVA Transformer with 3 feeders

Staked curves for cumulative power loss and corresponding normalize plot are shown in Figure 5-7 & Figure 5-8 respectively.

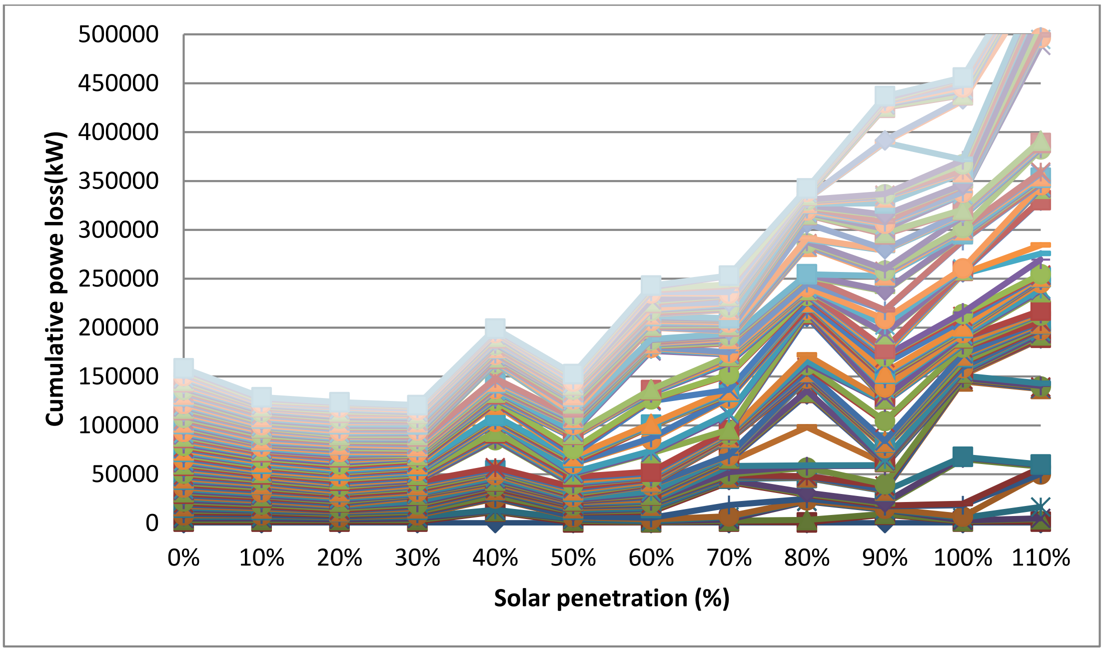

Figure 5-7 : Staked curves for 100 cases of 160kVA Transformer with 3 feeders

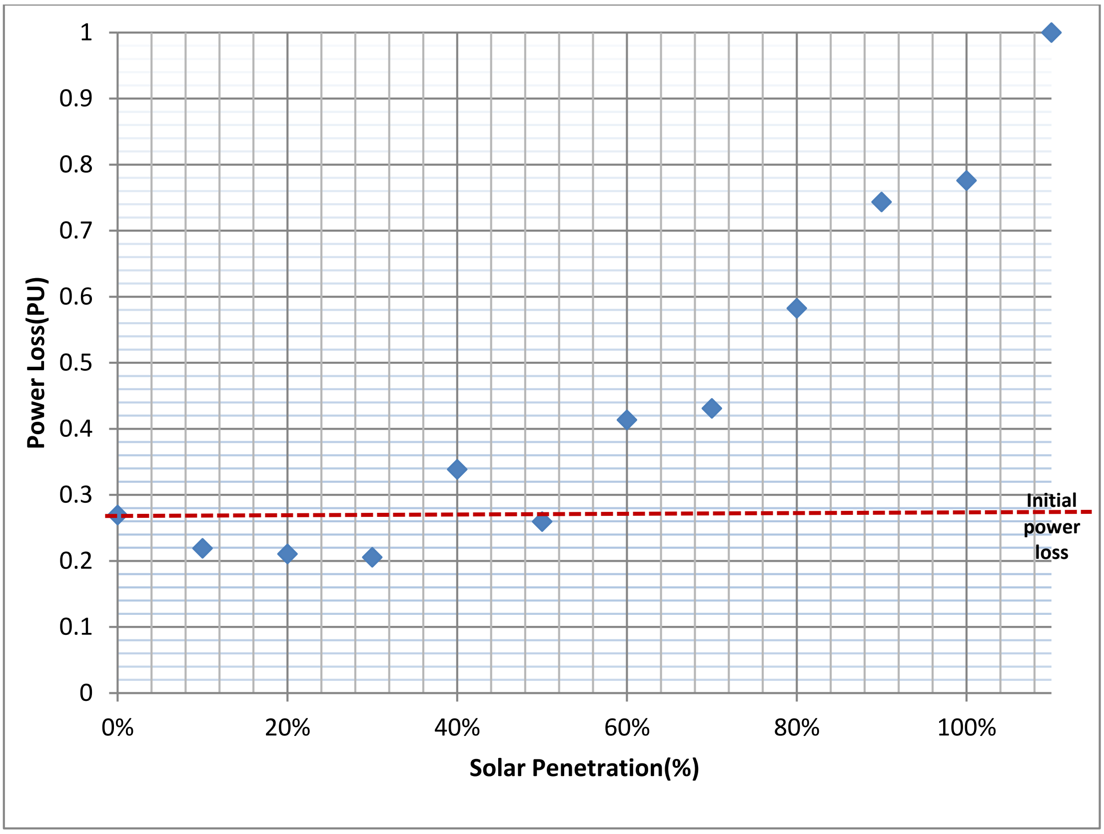

Figure 5-8 : Normalized power loss for 160 kVA Transformer with 3 feeders

As similar to the above four scenarios, limits of scenario 4 also in between 30%-40% and 50%-60%. Exact values from liner interpolation as follows.

- Limit 1 – 35%
- Limit 2 – 51%

5. 160 kVA Transformer with 4 feeders

Staked curves for cumulative power loss and corresponding normalize plot are shown in Figure 5-9 & Figure 5-10 respectively.

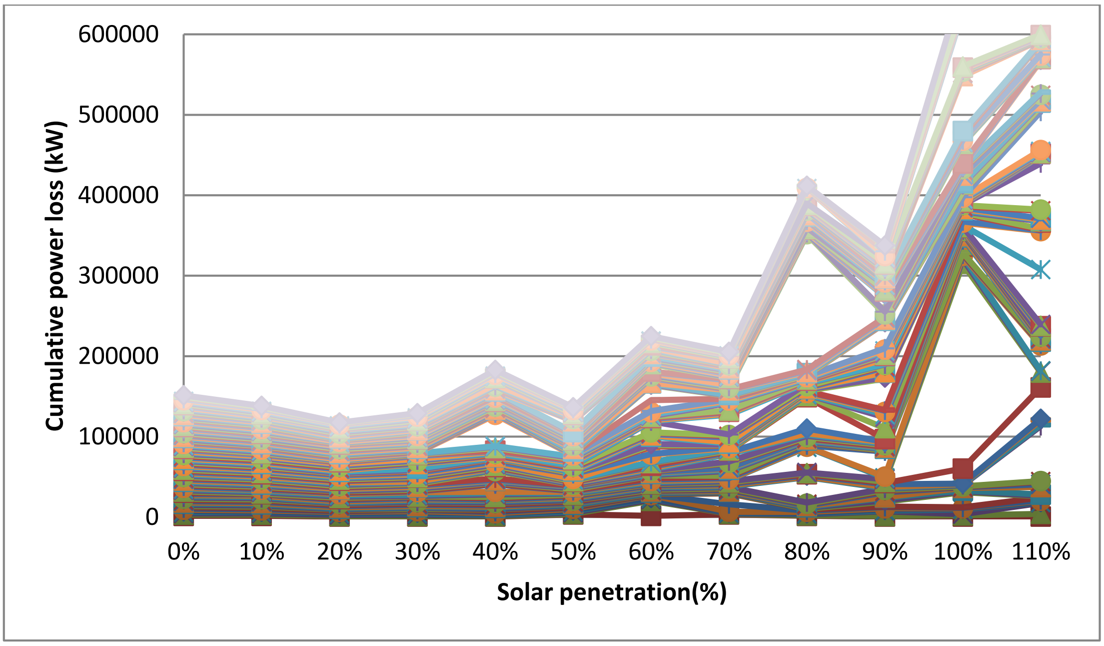

Figure 5-9 : Staked curves for 100 cases of 160kVA Transformer with 4 feeders

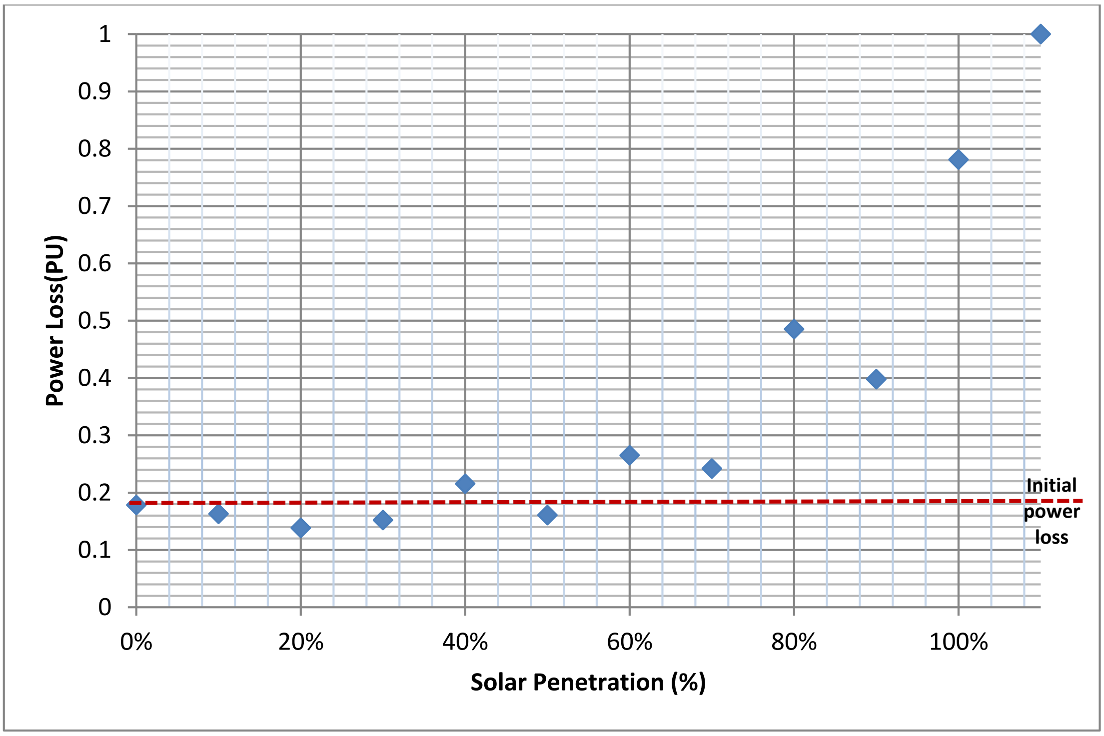

Figure 5-10 : Normalized power loss for 160 kVA Transformer with 4 feeders

Initial loss levels reach for scenario 5 also in between 30%-40% and 50%-60%. Values from linear interpolation are,

- Limit 1 – 34%
- Limit 2 – 52%

5.2 Summary of results

Summary of the result are shown in Table 5-1. Results demonstrate that initial loss level at solar penetration level 0% reaches twice with increase of solar penetration. Limit 1 is around 30%-36% and limit 2 is around 51%-52%.

Table 5-1 : Summary of results

LV Model	**Transformer Capacity**	**Number of feeders**	**Class I Limit**	**Class II Limit**
1	100kVA	2	36%	51%
2	100kVA	3	32%	50%
3	160kVA	2	30%	52%
4	160kVA	3	35%	51%
5	160kVA	4	34%	52%

From the above summary, two limitations were observed as,

- Limit 1 – Total losses are decreasing up to first minimum point of the curve. The ‘Limit 1’ limit is defined at the point where the power loss increases back to the initial loss. Solar penetration can be allowed up to this point without any conditions.
- Limit 2 – This is defined at the point where power loss starts increasing from the second minimum point up to the initial loss. Solar penetration between ‘Limit 1’ & ‘Limit 2’ limits can be allowed with certain conditions imposed by the network provider or the utility. Limit 2 is the maximum allowable solar penetration level for a given transformer.

5.3 Variation of Limit 2 with transformer loading level

Further case study was carried out to identify the variation of Limit 2 with transformer loading level. Under this, normalized curve of 100kVA transformer with 2 feeders and 59% loading level was compared with 80% loaded condition. Two curves are shown in Figure 5-6.

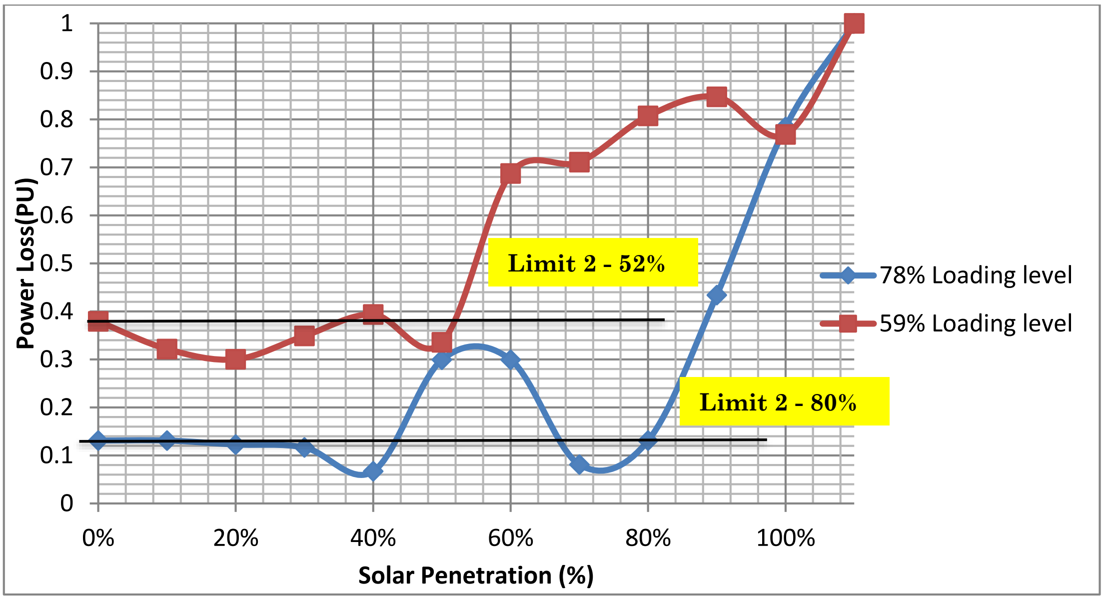

Figure 5-11 : Variation of Limit 2 with loading level

The above result confirms that Limit 2 rely on the loading level. Limit is almost proximate to the loading level of the transformer.

5.4 Power loss variation with the location of the load center

Two simulations were compared by varying load center of solar PV systems as shown in Figure 5-7 & Figure 5-8.

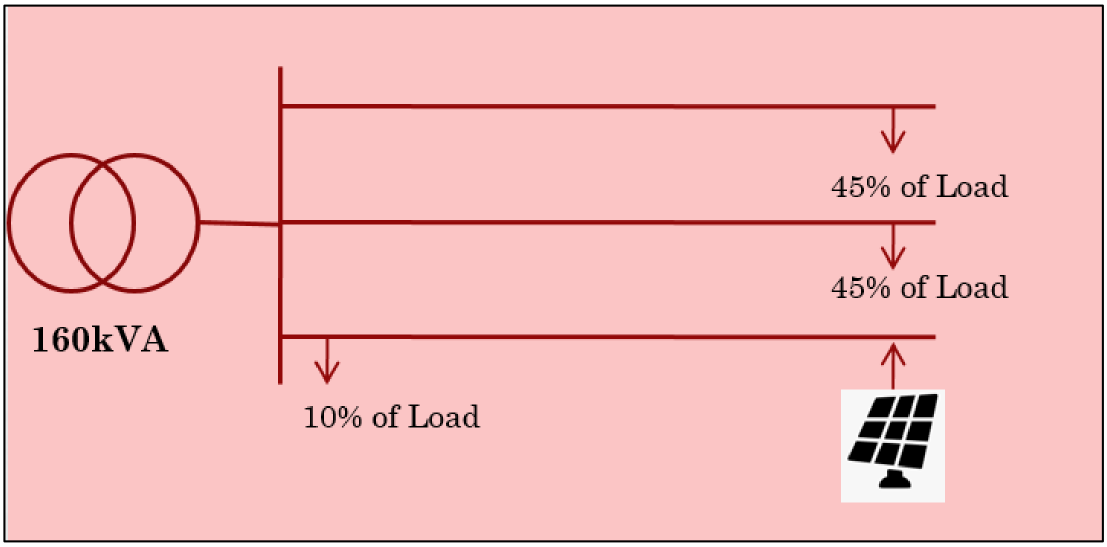

Figure 5-12 : A Network having long distance between load center and solar center

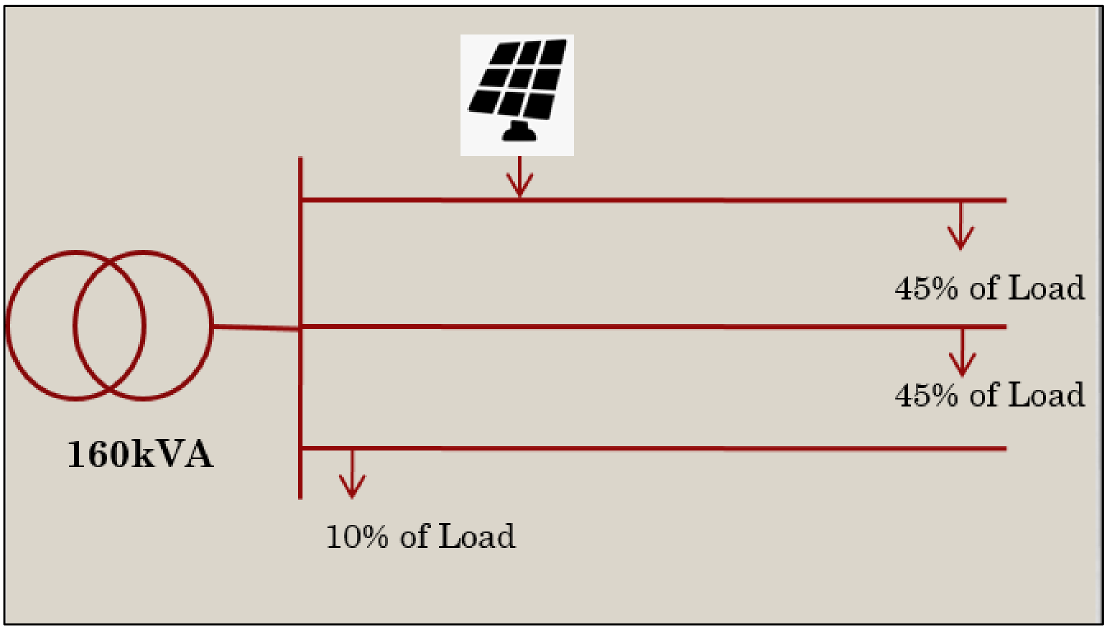

Figure 5-13 : A Network having long distance between load center and solar center

The above two cases were compared with the base case, without solar PV. Initial power loss without solar PV was 1.5kW. For the worse case (Figure 5-7) power loss was 1.8kW. For the best case, load center was manually calculated and all the solar PVs were added into that location. Power loss for the best case was 0.7 kW.

With the above result, we can conclude that if the load center and solar center is in same feeder segment, mostly the power loss will be low.

5.5 Solar PV approval criteria

Customer request / solar PV proposal initially submitted to the utility at the early stage. Utility have decided whether it could be acceptable or not and should inform the customer accordingly. Sri Lankan utilities currently allow to any customer to install solar PV system yup to their contract value. But this should be regulated by considering the potential impact to the grid. Detailed solar PV approval criteria, which is essential for power utilities when approving new solar applications.

Based on the findings of this research, simple approval criteria were introduced in Figure 2-1 by considering the two limits found from the research.

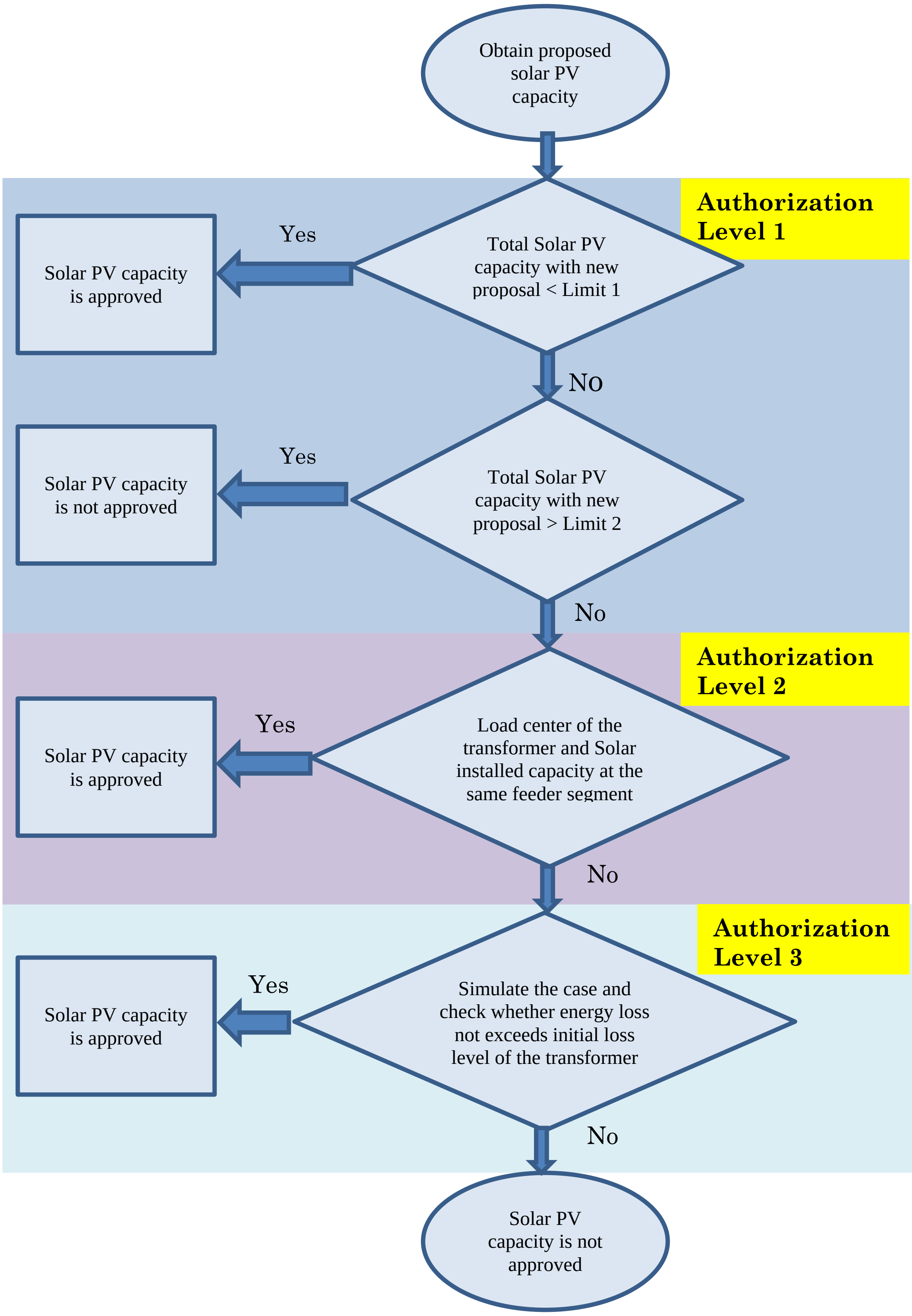

Figure 5-14 : Solar PV approval creteria

Three authorization limits were defined based on two limits. Defined authorization levels are possible to map with actual authorization levels of Sri Lanka.

At the first authorization level, quick decision can be taken without further analysis. At the second level, simple calculation is required and at the third level comprehensive study is required.

The main focus of this research is power loss and hence approval criteria limited to power loss. This can be further developed by considering other parameters such as load density of the network, feeder length, conductor types etc. The influence of the above parameters can examine by developing sample matrix with more possible scenarios. Universal solar PV approval criteria can be developed by comprehensive study with all possible scenarios as discussed above.

5.6 Discussion

As per the section 5.1 results, two limits were observed with two minimum points. Theoretical explanation for having two minimum points can be developed by considering uniformly loaded feeder.

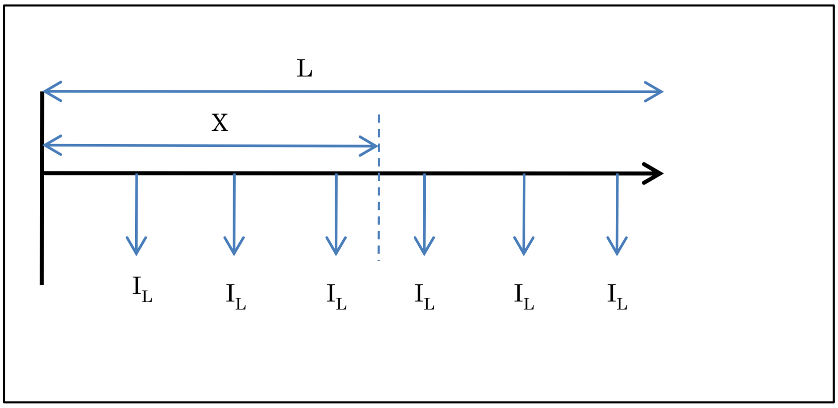

Figure 5-15 : Single line digram of uniformly loaded feeder

Current at point x and loss at point x will be,

$$I_x = (L - x)I_L \qquad \delta R = \frac{\rho}{A}\,\delta x$$

Consider a feeder with uniform load of I_L,

δ loss $= I_x^2\ \delta R$

Total loss $= \int_0^L I_x^2\, \delta R$

$$= \int_0^L (L-x)^2 I_L^2 \frac{\rho}{A}\, dx$$

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

Total loss will be quadric equation; hence number of minimum points is two for a uniformly loaded feeder.

Limit 1 always lies around 30% during the study. That is around half of the customer loading. It was observed that in section 5.3, Limit 1 also have some increment with transformer loading. It is recommended to consider Limit 1 as 30% for safe practice.

As per the section 5.3, Limit 2 varies with the transformer loading level. When total customers' loads are catered by solar PV generation, there will be minimum current flow in the feeder. Hence, Limit 2 always lies around transformer loading level.

Power loss variation in between Limit 1 and Limit 2 was observed in the results. This behavior can explain as a result of location randomness of the solar PV systems.

CHAPTER 6

6 CONCLUSIONS

6.1 Conclusions

High solar penetration in distribution network creates many issues in the LV network. As per the case study done on actual transformer, total power loss tends to reduce with solar addition, after some point again it increases. This issue has to study carefully, with an accurately defined model.

Generalized model developed in this study considering features and properties of actual network to obtain accurate result. Reasonable sample was defined for Monte Carlo study with increasing solar penetration.

Depending on the outcome of Monte Carlo analysis, two limits can be defined as a remedial action to control solar PV penetration. Limit 1 is around 30% of the transformer capacity. Any Solar PV proposal can be approved until the particular transformer reach Limit 1. Limit 2 is around loading level of the transformer. If the Solar penetration level of the transformer is between Limit 1 and Limit 2, further study is to be carried out.

If the Load center of the existing solar PV systems and the load center of the customer loads are in the same feeder segment, new solar PV proposal is acceptable. If not, complete simulation is to be carried out before approval. If the solar penetration level of the transformer exceeds Limit 2 of the transformer, further solar PV proposals cannot be accepted.

The above concluded limits can be practice in utility as remedial action against uncontrolled solar penetration. It will beneficial for utilities to understand and regulate power quality issues associate with solar penetration while providing fair opportunity to install solar PV systems to the customers.

6.2 Recommendation for further studies

The limitations of this study are listed below with the proposals for further studies.

- Variation of the Limit 2 with transformer loading and load center were studied considering two case studies. It could be proved with further analysis.
- Further analysis can be done to study whether there is any relationship between Limit 1 and transformer loading level.
- The study was carried out for steady state condition as snap shots. Further study can be carried out by considering load curves of customer loads and solar PV curves. With that, variation of the power loss during a day, and the effect of holidays, seasonal variations and climate changes can be analyzed.
- The limits were defined for the transformer, because it is easily applicable. Feeder level investigation may provide more accurate limits with conditions.
- This study carried out assuming network is balanced with randomness of load. Studies can be carried out to incorporate network unbalance.
- Similar studies for different parameters such as voltage variation, power quality issues associate with solar PV addition to the grid were done by researches. Integrated study to be carried out to define general limits and conditions.

References

1. Renewables 2019 Market analysis and forecast from 2019-2024, International Energy Agency, February 2020 [Online] Available : https://www.iea.org/
2. CEB Guide for grid interconnection of embedded generators, Sri Lanka, Part-2, pp.19 , December 2000
3. Luis(Nando) Ochoa, “probabilistic impact assessment of low carbon technologies in LV distribution systems”, *IEEE transactions on power systems*, May 2016
4. Pierluigi Mancarella, Luis F. Ochoa, “Low-Carbon LV Networks: Challenges for Planning and Operation”, *PESGM*, July 2012
5. W. K. V. Chan, A. D’Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, “Adaptive monte carlo sampling gradient method for optimization”, IEEE, *Simulation Conference (WSC)*, 2017 Winter
6. H.P.P Amarasinghe, “Feasibility study on distribution transformer based urban grid connected energy islands with distributed generation”, MSc dissertation, Dept. of Electrical Eng, University of Moratuwa, Chapter 5 , January 2018
7. Jeremy D. Watson, Neville R. Watson, David Santos-Martin, Alan R. Wood1, Scott Lemon, Allan J.V. Miller, “Impact of solar Photovoltaics on the low-voltage distribution network in New Zealand”, *IET Generation, Transmission & Distribution*, pp.8 , August 2015
8. D. Chathurangi, U. Jayatunga, M. Rathnayake, A. Wickramasinghe, A. Agalgaonkar, S. Perera, “Potential power quality impacts on LV distribution networks with high penetration levels of solar PV”, *18th International Conference on Harmonics and Quality of Power (ICHQP)*, pp. 2-6, May 2018
9. D Chathurangi, U Jayatunga, S Perera, A Agalgaonkar, “Evaluation of Maximum Solar PV Penetration: Deterministic Approach for Over Voltage Curtailments”, *IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 29 Sept. -2 Oct. 2019
10. D. Falabretti, M. Merlo and M. Delfanti, “Network reconfiguration and storage systems for the hosting capacity improvement,” *22nd International Conference and Exhibition on Electricity Distribution*, Stockholm, pp.4 , June 2013

11. J. Seuss, M. J. Reno, R. J. Broderick and S. Grijalva, “Improving distribution network PV hosting capacity via smart inverter reactive power support” *IEEE Power and Energy Society General Meeting*, Denver, October 2015
12. A.R. Malekpour, A. Pahwa and S. Das, “Inverter-based Var Control in Low Voltage Distribution Systems with Rooftop Solar PV,” *IEEE North American Power Symposium*, September 2013.
13. Electricity Act No.20 of 2009, Sri Lanka, April 2009
14. LECO GIS data and LECO billing database