FEASIBILITY STUDY ON DISTRIBUTION TRANSFORMER BASED URBAN GRID CONNECTED ENERGY ISLANDS WITH DISTRIBUTED GENERATION

H.P.P Amarasinghe

(139500H)

Degree of Master of Science in Electrical Engineering

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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Signature of the supervisor: Date

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

Abstract

Sri Lanka's distribution network has been facing drastic changes during recent past due to the continuous addition of distributed renewable generation into the network. Addition of rooftop solar PV into the low voltage distribution feeders has significantly increased during 2016-2017, due to the government initiative "Surya Bala Sangramaya" on promoting rooftop solar generation.

As a result, in highly populated urban areas, some distribution transformer service areas now have more than 50% of installed solar rooftop capacity, compared to the connected transformer capacity. These transformers export power to the medium voltage network from low voltage side during daytime due to high solar generation and low energy usage inside these service areas. An increasing number of transformers will experience such reverse power flow in near future with the acceleration of promoting rooftop solar programs.

Operating with higher density of rooftop solar in distribution transformer service areas will result in numerous power quality issues and higher distribution losses in spite of the advantages of utilizing household rooftops for solar PV generation.

In this study, a futuristic solution is proposed to effectively utilize the daytime solar PV generation in a single distribution transformer service area itself with the formation of smart grid type operation.

Distribution transformer based smart grid, which operates with controlling mechanisms, loads, rooftop solar and battery storage systems is discussed in this report. This system can be developed and operated as a community-based smart grid that is formed inside the distribution transformer service area with the contribution of the electricity customers.

Other than operating as individual energy customers and energy producers, public can become procumers who operate and control their loads and PV generation together to optimize load flow, power quality and economics in this proposed smart grid.

This research is a preliminary study to identify the possibility of such distribution transformer based smart grid for Lanka Electricity Company Private Limited operation area. Extensive simulations were carried out using Matlab Simulink by modeling the three phase four wire LV network for a single transformer area to identify the present behavior of the LV Network. Then the model was upgraded to proposed future smart grid arrangement. Results on the customer behaviors, load flows and power quality on both normal and smart grid type scenarios are presented for several case studies including the present situation, future expected situation and for the proposed smart grid.

As the outcome of this research, simulated results were obtained for smart grid arrangement inside an actual transformer service area and technical compatibility of the concept is presented to the Sri Lankan urban distribution transformers.

Acknowledgement

It is my great pleasure to express gratitude to those who were behind me in completing my research project.

First, I would like to express my sincere gratitude to my supervisor Dr. Narendra De Silva for providing this visionary concept to study and for his continuous guidance throughout the period.

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My sincere thanks go to my immediate supervisor, LECO system development manager Mr. S.D.C Gunawardhana and all my colleagues at Lanka Electricity Company Private Limited who helped me in many ways during this period. Further I would like to thank LECO IT Department for providing the required network data related to the research.

Last but not least, I would express my heartiest gratitude and love to my wife, my father, my mother and my brother who took a lot of burden and patient, which helped me to complete this work in difficult circumstances.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Description
IEEE	Institute of Electrical and Electronics Engineers
ICT	Information and communication Technology
PUCSL	Public Utilities Commission of Sri Lanka
LECO	Lanka Electricity Company Private Limited
CEB	Ceylon Electricity Board
LV	Low Voltage
MV	Medium Voltage
PV	Photovoltaic
XLPE	Cross-Linked Polyethylene
ABC	Arial Bundled Conductor
GIS	Geographic Information System

CHAPTER 1

1. INTRODUCTION

1.1. Background

The concept of conventional grid evolved with the combination of centralized generation, transmission and distribution. With highly increasing demand and limitations of conventional energy sources, global challenge has arisen on reducing power loss in the grid and integrating carbon free renewable energy sources to the network.

Distributed generation is an onsite electricity generation topology which comes mostly with the addition of small scale renewable energy sources. The advantages of having distributed generation are the ability of utilizing renewable sources, reduction of network energy loss, reduction of fossil fuel usage based electricity generation, ability of de-centralizing the generation and generate electricity nearer to the load. Distributed generation is considered to be a promising alternative energy extraction methodology compared to the large scale centralized power generation.

Since 1980's, electricity grids worldwide continued to modernize by aggregating distributed energy sources wherever possible. Small scale renewables including solar, hydro power and wind were added to the grid at the point of generation at medium or low voltage levels of the network. Sri Lanka commenced its distributed generation facilities in 1996.

The high penetration of distributed energy sources has facilitated increased utilization of renewable energy sources, but also created some challenges to the utilities on maintain stability, reliability and quality of supply. These drawbacks have produced upper limits to the integration of distributed energy to any electrical network. For a grid like in Sri Lanka, where the grid is islanded, small in capacity and having lower inertia, the effect of these drawbacks are significant compared with the larger interconnected grids in the world.

However, the novel concepts of controlling and storing mechanisms can be used with the distributed energy sources to absorb maximum possible energy at the point of generation and at the time it is available. This will remove the limitations on having distributed energy sources and the electricity generated by renewables can be used to achieve economic and environmental benefits in operation.

1.2. Smart Grids

Smart grid is a grid with loads, renewables, smart meters, smart appliances and other energy sources which operates in controlled environment in order to utilize and manage the energy and consumption in a most efficient, economic and environmental manner.

According to various international institutes including IEEE, in summary the concept of smart grid can be defined as “Combination of modern power system technologies, power electronics, ICT, services, and regulatory structures which enable sustainable management of environmental impacts in the power sector”.

For a grid to become smarter, communication and controlling of each device shall be coordinated in a way to utilize the renewables in an optimal manner without affecting the quality of supply and operate subjected to economic, technical and environmental constraints.

The scale of the smart grid may vary from entire grid to a small section of consumer premises depending on what is being controlled and for which purpose. Smart grid technologies are rapidly evolving and the concept is being used for energy efficiency, improve the quality and reliability of the network and managing renewables.

1.3. Sri Lankan Distribution Network

The distribution network of Sri Lanka is almost all overhead, operates in 33 kV and 11 kV medium voltages and 400 V/ 230 V low voltage.

As a regulator in Sri Lankan energy sector, PUCSL has issued five licenses for electricity distribution in Sri Lanka. Out of these five, CEB has four and one license is issued to LECO. PUCSL has provided guidelines and regulations to the utilities on maintaining quality of supply and set goals on reducing energy losses in the network.

The structure of the country's distribution network has not been changed significantly from its formation in early 50s until recent past. The conventional distribution network included only the typical items such as primary substations, MV feeders, distribution Transformers, low voltage feeders, protection and metering mechanisms etc. The power flow was vertically downwards from grid substation to the customer premises through primary substation, MV network, distribution transformer and LV network.

However, the things are now being changed with the rapid addition of distributed energy sources such as mini hydro, wind and solar to the MV and LV distribution network. As a tropical sun shining country and an island surrounded by sea, Sri Lanka has a salient capability and capacity to absorb more solar and wind additions in country's perspective if the electricity grid has the ability of integration.

With the government involvement in increasing renewable generation and with increasing global economic and technical feasibility in renewable energy extraction, distributed renewable sources are now being connected to the Sri Lanka's distribution network in a considerable rate.

With these new additions of unpredictable, fluctuating sources to the conventional distribution network, now it is time for utilities to rethink on the arrangement, controlling and operation of their distribution network.

The network administrator has to reduce the technical impacts imposed by these renewable additions while maintaining the quality of supply in the electricity grid. Therefore solutions may require to extract whatever possible renewable generation at the time of generation and its generation rates without affecting to the quality and stability of the grid.

1.4. Lanka Electricity Company (Private) Limited

LECO is a distribution utility operating in southern-western costal belt of Sri Lanka under the regulation of PUCSL. The main operational objective of LECO is maintaining a quality electricity supply while reducing the loss in the distribution network.

LECO service area consists of highly populated urban townships near Colombo main city, where large number of high end customers are concentrated in geographically small areas. LECO distribution voltage is 11 kV and the distribution network arrangement is maintained in a “small transformer-small feeder” basis.

The practice of “small transformer-small feeders” concept followed by LECO have increased the number of distribution transformers in the network and reduce the lengths of LV feeders. This has reduced the number of service connections added to a single transformer or a single LV feeder and reduced the voltage drops and line losses in the network.

1.5. Rooftop Solar Sri Lankan Context

Small scale distributed solar is a key player of renewable energy sector in the world. The drastic reduction of panel prices and improving technology of appliances related to rooftop solar generation have made solar generation affordable to many of the potential customers during past decade.

The integration of grid connected rooftop solar to the national grid was initiated with the introduction of net metering concept to Sri Lanka in 2010. Net metering is one of the world famous method that enable customers to connect their own on-site generation system to the utility grid and receive credits on their electricity bills for their own renewable generation in excess of their electricity consumption.

With providing more opportunities to the customers, government introduced payment method for rooftop solar along with the net metering in year 2016. In this initiative, two other schemes have been introduced named as net plus and net accounting. In this schemes utilities pay for the customers on their excess electricity generation at the end of the month.

These encouragements have led to the addition of small scale solar PV installations into Sri Lankan distribution network in large numbers within a very small time period. The initiative is highly successful and within just more than one-year time, total installed solar capacity in Sri Lanka had exceeded 100 MW limit.

1.6. Advantages disadvantages

Addition of rooftop solar to the distribution network have made advantages and disadvantages to both utility and consumers.

1.6.1. Advantages to the utility

1. Reduction of line losses due to power generation at the point of consumption
2. Reduction of fossil fuel emissions
3. Reduction of day peak of the load profile
4. Increase the factor of renewable energy generation in the grid

1.6.2. Disadvantages to the utility

1. Effect to the stability of the network by heavy fluctuations in the solar generation profile
2. Effect of uncertainty of generation to planning and forecasting
3. Deviation from the regular load flow
4. Imbalances occur in the phases due to single phase inverters
5. Exceeding the voltage regulations due to higher addition of solar along the feeders
6. Effects due to harmonics generated by the inverters

1.6.3. Advantages to the customer

1. Capability of using free rooftop space for electricity generation
2. Reduction of energy costs
3. Contributing to carbon free green initiatives as a social responsibility

1.6.4. Disadvantages to the customer

1. Requirement of having capital cost for electricity
2. Longer payback periods
3. Cannot utilize the solar power during the grid failure due to anti islanding protection

1.7. Limitations

Even though solar radiation is unlimited and total available rooftop area is much higher than which is already utilized, there are several technical and economic factors which limits the integration of rooftop solar.

Technical limitations arise on adding solar capacities while trying to operate with maintaining the supply regulations and minimizing the losses. Economical limitations arise with the cost of installations and pricing methodology for solar PV by the utility.

Limitations to the rooftop solar additions which appear in both technical and economical manners are summarized below.

1.7.1. Technical Limitations

Solar energy generation is directly proportional to the real time solar radiation which is subjected to very high and speedy fluctuations. Additions of these fluctuating sources in higher numbers may affect the grid stability by a considerable amount.

1. It is an advantage that the rooftop solar generation is available at the point of customer load and hence reduce the network line loss by removing the losses occur to bring power from the centralized generation to the customer doorstep.

   Due to the low domestic loads at daytime where higher solar generation is available, rooftop solar generation exceeding customer loads in distribution transformer LV networks will result a reverse power flow.

   This may again increase the LV line losses due to higher backwards power flow in LV lines. So it is a debating argument whether to allow this backward line loss by accepting more solar additions or introduce limitations to the maximum allowable rooftop solar capacity for a single LV feeder/ transformer.

2. Solar inverters provide energy to the existing grid in day time when the solar generation is available. With the addition of large number of solar inverters

along a single feeder, voltages along the feeder may get increase during daytime.

This is an advantage up to some extent, but with large number of installed solar PV, feeder voltages exceed the upper limits of allowable system voltage.

3. All small scale rooftop solar inverters available in single phase. LV network is balanced up to an extend by connecting single phase customers dividing into three phases along the feeder. However, the addition of single phase inverters in different sizes and in different phases discretely, leads to high unbalances in LV feeders during day time. This has also lead to flow high neutral currents in the neutral conductor and increase the voltage of the neutral.
4. The present integration of rooftop solar has no battery backup systems and operates with anti-islanding protected mode. Hence when the main grid is down, inverters cannot operate in islanding mode and maintain the supply.

1.7.2. Economical Limitations

1. The main financial limitation for a rooftop solar installation is simply the higher capital cost and the time taken for the recovery of the investment. Even with the present tariff structures, the payback period of the capital investment may longer than 4 - 5 years or more for customers.
   Since the Sri Lankan domestic tariff structure is not cost reflective and the environmental effect is not taken into consideration, financial limitations arise due to the present payment methods may not be the real economic picture of the value of adding roof top solar.

In summary, high fluctuations in solar radiation results fluctuations in solar generation and with the large number of solar additions, the effect of these fluctuations may impact on the stability of the network. Higher penetration of rooftop solar may result to a voltage increases in LV networks and the backward flow of power may occur high line losses. Unbalanced PV additions in three phases may increase the neutral conductor voltage and high neutral currents.

Due to above reasons the maximum possible network addition of rooftop solar for certain transformer, feeder or for entire grid have to be limited in a systematic manner or utilities have to introduce controlling managing and storing methods along with the solar additions to the network.

1.8. Small scale Energy Storage

Implementation of rooftop solar as a distributed renewable source has become viable due to reduction of cost of related equipment during recent past. This is mainly due to the continuous technical innovations and the involvement of large scale commercial manufacturers.

But still the cost of battery backups are not affordable for many of the customers, even though the rooftop solar with batteries make the solar PV installation more independent and less trouble to the grid.

Now with the involvement of giant companies like TESLA, investing on innovative battery technologies and manufacturing affordable batteries for specific appliances including the batteries for households, it can be expected to change the market of batteries in near future.

Hence, integration of battery backups with solar may be the next level of controlling and optimizing methodology for distributed renewable generation. Selecting the suitable amount of battery capacity for a grid connected solar capacity is a challenging task and highly depending on the required outcome. With the properly sized battery storage and control mechanism, renewable integration to the network can be managed smartly.

1.9. Motivation

It is clear that the maximum allowable rooftop solar installations have upper limit due to technical restrictions occur on stability and quality of the supply. In Sri Lanka, with the encouragement of government and the introduction of new tariff structures, rooftop solar additions had a rapid growth during last few years and the trend is still ongoing.

Even though there is no defined upper limit for the rooftop solar as a country, issues occur due to high penetration of solar is now can be seen when study the distribution transformers with large number of net metering customers available.

Highly residential LECO service areas like Kotte, Maharagama and Nugegoda , distribution transformers are now available with exporting energy to the MV network during daytime due to large amount of rooftop solar installations in each transformer service areas.

Other than limiting of rooftop solar installations due to technical restrictions, it is worthy to find possible alternatives of controlling and managing these carbon free energy addition to the grid.

As one of the alternative concept on managing and controlling the rooftop solar, community based smart grid is introduced and feasibility on such kind of smart grid for Sri Lankan urban distribution transformer service area is presented in this report.

CHAPTER 2

2. PROJECT OVERVIEW

2.1. Research Study

Research presented in this report is a feasibility study carried out to find the possibilities of having distribution transformer service area based smart grid. The scope was defined to study the concept for urban areas of Sri Lanka, where high penetration of rooftop solar installations are already available and more potential customers are ready for further installations.

Presented smart grid methodology controls the real time power flow through the distribution transformer and optimizes the utilization of rooftop PV generation inside the distribution transformer service area using decentralized battery storages.

Controlling the battery charging and discharging is carried out with the centralized controller by monitoring in-out power flows through the transformer and communicating with the distributed inverters.

The final objective is to completely utilize the energy generation from rooftop PV inside the transformer service area with contributing to the grid stability quality and cost concerns.

To study this futuristic scenario, the research study was carried out in three phases.

1. Study the present LECO network related to the rooftop solar installations, customer behaviors and distribution transformer characteristics in urban areas.
2. Model an actual urban LECO distribution transformer service area using MatLab Simulink and simulate for present and future expected scenarios.
3. Update the model for proposed smart grid design and simulate for different cases.

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

2.2. Scope of the Project

As an methodology for optimize the generation from rooftop solar, this research concept is applicable to Sri Lanka’s urban distribution transformer service areas due to the uniqueness in the urban distribution network in Sri Lanka. For all the analysis, data related to the LECO operational area was used and LECO distribution transformers and customers were considered.

For the analyzing purposes, simulation model of an urban distribution transformer service area was developed using MatLab Simulink which represents the present actual situation of the transformer service area. This model is a three phase four wire load flow model that can analyze the behavior of transformer, lines including neutral conductor characteristics, loads and solar PV available in LV feeders.

The model was included the transformer, feeders, customer loads and solar PV. Model was simulated for one complete day using actual data of solar generation, customer loads and transformer load curves which are available in 15 minutes time intervals.

Then the model was upgraded by increasing the loads and PV generation as expected in near future. Battery backups and centralized controlling methodology to the batteries were modeled as a part of the proposed smart grid concept. Results including load profile of the transformer, voltage profile of the feeders, battery charging and discharging curves were obtained by simulating to achieve several objectives including the sizing of the battery.

2.3. Objectives of the Study

The objectives of the study are listed as below.

a. Analyze the available energy sources, loads and battery backups to formulate smart grid type energy island in a distribution substation area.
b. Feasibility study on developing self-controlling distribution substation based smart grid by optimizing distributed energy resources, loads and storage.

2.4. Methodology

Methodology steps of the study are listed as below.

a. Study the LECO network and identify thepotential distribution transformers to be operated as islanded smart grids in LECO network.
b. Analyze the behavior of the energy sources, customer load curves and transformer load curves in a selected potential distribution transformer in LECO operational area.
c. Modeling the distribution substation including the loads and rooftop solar PV.
d. Upgrade the model for simulating distribution substation based smart grid.

2.5. Distribution Transformer Based Smart Grid

2.5.1. LV distribution network

Arrangement of conventional LV distribution network starts from transformer LV terminals and ends by customer meter point. LV feeders are three phase four wire radial feeders. LV neutral is earthed by transformer end and each LV feeder end.

Power flow of the feeders is always in downwards from transformer to customer via LV feeders and service conductors since there is no electricity generation available in the LV side. Customer meter is measures uni-directional energy usage of the customer loads.

The Figure 2.1 represents the typical arrangement of LV distribution network starting from the distribution transformer.

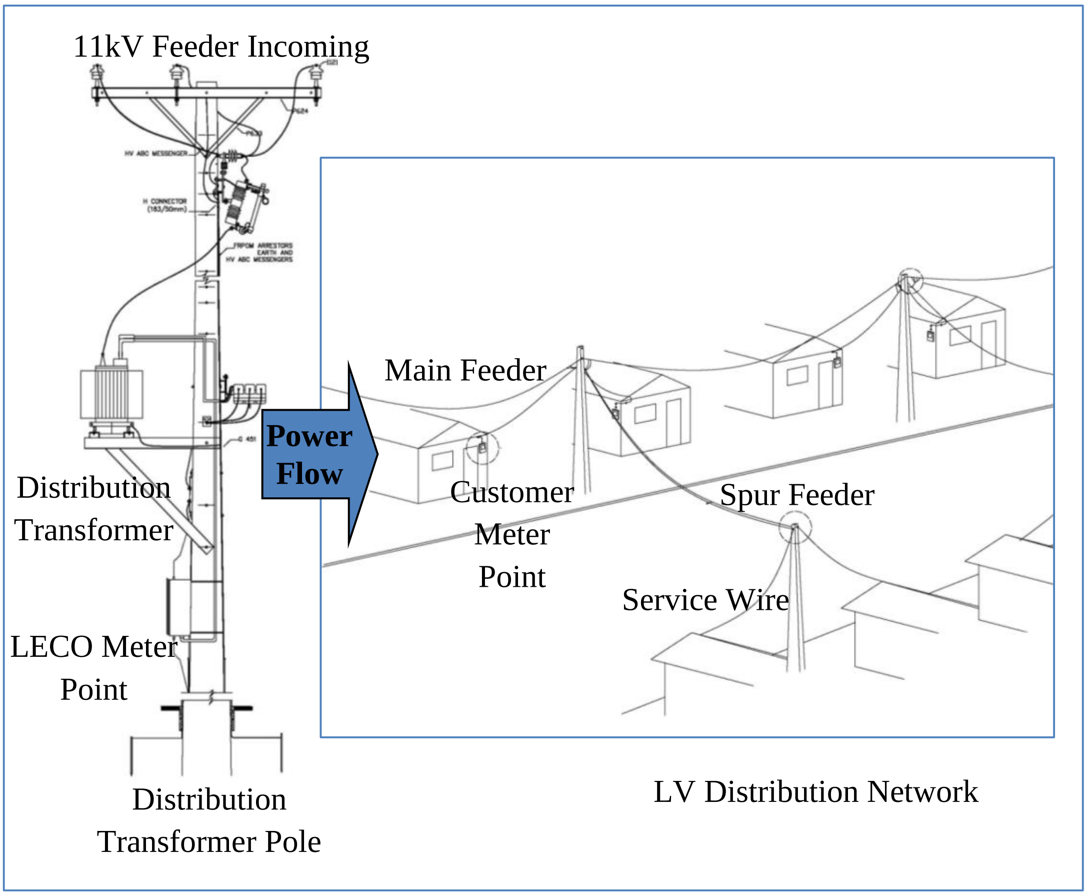


Figure 2.1 Arrangement of the conventional LV distribution network

2.5.2. LV distribution network with Rooftop Solar

Rooftop solar additions have installed at customer premises and connected to the LV network through the customer meter point as shown in Figure 2.2. These PV installations have not made any significant changes in the physical arrangement of the LV network instead of replacing the energy meter by import/export energy meter for billing purposes.

Excess electricity generation during day time can create reverse power flow in feeders when the instantaneous solar generation is higher than the customer consumption.

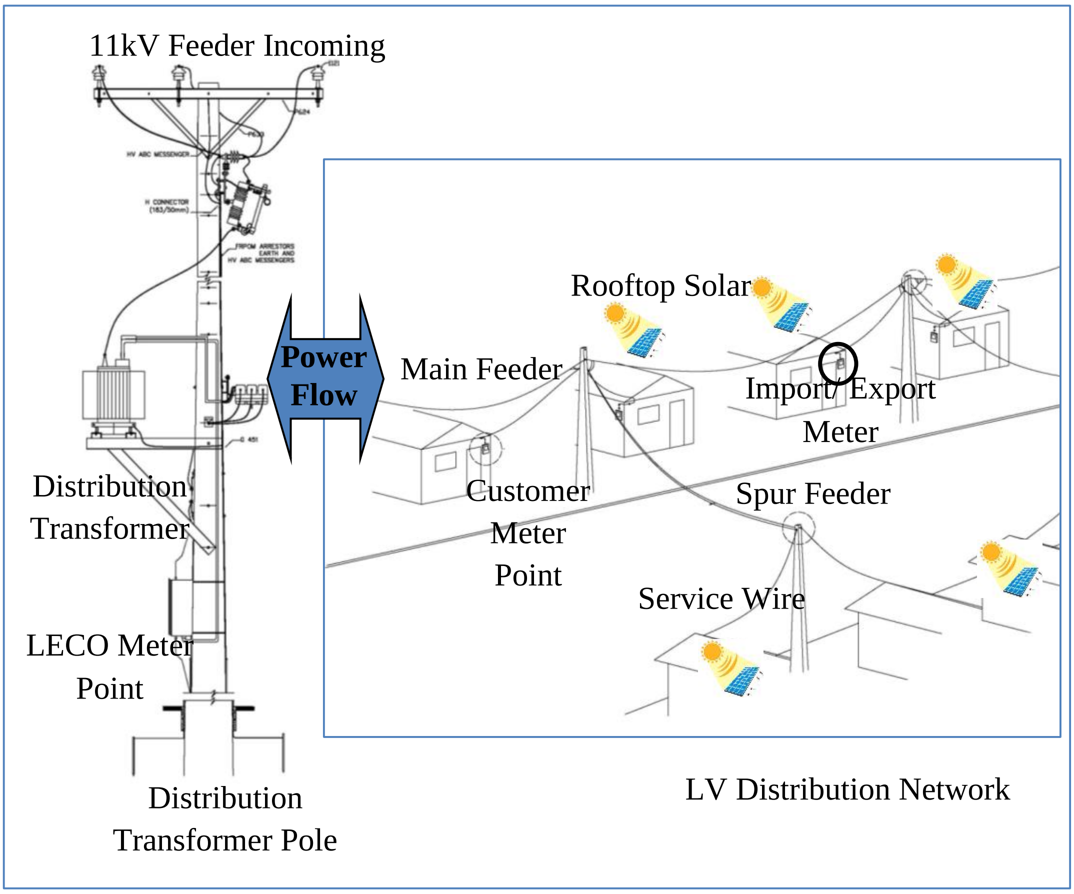


Figure 2.2 LV Distribution Network with Rooftop Solar

2.5.3. LV Network Based Smart Grid

Smart grid formulating in urban distribution transformer service area may include loads, energy sources, load controlling mechanisms, energy storage capabilities, smart grid control and point of connection to the main grid as shown in Figure 2.3.

In urban distribution transformer service areas, most loads are domestic. Available distributed energy sources are rooftop solar PV. There may be small scale diesel generator units like backup generators can be present. Loads can be controlled using smart meters which can communicate to the main controller and have the facilities of connecting and disconnecting the load or further have the capability of connecting and disconnecting selected individual appliances in households.

Storage systems can be battery backup units specifically used for the smart grid or it can be electric vehicles which have the capacity of utilizing the vehicle battery with V2G technology. Main grid available from transformer side and the centralized controller is available with communication with each load and source.

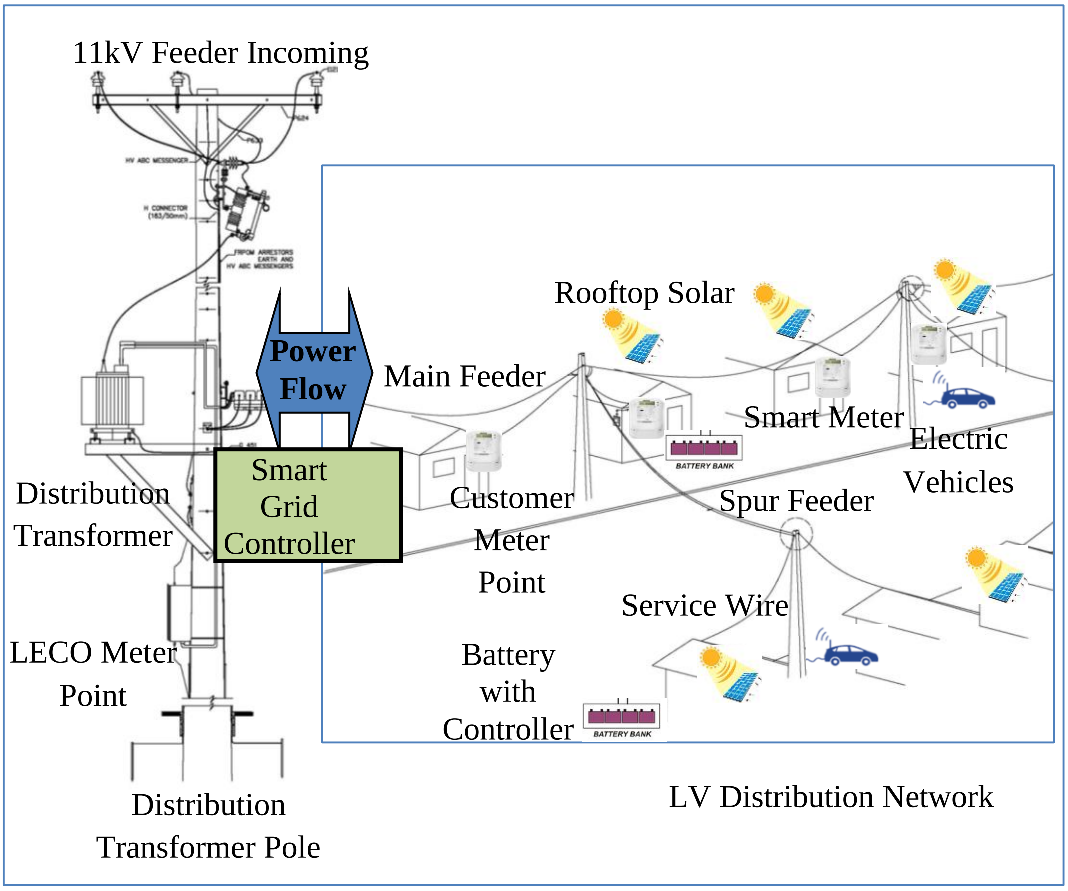


Figure 2.3 Distribution Transformer Based Smart Grid

Figure 2.4 shows the basic block diagram of the proposed LV smart grid representing available appliances, devices, power flow directions and communication.

In this smart grid structure, assets of the smart grid are owned to both individual customers and to the utility. Operation is controlled by the centralized operating mechanism which decide the charging or discharging of batteries and controlling loads.

By such controlling mechanism, it is expected to mitigate the effects on solar fluctuations, quality issues related to voltage and line losses by intelligently controlling storage capacities and controllable loads.

The research simulation was limited to the distribution transformer service area based smart grid simplified with the availability of non-controllable loads, rooftop solar and battery backups only. The study carried out to design the simulation model for present LV distribution network using actual data and upgraded this model to proposed smart grid arrangement for sizing and controlling the battery backup to achieve specific outcomes.

The simplified LV network arrangement considered for the research is shown in Figure 2.5

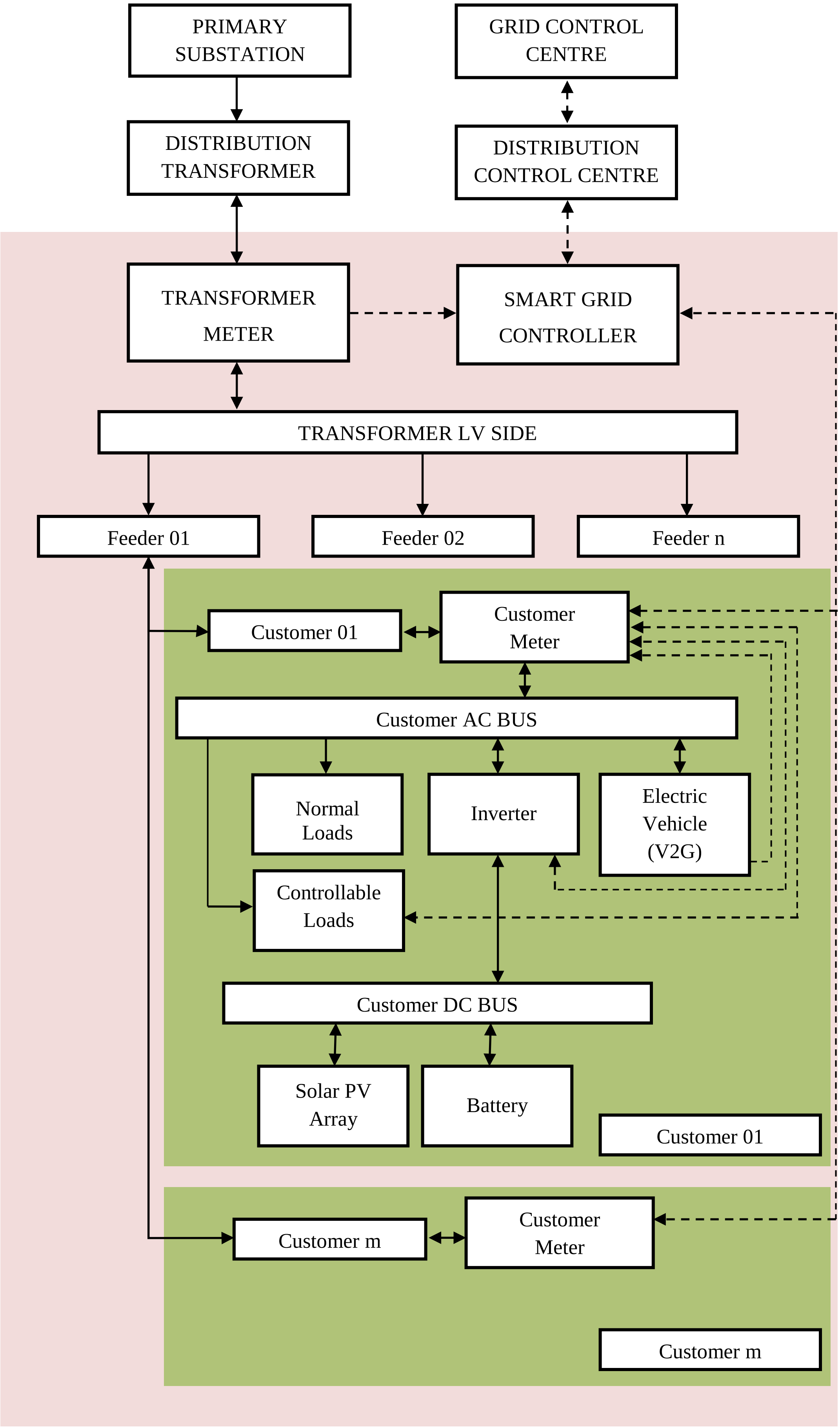


Figure 2.4 Line Diagram of the Smart Grid

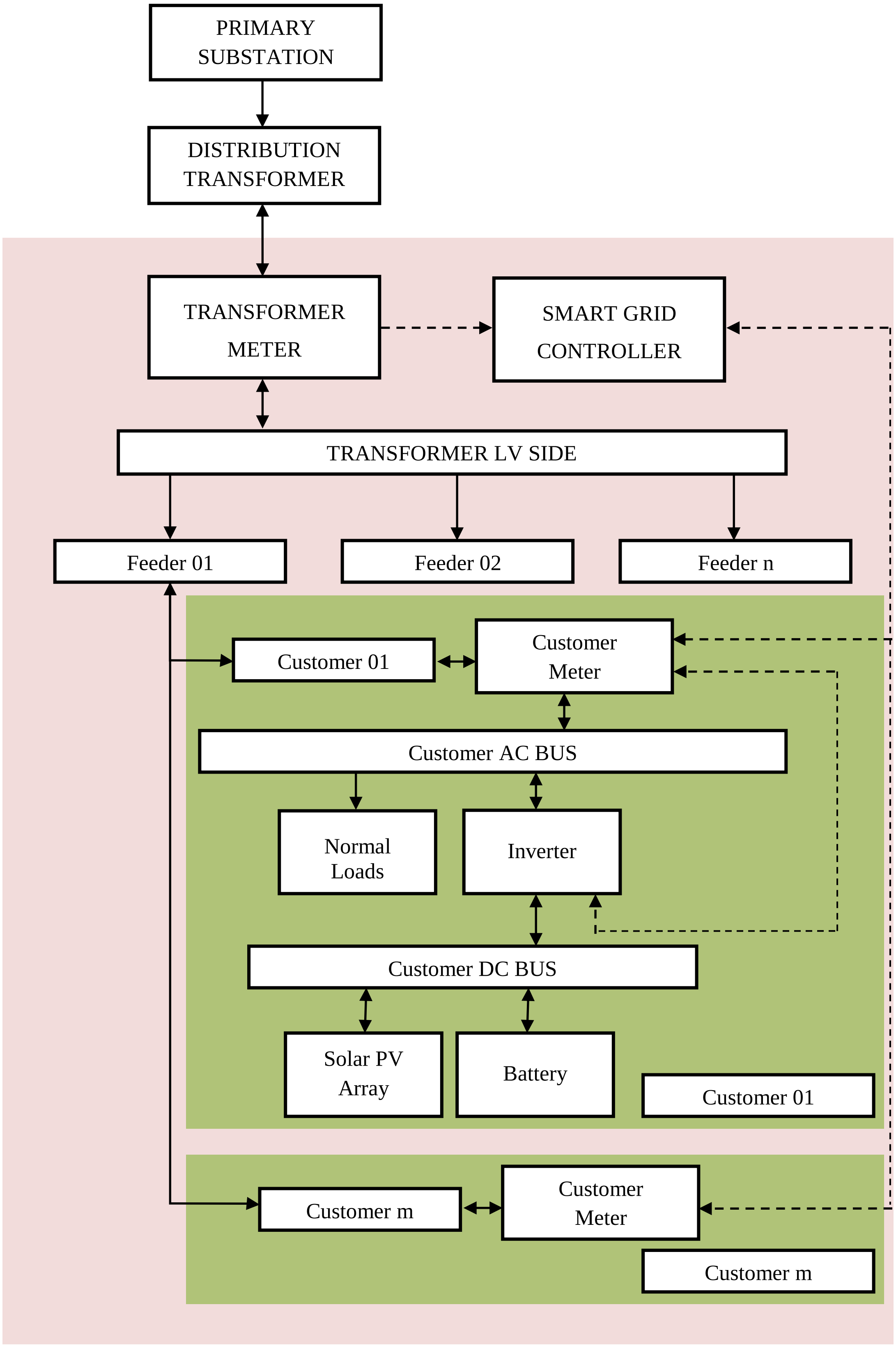


Figure 2.5 Simplified Smart Grid Arrangement

3. EFFECT OF ROOFTOP SOLAR PV IN LECO NETWORK

3.1. LECO Distribution Network

LECO network is established in Sothern- western costal belt of Sri Lanka. LECO serves for around 545,000 customers as shown in Figure 3.1 and the LECO operating geographical area includes many of the Colombo suburbs such as Nugegoda, Kotte, Moratuwa, Kelaniya, Rajagiriya and Panadura, where the customer density is very high.

Figure 3.1 LECO Operational Area

LECO purchase electricity from Sri Lankan transmission utility (CEB) and sell to the customer base in LECO service area.

LECO medium voltage network is 11 kV radial operating network constructed in the form of ring type feeder design. This 11 kV feeders are routed mostly along road corridors and other such access routes. Three phase four wire low voltage system comprises of approximately 150-200 A rated feeder circuits with 15 A, 30 A and 60 A service connections.

Transformers used by LECO are three phase 11 kV/ 415 V double wound, Dy11 hermetically sealed type with the capacities of 100 kVA, 160 kVA, 250 kVA, 400 kVA and 630 kVA. Only the transformer sizes up to 250 kVA are used in LECO as distribution transformers.

LV feeders are constructed by ABC conductors. Four core and twin service conductors are used as service conductors. The general summary of LECO network is tabulated in Table 3.1.

Table 3.1 LECO Network Summary

LECO Network Summary	
Total Number of Customers	545,000
Total Number of Branches	7
Total Number of CSC	23
11kV line length	1,070 km
LV line length	3,500 km
11kV/400V substations - Total	4,097
11kV/400V Distribution Substations	2,371
11kV/400V Distribution Substations Capacity	374,528 kVA
Total Energy Sales in MWh (2017)	1,518,000 MWh
Total Solar Exports to the Network (2017)	13,724 MWh
Average Distribution Loss in the Network	4.0%

As per the past data domestic customer contribution to the LECO network is around 80% in number of customer vise and over 40% in total energy consumption vise.

This indicates that the any implementation on domestic consumer base has the ability to affect the network in significant manner.

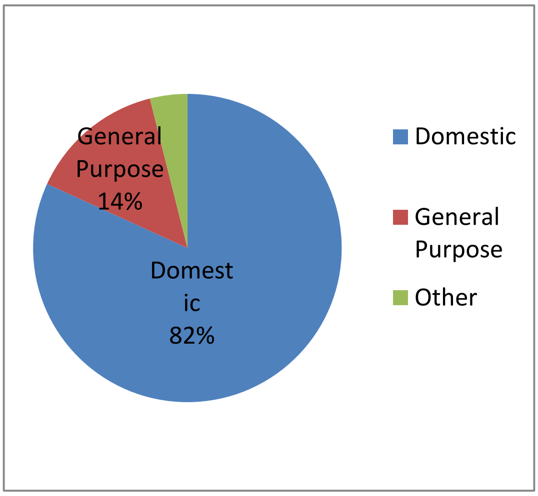


Figure 3.3 LECO Customer Mix

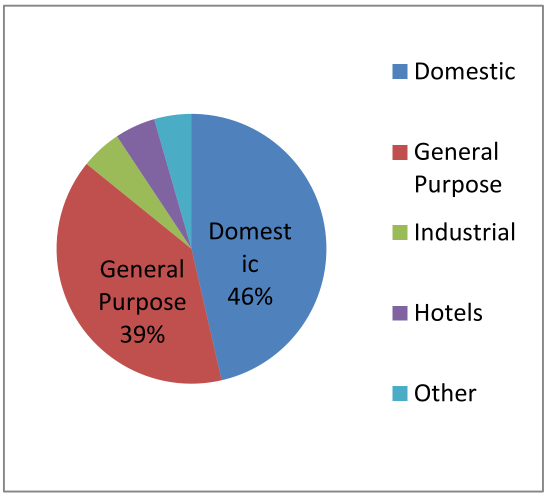


Figure 3.2 Energy Mix

3.2. Rooftop Solar Installations in LECO Area

Addition of rooftop solar PV in to the utility grid has initiated in 2009 with the introduction of net metering scheme to Sri Lanka. But the significant growth of rooftop solar PV customers and capacities were recorded during last two years with the implementation of Surya Bala Sangramaya, the government initiative on promoting rooftop solar.

While total Sri Lankan installed rooftop solar PV capacity exceed 100 MW, total installed rooftop solar PV capacity in LECO service area reached to 10 MW in the end of year 2017. Growth of number of rooftop solar PV customers and installed rooftop solar PV capacities in LECO service area is presented in Figure 3.4.

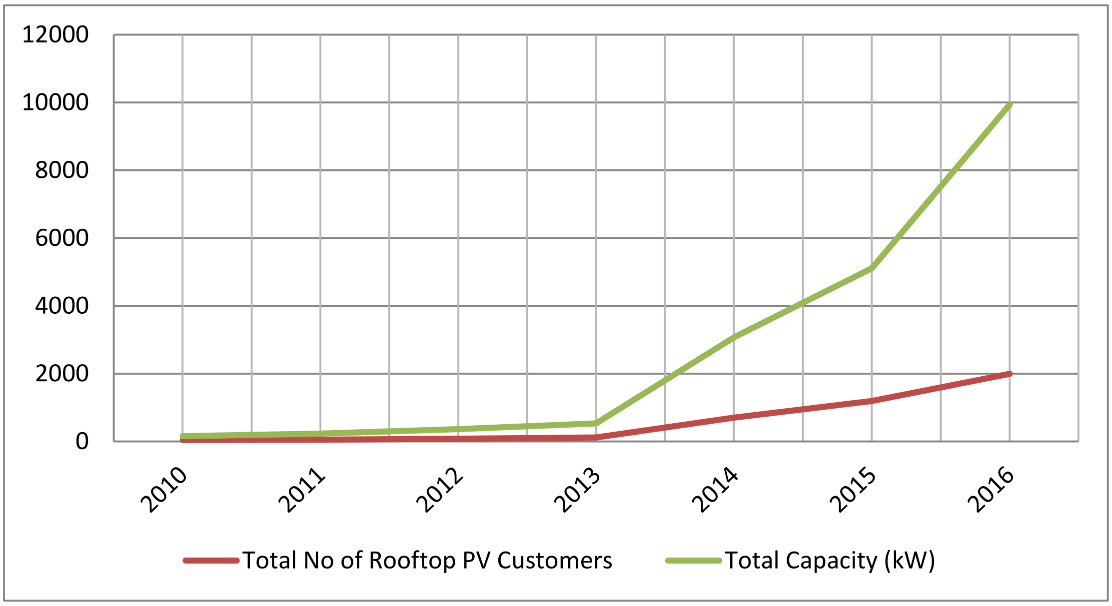


Figure 3.4 LECO Rooftop PV Customer/ Capacity Growth

3.3. Statistical Analyze on LECO Rooftop Solar

Statistical analyze has been done using data related to the rooftop solar customers in the LECO service area to identify the behavior of the rooftop solar additions in urban Sri Lankan electrical network. Results of the analysis are summarized in below categories.

3.3.1. Contribution of Rooftop Solar to the network

With the total installed rooftop solar capacity of more than 10 MW, 13,323 MWh of excess energy has been exported to LV network by all rooftop solar installations in LECO area during year 2017.

The excess energy export to the grid at the metering point is the difference between instantaneous generation and customer load at a particular time. The amount of annual rooftop solar energy exports are still around 1% of the annual energy purchase by LECO from CEB primary substations.

3.3.2. Propagation of rooftop solar customers in distribution transformers

As a distributed energy source, customer selects the capacity of the rooftop solar PV depending on several factors. Payback period of the capital cost of rooftop solar PV installation is defined by the customer tariff category, customer load and plant capacity.

With the statistics of installed solar capacities by LECO customers it can be seen that more than 85% of solar PV installed customers have panel capacities less than 10 kW in size. The highest numbers of installations are in the range of 3 kW to 6 kW.

Out of 10 MW of total installed solar PV capacity in entire LECO area, 2 MW from the installations with panel capacity higher than 10 kW. Many of these have installed by bulk customers who have dedicated transformer for the service connection.

Other than this 2 MW installations all the other 8 MW of PV comes from the installations less than 10 kW panel capacity in size. Hence, 80% of installed solar capacity has obtained from the small scale solar installations mostly less than 10 kW. The number of customers compared with each installed solar PV capacity is presented in Figure 3.5.

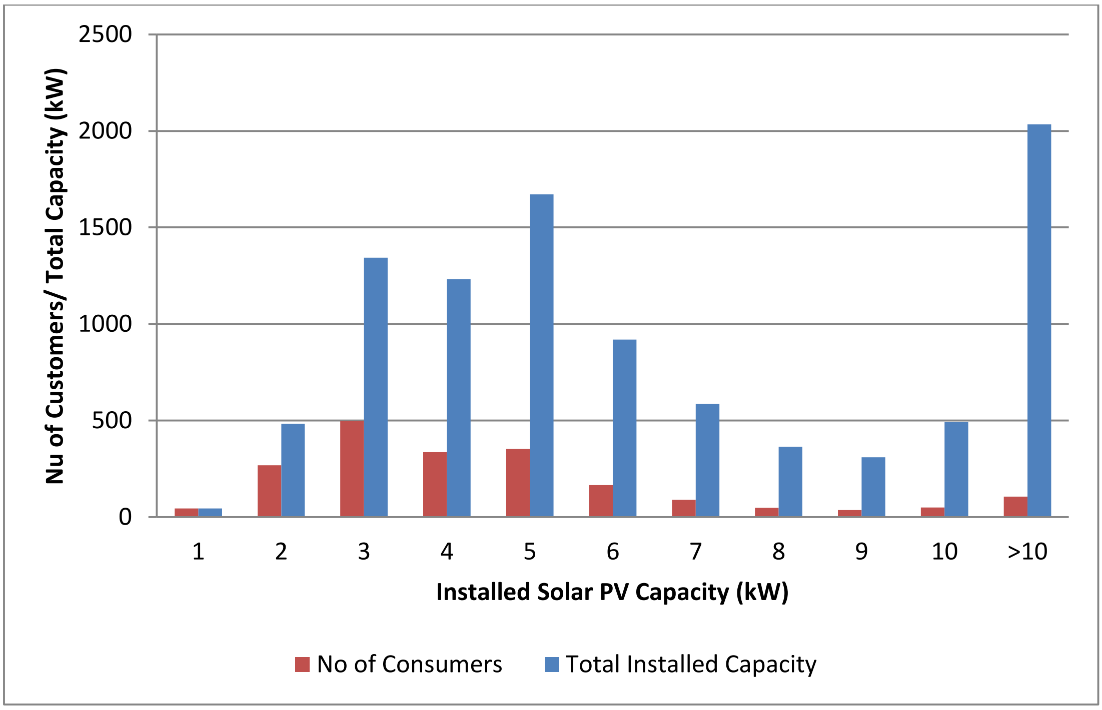


Figure 3.5 Installed capacity vise number of customers/ total capacity

Further, out of 2,300 distribution transformers operate in LECO service area, around 950 transformers are available with rooftop solar customers. Most of these transformers are located in highly urban town areas where still many of the potential customers are available for new solar installations in future.

According to these statistics, it can be clearly seen that most of the solar PV installations are small scale installations in capacity vise and they all are connected in small number of transformers located mostly in urban areas. This shows that, rooftop solar PV penetration is highly distributed by size but concentrated to small geographical areas.

3.3.3. Transformers with highest solar densities

The issues discussed in previous chapters related to higher solar PV additions, are initially appear in the distribution transformers with highest rooftop solar PV installations. Out of 950 distribution transformers where rooftop solar customers are now available, the density of solar PV installations taken as percentage of rooftop PV capacity to the transformer capacity is presented in the Figure 3.6.

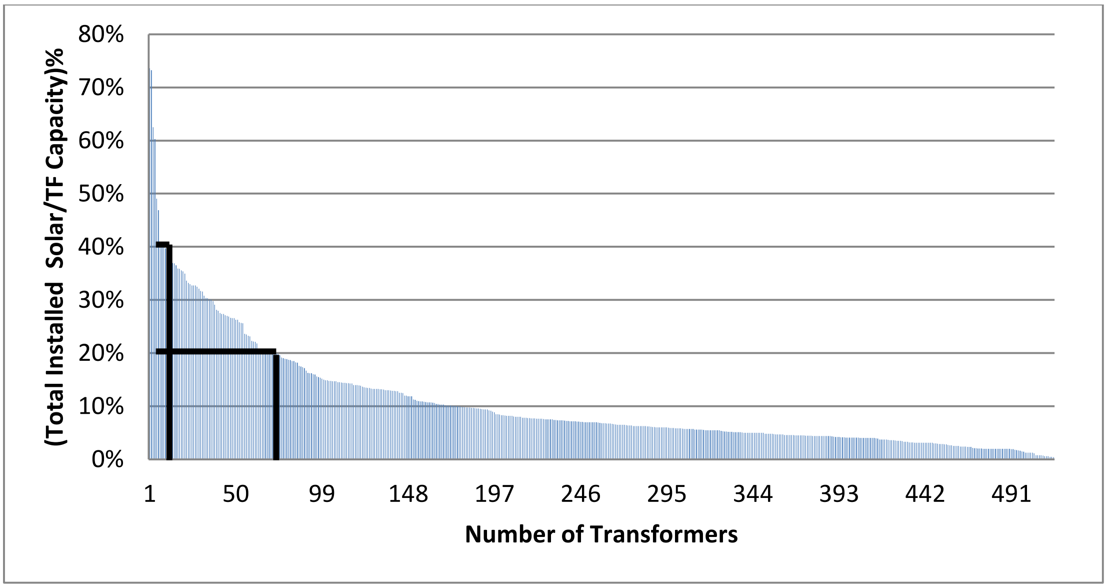


Figure 3.6 Installed Solar PV Densities in Distribution Transformers

There are around 75 transformers with solar installations available in the transformer service area exceeding more than 20% of the transformer size. The highest numbers of solar additions are available in 15 transformers where the total installed solar capacities are exceeding 40% of the transformer capacity.

3.4. Selected Transformer for Study

This research study required a real time simulation of the distribution transformer including rooftop solar installations. There were several transformers available with the high penetration of rooftop solar installations in LECO area which were suitable for this study.

A 250kVA transformer located in Kotte area was selected for the study considering the following factors. The detail of the selected transformer is shown in **Error! Reference source not found.**.

a. Located in a heavily urbanized area
b. Higher number of high end domestic customers were available in the transformer area
c. Availability of around 120kW of total solar installations
d. Domestic customers were metered using smart meters which are available with customer load profiles

Table 3.2 AZ0228 Transformer Details

LECO Transformer Code	AZ0228
Transformer Capacity	250 kVA
Location	Epitamulla Road - Kotte
Total Number of Pole Nodes	120
Total Number of Customers	502
Domestic	320
General Purpose	21
Total net metering Customers	24
Total Installed Solar PV Capacity	121 kW

Imports and exports of electrical energy for one complete day in selected AZ0228 distribution transformer in 15 minutes time intervals are presented in Figure 3.7. Here the import energy is the energy flows from transformer MV side to LV. Exports are the excess energy generated in the LV network flow from transformer LV side to MV.

During day time electrical energy import by the utility grid has reduced due to reduction of domestic loads and increasing solar generation in rooftop solar PV installations. During midday where solar radiation is higher, there was an excess energy generation inside transformer service area which are exported to the MV network.

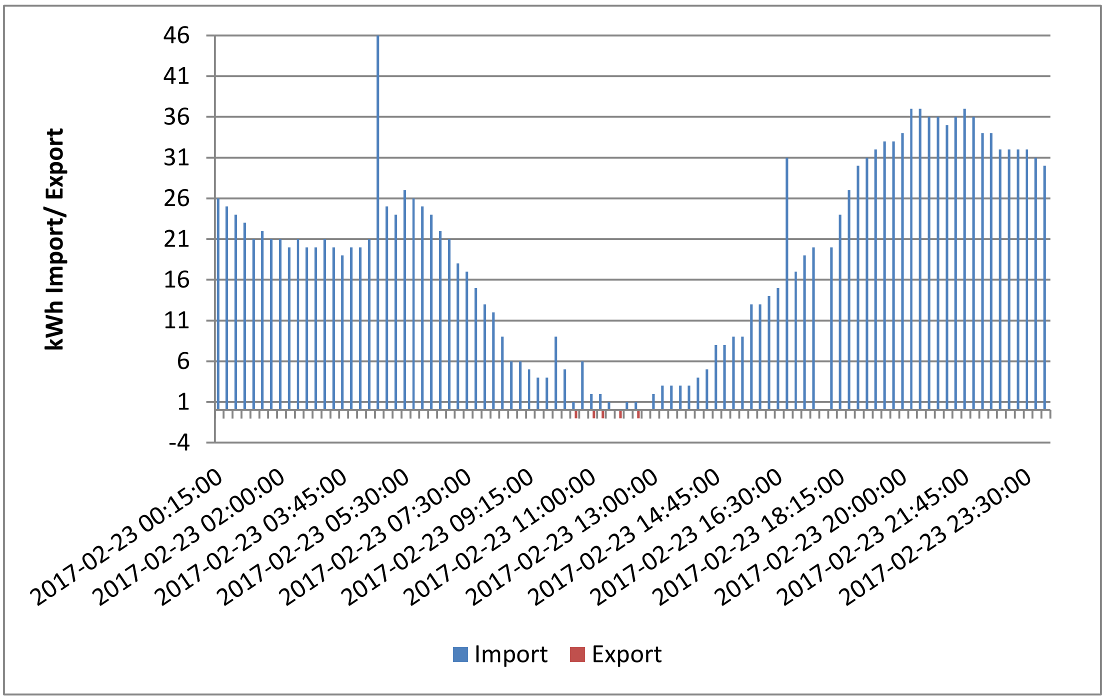


Figure 3.7 One Day Profile of kWh Import/ Export – AZ0228 Transformer

The geographical area of the transformer was covered by 3 main LV feeders and several spur feeders. Map of the selected transformer and the transformer service area are extracted from LECO GIS maps with line and pole details as shown in Figure 3.9.

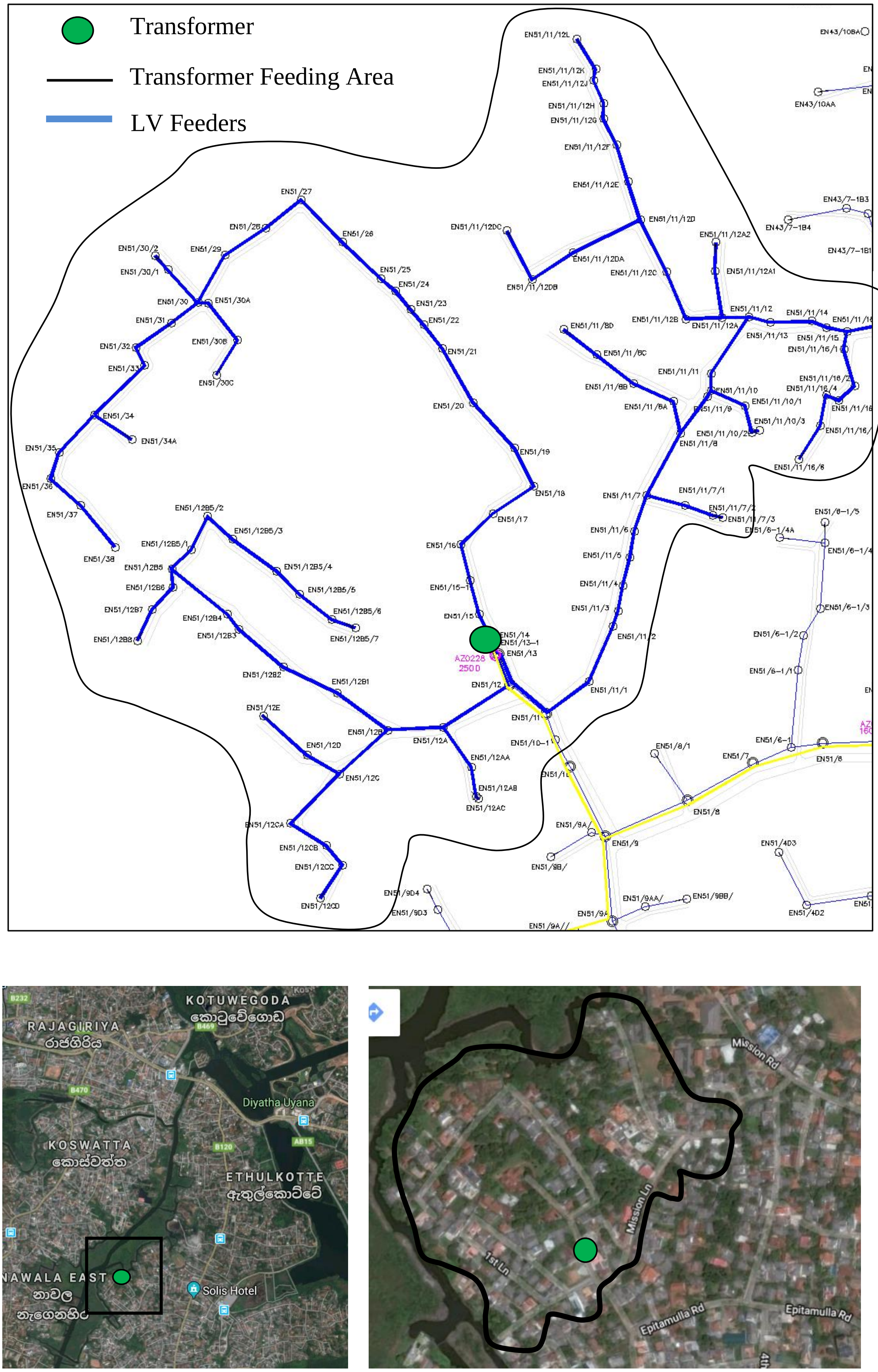


Figure 3.8 Geographical Area Map for AZ 0228

CHAPTER 3

4. Modeling the Network

4.1. Matlab Simulink

MatLab Simulink is model base design and simulation software which provides graphical environment to design and simulate. The software is available with inbuilt block models that are the mathematical representations of actual basic components which can be graphically connected in Simulink environment to create more advance models and systems.

Simulink Simscape Simpowersystems is the extensive tool related to modeling power system applications in Simulink. SimPowerSystems can be used for load flow problem analysis and in this research Simulink SimPowerSystems model was used to analyze the LV load flow of the distribution transformer service area for complete one day time period.

Domestic loads, solar PV, transformer, LV Feeders, batteries and other related equipment are modeled and interconnected to have the complete system model for entire transformer service area.

4.2. Literature Review

LV network simulation methods have become a prominent study area with the addition of distributed sources and smart grid concepts. Solving methods for four wire load flow and the analysis on various types of LV smart grids are available in literature.

Ciric [1] has suggested a method of solving four wire LV load flow with the presence of the effects by neutral wire and ground. Methods used in [1] for model a line section as impedance matrix and load as constant current source was used to develop Simulink models of each in this research.

The elaborated method of the [1] presented by Alam [2] with including rooftop solar PV to the four wire LV load flow by modeling solar PV as constant current source. This model has used to study PV impact on the network with the practical test network results of Australian distribution feeders. Simulink model developed in this research for rooftop solar PV was adopted from this.

However the studies [1] and [2] have not used simulation softwares and the results were obtained by solving the load flow algorithms.

Benoit [3] presented the advance load flow results in a network which includes the renewables, loads and battery backups. The operation methodology of the network was not exactly a smart grid but the controlling of the battery and loads were taken into consideration.

In each of the above studies results were obtained to study the impact on the neutral conductor, voltage regulation and losses in the network. In [3] optimizing the power flow to reduce the impact has also been discussed.

4.3. Mathematical Representation of LV Network Model

In power systems related studies, three phase balanced load flow representation has been considered most of the time due to simplification of calculations and analysis.

In most of the three phase four wire LV network models, mathematically simplified modeling has been used neglecting the unbalance of phases and behavior of neutral conductor. Such kind of reduction was not used in this study since the objective of this research is to accurately represent the LV load flow including the neutral conductor.

The single line diagram of the distribution transformer service area can be represented as in Figure 4.1. The detailed modeling and the mathematical representations on each model segment is summarized below.

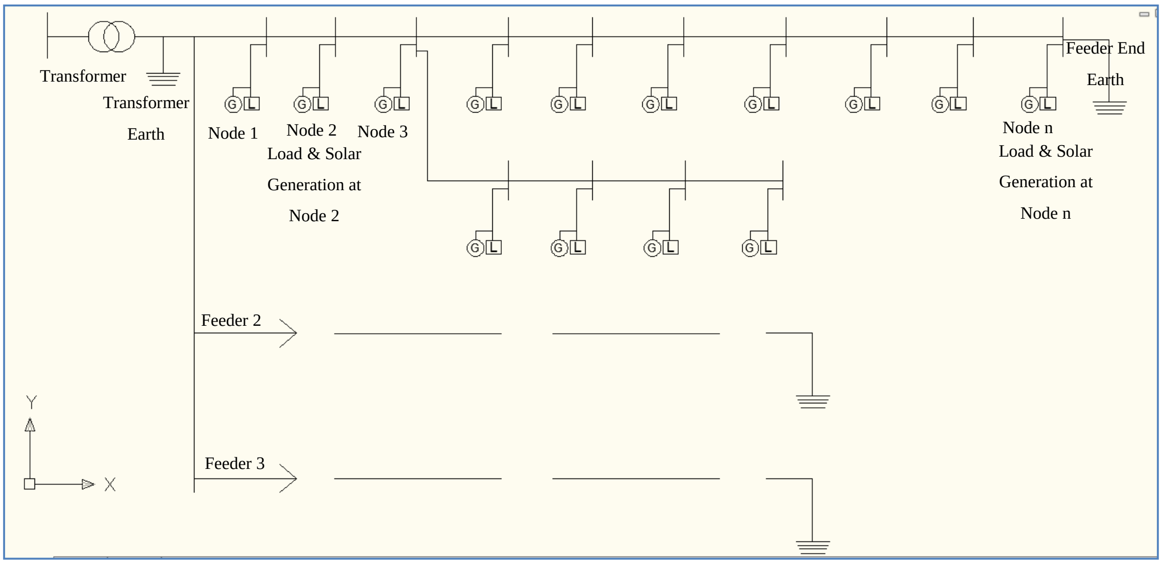
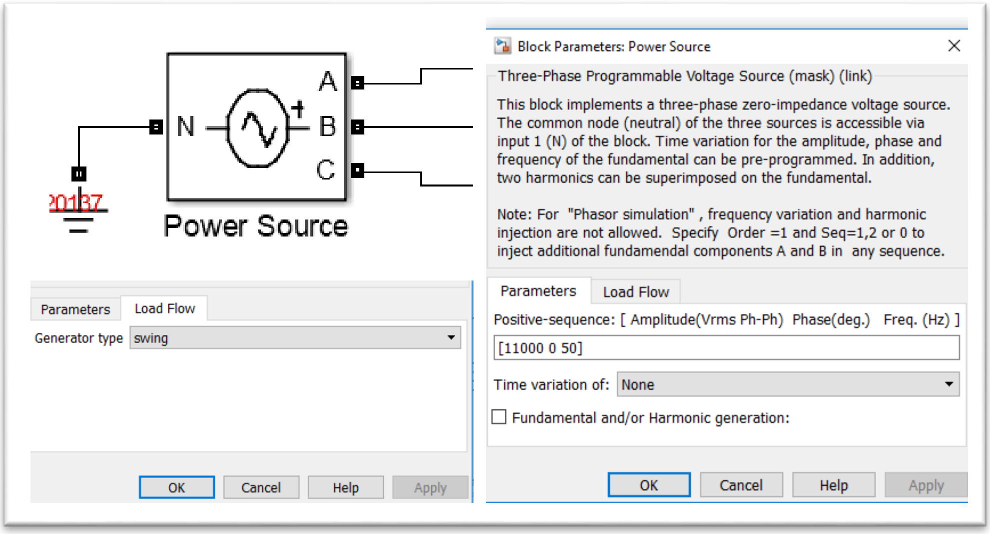


Figure 4.1 Distribution Transformer Single Line Diagram

4.3.1. Modeling of Slack Bus

Model includes 11 kV, 50 Hz power source which was considered as the medium voltage input of the distribution substation and the slack bus for the model. This is represented by 11 kV, 50 Hz power source block available in the Simulink library as shown in Figure 4.2.

The primary assumption of the module is that the transformer input voltage is 11 kV and 50Hz without variations. LECO medium voltage feeders are very short in route, hence it can be assumed that no significant voltage drops occurs in medium voltage network.



Generator type: swing

Three-Phase Programmable Voltage Source (mask) (link)

This block implements a three-phase zero-impedance voltage source. The common node (neutral) of the three sources is accessible via input 1 (N) of the block. Time variation for the amplitude, phase and frequency of the fundamental can be pre-programmed. In addition, two harmonics can be superimposed on the fundamental.

Note: For "Phasor simulation" , frequency variation and harmonic injection are not allowed. Specify Order =1 and Seq=1,2 or 0 to inject additional fundamendal components A and B in any sequence.

Positive-sequence: [Amplitude(Vrms Ph-Ph) Phase(deg.) Freq. (Hz)]
[11000 0 50]

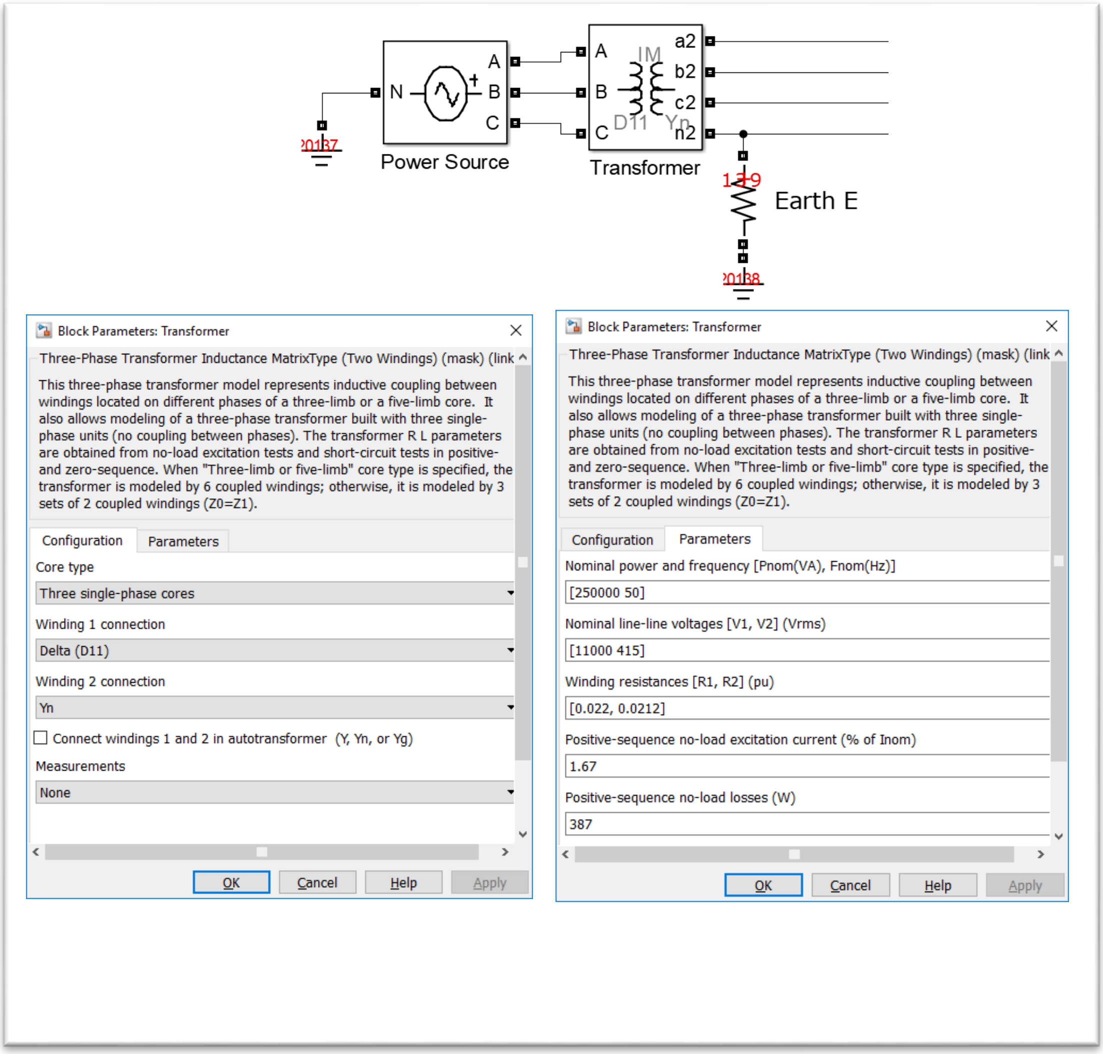
Time variation of: None

☐ Fundamental and/or Harmonic generation:

Figure 4.2 Model Details of 11 kV Power Source

4.3.2. Modeling of Distribution Transformer

Distribution transformers used by LECO are three phase 11 kV/ 415 V double wounded DY11 hermetically sealed type. Transformer star winging has grounded at the transformer point using Copper earth rods. Technical data available in transformer test certificates and technical data sheets for 250 kVA transformer was used to setup the available Simulink transformer library model block according to LECO distribution transformer as in Figure 4.3.



Three-Phase Transformer Inductance MatrixType (Two Windings) (mask) (link

This three-phase transformer model represents inductive coupling between windings located on different phases of a three-limb or a five-limb core. It also allows modeling of a three-phase transformer built with three single-phase units (no coupling between phases). The transformer R L parameters are obtained from no-load excitation tests and short-circuit tests in positive- and zero-sequence. When "Three-limb or five-limb" core type is specified, the transformer is modeled by 6 coupled windings; otherwise, it is modeled by 3 sets of 2 coupled windings (Z0=Z1).

Configuration | Parameters

Core type: Three single-phase cores

Winding 1 connection: Delta (D11)

Winding 2 connection: Yn

☐ Connect windings 1 and 2 in autotransformer (Y, Yn, or Yg)

Measurements: None

Nominal power and frequency [Pnom(VA), Fnom(Hz)]: [250000 50]

Nominal line-line voltages [V1, V2] (Vrms): [11000 415]

Winding resistances [R1, R2] (pu): [0.022, 0.0212]

Positive-sequence no-load excitation current (% of Inom): 1.67

Positive-sequence no-load losses (W): 387

Figure 4.3 Model Details of the Transformer

4.3.3. LV Feeders

Four core 70mm^2 and 50mm^2 areal bundled cables are used for LV feeders in LECO. ABC conductor data is tabulated in **Error! Reference source not found.**.

Table 4.1 LV Feeder Conductor Details

	Conductor		3x70 +1x50 mm^2	3x50 +1x35 mm^2
1	Phase conductor size	mm^2	70	50
2	Neutral / messenger conductor	mm^2	50	35
3	Conductor Resistance (20^0C)			
	a. Phase conductor	Ohm/km	0.443	0.641
	b. neutral / messenger conductor	Ohm/km	0.0868	0.0868
4	Conductor Reactance for 50Hz (20^0C)			
	a. Phase conductor	Ohm/km	0.630	0.0848
	b. neutral / messenger conductor	Ohm/km	0.0868	0.0879
5	Stranding			
	a. Phase conductor	No / mm	19/2.14	19/1.78
	b. neutral / messenger conductor	No / mm	7/3.00	7/2.52
	c. street lighting conductor	No / mm	7/1.70	7/1.70
6	Voltage rating	V	600/1000	
7	Insulation Thickness			
	a. Phase conductor	mm	1.8	1.6
	b. neutral / messenger conductor	mm	1.6	1.6
	c. street lighting conductor	mm	1.2	1.2
8	Insulation Material		XLPE	XLPE
9	Conductor material			
	a. Phase conductor and street lighting		AAC	AAC
	b. Neutral / messenger		AAAC	AAAC
10	Maximum permissible temperature of cores	^{0}C	90	90
11	Maximum current rating phase and neutral	S	213	168

Whe

n modeling the LV feeders, explicit representation of the ABC including the neutral and grounding method was taken into consideration. Four wire line segment block represent the ABC line between two pole nodes.

Impedances of each conductor in the ABC were used for 4x4 impedance matrix which included the self-impedance of conductors and the mutual impedances.

The nodes represent here are the poles in actual network where the loads are connected via service cables. The shunt admittance of the line was considered negligible since the study was on low voltage.

The representation of the line segment between two pole nodes as a model is shown in Figure 4.4.

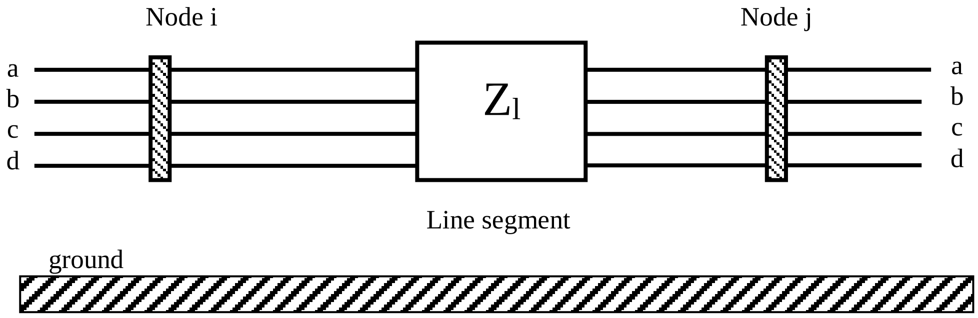


Figure 4.4 Three Phase Four Wire Line Section

The 4x4 matrix consists of self and mutual reactance of three phases and neutral wire between two pole nodes with the length l is shown below.

$$Z_l = \begin{pmatrix} Z_{aa} & Z_{ab} & Z_{ac} & Z_{an} \\ Z_{ba} & Z_{bb} & Z_{bc} & Z_{bn} \\ Z_{ca} & Z_{cb} & Z_{cc} & Z_{cn} \\ Z_{na} & Z_{nb} & Z_{nc} & Z_{nn} \end{pmatrix} l$$

4-1

Where

$$Z_{xx} = R_{xx} + jX_{xx}$$

4-2

R_{xx} = Conductor X Resistance Ω/km

X_{xx} = Conductor X reactance Ω/km

l = Conductor length between two nodes - Span (Poles)

R_{xx} and X_{xx} are the per kilometer resistance and reactance of each conductor. Resistance and reactance of each line section can be derived from the span of the section and the per kilometer impedance data available for the conductor.

Z_{xy} (Where $x \neq y$) is the mutual inductive reactance of conductor x due to currents in conductor y. In modeling, mutual inductive reactance was considered negligible since the conductors are XLPE insulated, cross wounded and operates in low voltage.

The impedance matrix represented in Simulink model for the LV feeder section is shown below and the model was designed using standard impedance model blocks available in Simulink. Simulink model for the LV feeder is shown in Figure 4.5.

$$Z_l = \begin{pmatrix} R_{aa} + jX_{aa} & 0 & 0 & 0 \\ 0 & R_{bb} + jX_{bb} & 0 & 0 \\ 0 & 0 & R_{cc} + jX_{cc} & 0 \\ 0 & 0 & 0 & R_{nn} + jX_{nn} \end{pmatrix}$$

4-3

Since,

$R_{aa} = R_{bb} = R_{cc} = R_{phase}$

$R_{nn} = R_{nutral}$

$X_{aa} = X_{bb} = X_{cc} = X_{phase}$

$X_{nn} = X_{nutral}$

Where

R_{phase} = Resistance of Phase conductor Ω/km

X_{phase} = Reactance of Phase conductor Ω/km

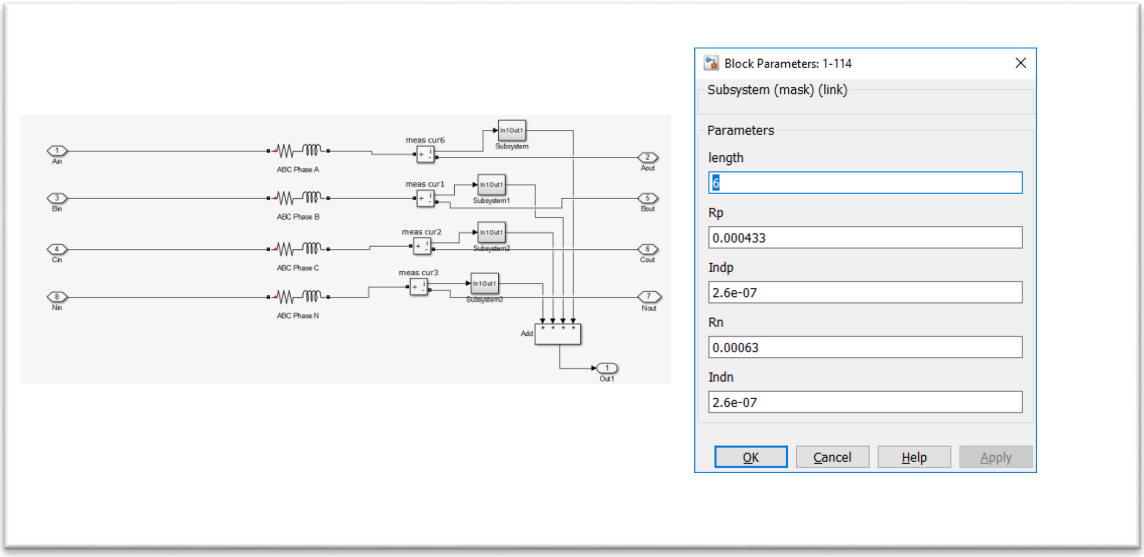
R_{phase} = Resistance of Neutral conductor Ω/km

R_{phase} = Reactance of Neutral conductor Ω/km

All reactance values are calculated in 50Hz frequency.

$$Z_l = \begin{pmatrix} R_{phase} + jX_{phase} & 0 & 0 & 0 \\ 0 & R_{phase} + jX_{phase} & 0 & 0 \\ 0 & 0 & R_{phase} + jX_{phase} & 0 \\ 0 & 0 & 0 & R_{neutral} + jX_{neutral} \end{pmatrix}$$

4-4



Block Parameters: 1-114

Subsystem (mask) (link)

Parameters

length: 6

Rp: 0.000433

Indp: 2.6e-07

Rn: 0.00063

Indn: 2.6e-07

Figure 4.5 Model Details of the Line

4.3.4. Loads

In a LV distribution feeder, loads are connected in customer premises beyond the utility meter point. These loads can be either single phase or three phase. Total load visible to the LV feeder at the point of connected pole node is the sum of all customer loads connected in that node.

In a particular pole node, both single phase and three phase customers are available. The final load in a pole node can be represented as three phase unbalance star connected load considering the addition of all loads in phase vise. Hence the load model was represented as star connected unbalance three phase load.

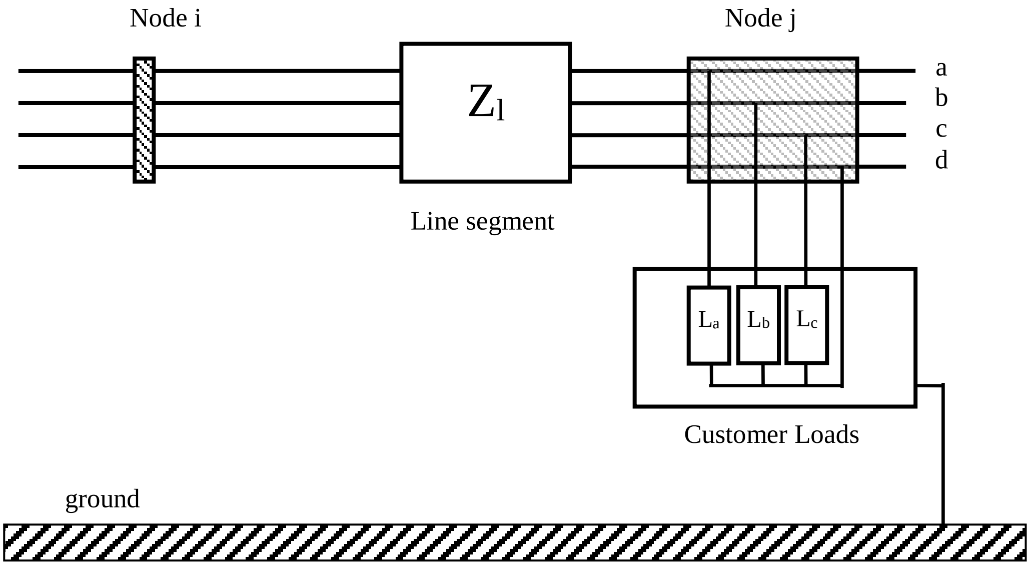


Figure 4.6 Customer Loads

In Simulink, loads were presented as constant current sources connected to each phase and neutral of the LV feeder conductors at pole nodes. For the easy use, three phase load was defined by three single phase constant current sources. The relation between the load and the injected current is derived as below. The Simulink model is shown in Figure 4.7.

$$S_{phase,l} = P_{phase,l} + jQ_{phase,l} \tag{4-5}$$

$$Q_{phase,l} = P_{phase,l} \tan[\cos^{-1}(PF)] \tag{4-6}$$

$$I_{phase,load} = \left(\frac{P_{phase,l} + jQ_{phase,l}}{V_{phase-neutral}}\right)^* \tag{4-7}$$

Where

PF = power factor

$P_{phase,l}$ = Active Power of the load

$Q_{phase,l}$ = Reactive Power of the load

Phase current ($I_{phase,load}$) is defined as the complex conjugate of apparent power of the load divided by the phase to natural voltage of the node.

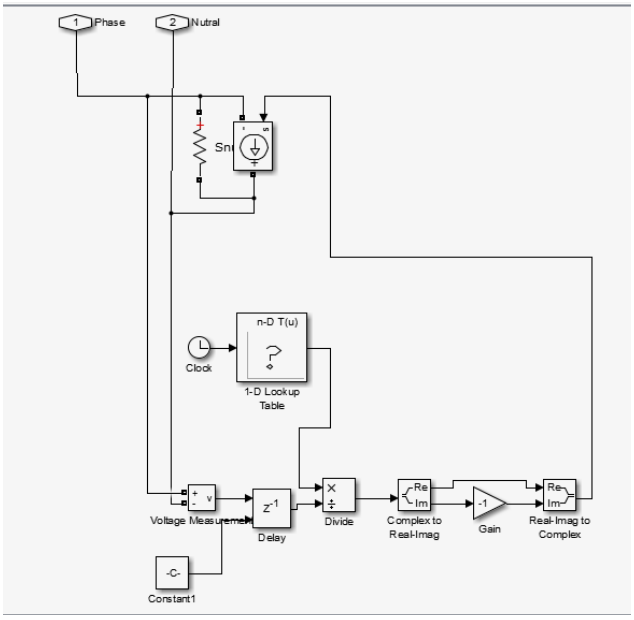


Figure 4.7 Model Details of the Load

Active power data obtained from each meter readings and load curves are summed up to get the total loads at each pole nodes. For one complete day, load profile with 96 time series data sets were used as input to the loads at each pole node.

4.3.5. Rooftop Solar

Same as loads, solar PV installations at pole nodes were added to obtain the total pole node solar PV injection and represented as a constant current source where the direction of the current injection is opposite to the load.

Current injection of the PV source assuming unit power factor operation of the inverter can be derived as below.

$$I_{phase,solar} = -\left(\frac{P_{phase},s}{V_{phase-neutral}}\right)^{*}$$

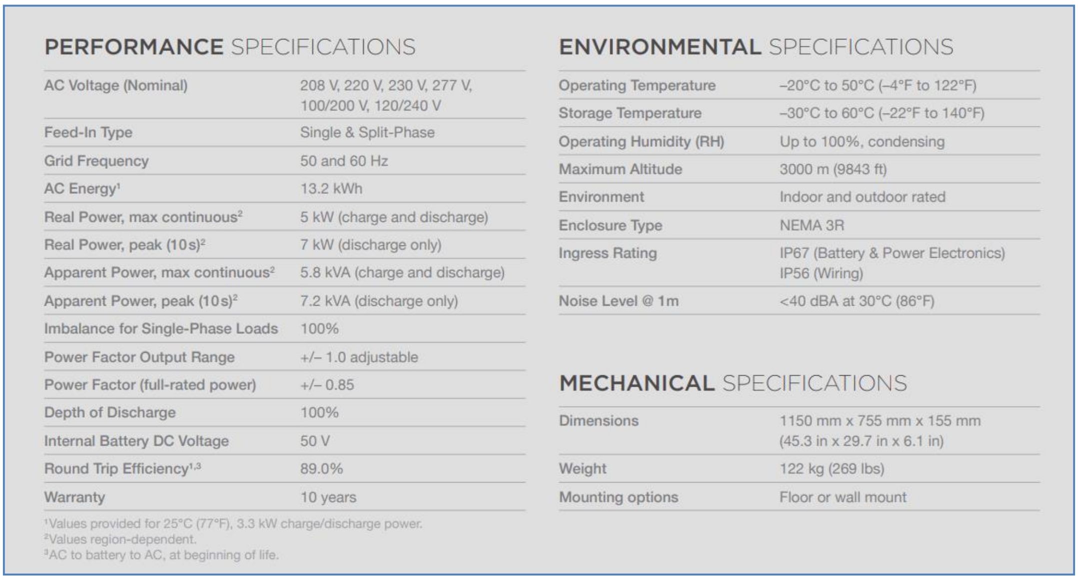
4-8

P_{phase},s = Solar generation active power

4.3.6. Battery Backup

Representing the battery in the model as an energy storage system with the capability of energy absorbing and extracting was modeled as bi directional current source with integrated memory and other limiting restrictions on charging rate and size.

Technical specifications of TESLA Wall E2 battery was used in modeling the battery model and the details are shown in Figure 4.8.



PERFORMANCE SPECIFICATIONS

AC Voltage (Nominal)	208 V, 220 V, 230 V, 277 V, 100/200 V, 120/240 V
Feed-In Type	Single & Split-Phase
Grid Frequency	50 and 60 Hz
AC Energy[1]	13.2 kWh
Real Power, max continuous[2]	5 kW (charge and discharge)
Real Power, peak (10 s)[2]	7 kW (discharge only)
Apparent Power, max continuous[2]	5.8 kVA (charge and discharge)
Apparent Power, peak (10 s)[2]	7.2 kVA (discharge only)
Imbalance for Single-Phase Loads	100%
Power Factor Output Range	+/– 1.0 adjustable
Power Factor (full-rated power)	+/– 0.85
Depth of Discharge	100%
Internal Battery DC Voltage	50 V
Round Trip Efficiency[1,3]	89.0%
Warranty	10 years

[1] Values provided for 25°C (77°F), 3.3 kW charge/discharge power.
[2] Values region-dependent.
[3] AC to battery to AC, at beginning of life.

ENVIRONMENTAL SPECIFICATIONS

Operating Temperature	–20°C to 50°C (–4°F to 122°F)
Storage Temperature	–30°C to 60°C (–22°F to 140°F)
Operating Humidity (RH)	Up to 100%, condensing
Maximum Altitude	3000 m (9843 ft)
Environment	Indoor and outdoor rated
Enclosure Type	NEMA 3R
Ingress Rating	IP67 (Battery & Power Electronics) IP56 (Wiring)
Noise Level @ 1m	<40 dBA at 30°C (86°F)

MECHANICAL SPECIFICATIONS

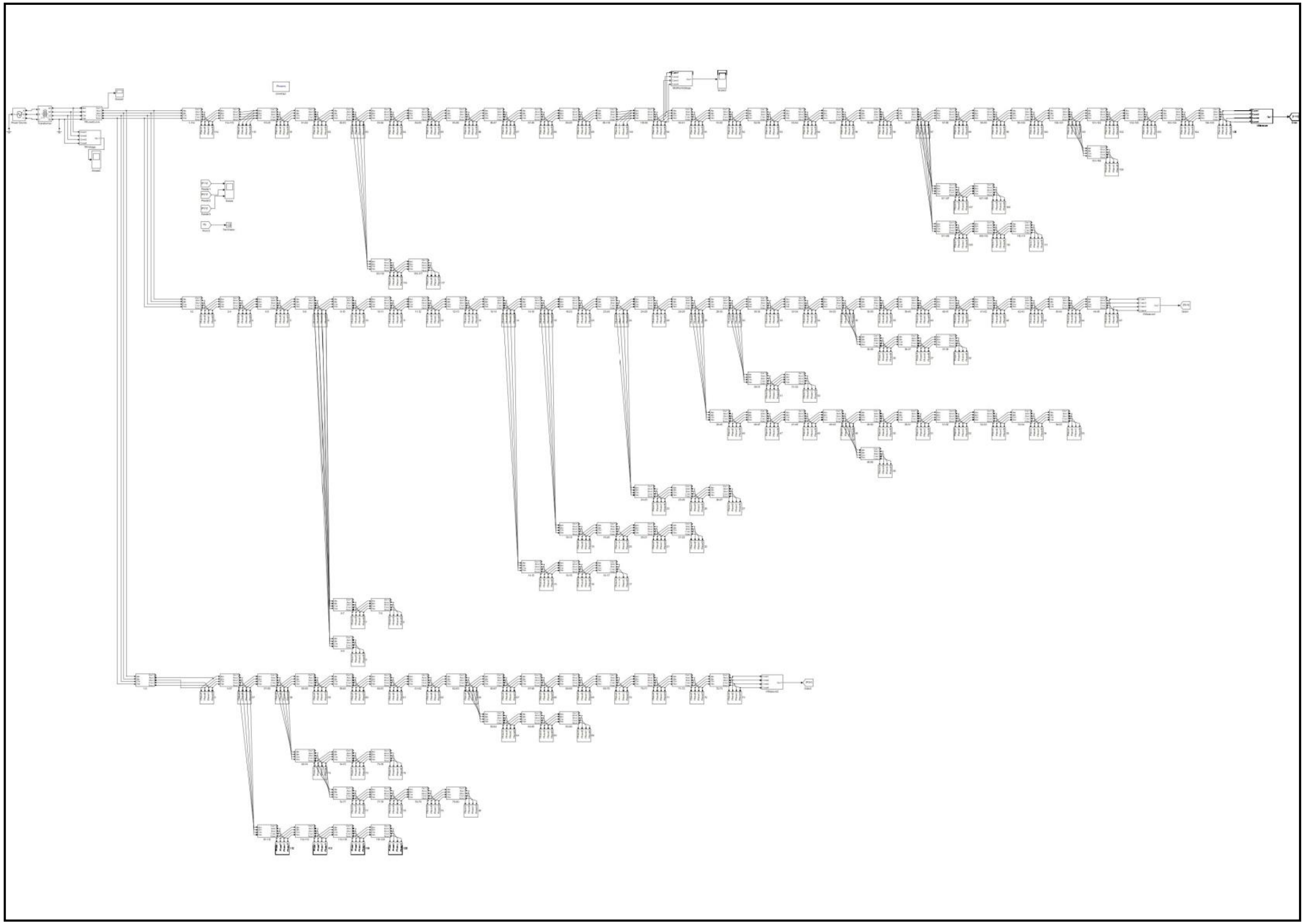
Dimensions	1150 mm x 755 mm x 155 mm (45.3 in x 29.7 in x 6.1 in)
Weight	122 kg (269 lbs)
Mounting options	Floor or wall mount

Figure 4.8 Tesla Wall E2 Battery Specification

4.4. Transformer Area Simulink Model

Complete model for selected transformer service area including the transformer consist of above described sub models such as 250kVA transformer, 120 pole nodes with loads, solar PV and batteries. Duration of simulation was set to 86400 seconds which is complete day starting from 00 00 Hrs to 24 00 Hrs. Matlab Simulink phasors mode is used as simulation method due to the availability of higher number of items in the model.

The complete Simulink model is shown in Figure 4.9.



5. LV Network Simulation

The purpose of the simulation is to study the behavior of the selected distribution transformer service area for one complete day. Hence, the simulation duration was selected as 86,400 seconds.

The main requirement of simulating the actual LV network behavior is having actual and accurate data. Customer load profiles and solar PV generation profiles were generated using LECO billing data, smart meter data and standard solar load curves up to the maximum extend of accuracy. On some cases assumptions had to be made on unavailability of data.

Simulation date is selected as 07/07/2017 where the selected date was a general weekday, without rain and less cloud coverage.

5.1. Customer Load Curves

In the selected transformer service area, there were 342 customers. In electricity utilities, only electrical data available with the utility related to customers is monthly energy usage. Typical energy meter provides only the cumulative energy usage only.

But in the selected transformer area, there were 96 single phase smart meters had installed as customer meters. These meters log the daily cumulative energy curves of the customers in 15 minutes time intervals and these data was available in LECO central servers.

Using this energy consumption curves, customer load profiles were generated for one complete day in 15 minutes time intervals assuming the constant power usage during 15 minutes interval time. Sample customer load profiles of three customers in the selected transformer service area are shown in Figure 5.1.

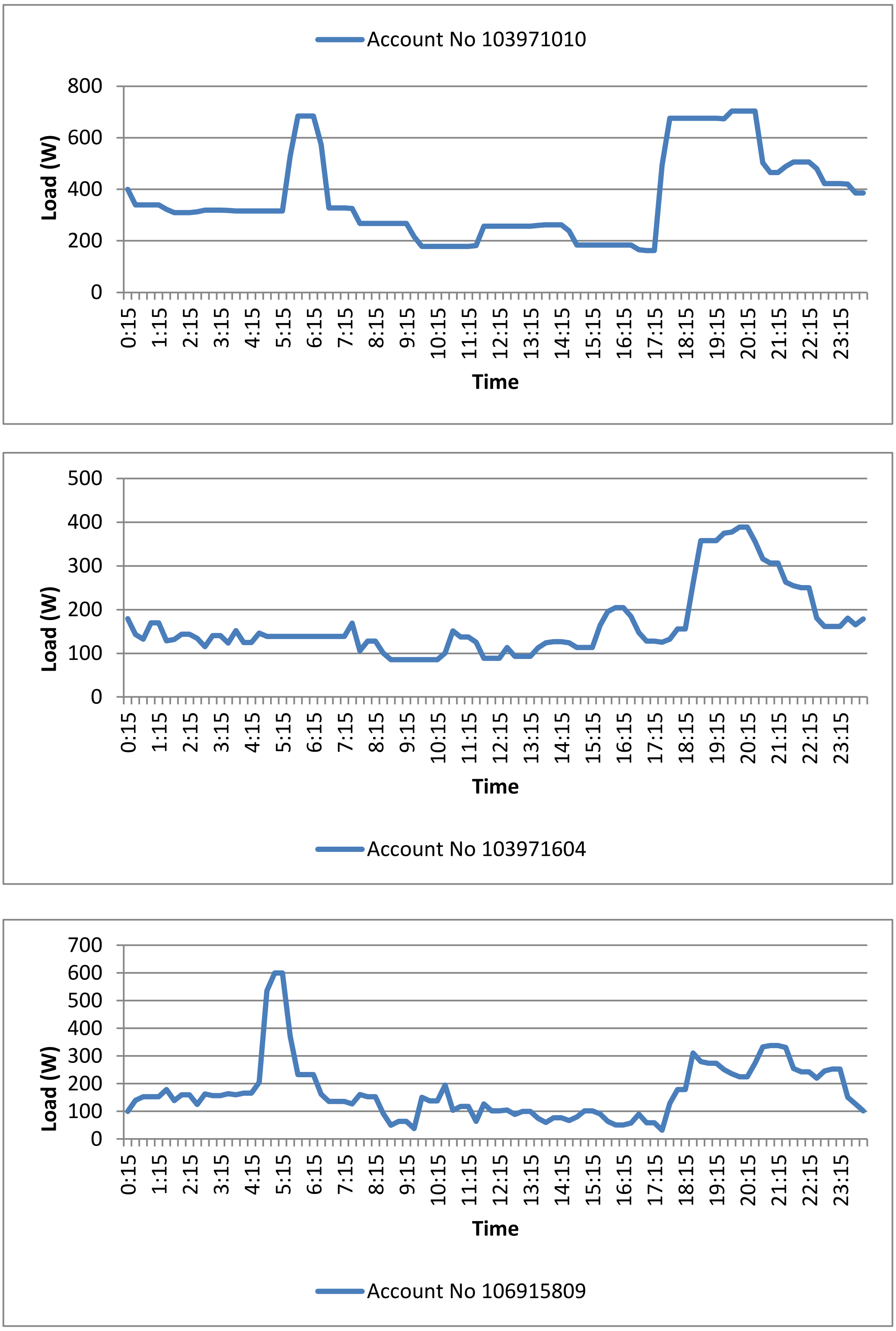


Figure 5.1 Load Profiles of Domestic Customers

Several identical characteristics of domestic customers can be seen in this profiles. High night peak medium morning peak and very small and flat day time load is available in a typical weekday for many of the domestic customers.

For customers with smart meter data available, actual load profiles obtained from the smart meters were taken as the each customer's daily load profile.

Cumulative addition of all load curves together made a load pattern that can be considered as the general load pattern of domestic customers in the transformer area. The cumulative additions of all smart meter load curves are shown in Figure 5.2.

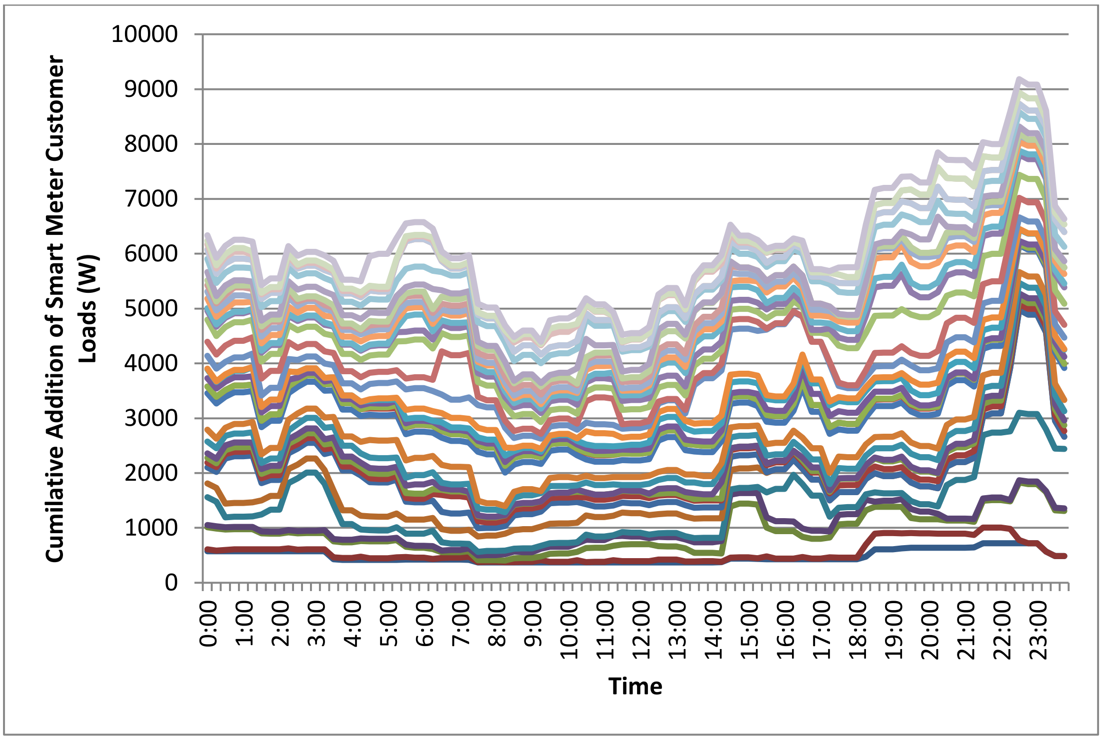


Figure 5.2 Smart Meter Load Profiles Stacked View

Standard unit load curve was derived from averaging all smart meter load profiles such that the total energy consumption shown by the unit load curve to be taken as 1 kWh. The unit load curve matrix U_t has 96 load data in 15 minutes interval time where the total energy represented by the curve is 1 kWh.

$$\mathrm{U_t} = \frac{\sum_{i=1}^{n} \mathrm{P_{t,n}}}{\sum_{t=0}^{24\,00} \sum_{i=1}^{n} \mathrm{P_{t,n}} \; \mathrm{X}\; 0.25} \qquad \text{5-1}$$

$\mathrm{U_t}$= Unit load curve value at time t (for 0.25 h time interval)

n = Number of customers with smart meters

$\mathrm{P_{t,n}}$= Load value of $\mathrm{n^{th}}$ customer at time t interval

t = 00.00, 00.15,……,24.00

The unit load curve matrix $[\mathrm{U_t}]_{1\mathrm{x}96}$ consists of 96 load values each for 15 minutes interval time duration. Unit load curve derived from smart meter data is shown in Figure 5.3.

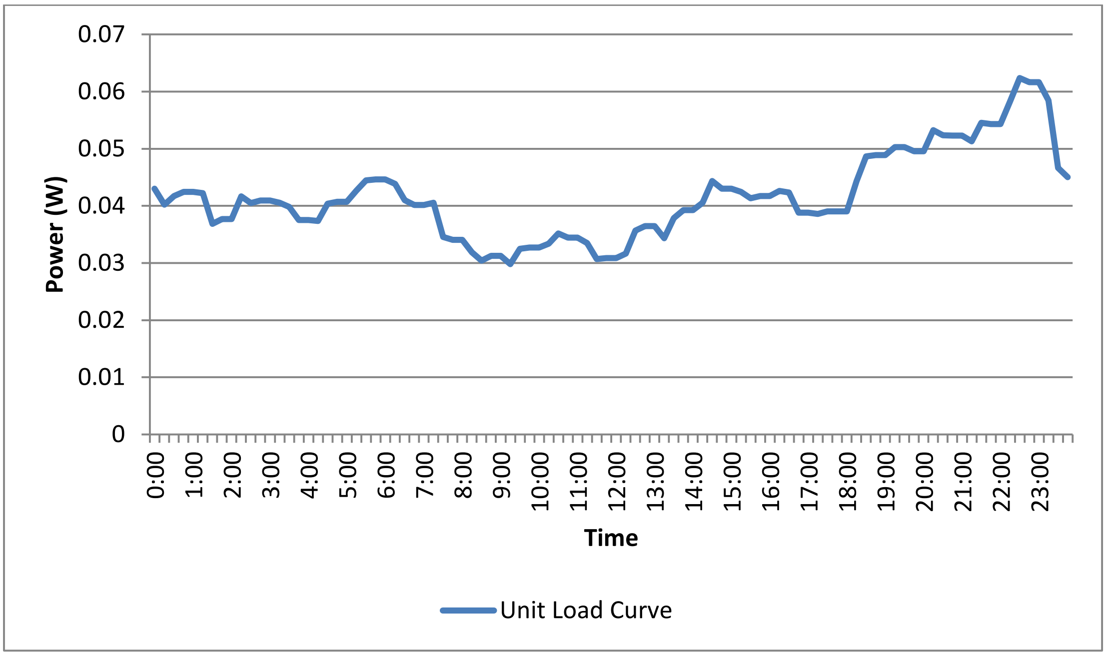


Figure 5.3 Unit Load Curve

Using the unit load curve and the monthly energy consumption data, single phase load curves of other customers were generated.

For single phase customers

$$[Customer\ Load\ Curve_{single\ ph}] = (\frac{Customer\ Energy\ Usege\ of\ the\ month}{billing\ cycle\ days})X\ \mathrm{U_t}$$

5-2

For three phase customers

$$[Customer\ Load\ Curve_{single\ ph}] = (\frac{Customer\ Energy\ Usege\ of\ the\ month}{billing\ cycle\ days\ x\ 3})X\ \mathrm{U_t}$$

5-3

Three load curves for each phase were provided for three phase customers assuming the equal utilization of power in three phases.

For customers with rooftop solar, deriving the load curve was a challenging task using currently available details.

Import export energy meters at the customer premises provides monthly imports and exports energy details of the customer. The amount of energy imports from the grid at the time the solar energy is not available or the load is higher than the solar generation is recorded as meter import energy. The amount of energy export to the grid at the time of solar generation available and the customer load is lower than the energy generation is recorded as meter export energy. Hence the meter detail at the rooftop solar customer primises directly not providing either customer load or solar generation.

Installed solar panel capacity and the estimated average monthly solar generation per 1kW of solar installation is taken into consideration for defining the load curves of rooftop solar installed customers.

For single phase customers with rooftop solar

$$[Customer\ Load\ Curve_{single\ ph}] = \frac{E_{Im} + C_{Panel} x SG_{per\ 1kW,month} - E_{Xp}}{billing\ cycle\ days} X\ \mathrm{U_t}$$

5-4

For three phase customers with rooftop solar

$$[Customer\ Load\ Curve_{single\ ph}] = \frac{E_{Im} + C_{Panel} x SG_{per\ 1kW,month} - E_{Xp}}{billing\ cycle\ days\ x\ 3} X\ \mathrm{U_t}$$

5-5

Where

E_{Im} = Total monthly import energy from the grid to the customer

E_{Xp} = Total monthly import energy from the customer t te grid

C_{Panel} = Installed panel capacity of the customer in kW

$SG_{per\ 1kW,month}$ = Energy generation of solar panels per kW per month

Data available in LECO billing system for E_{Im}, E_{Xp} and C_{Panel} was used for the calculation of customer load curves.

5.2. Total Load curve at Pole Nodes

Required data for the simulation was the load curves of each phases at each pole nodes. The reference pole number where the customers are connected is available with the LECO billing data. All customers were linked to the related pole node using this data.

But for the single phase customers connected phase of the customer was not available with LECO. Hence to allocated customers to each phase random balanced allocation had to be manually carried out.

Addition of each customer load at each pole node and phase, pole node load curves were obtained. These pole node load curves were linked to the input data in Similink load Model blocks.

5.3. Solar Generation Curves

Shape of the solar generation curve is identical to the solar irradiation curve for a day. General solar irradiation curve was taken and 1 kW panel output curve was obtained which was taken as a unit solar generation curve as shown in Figure 5.4.

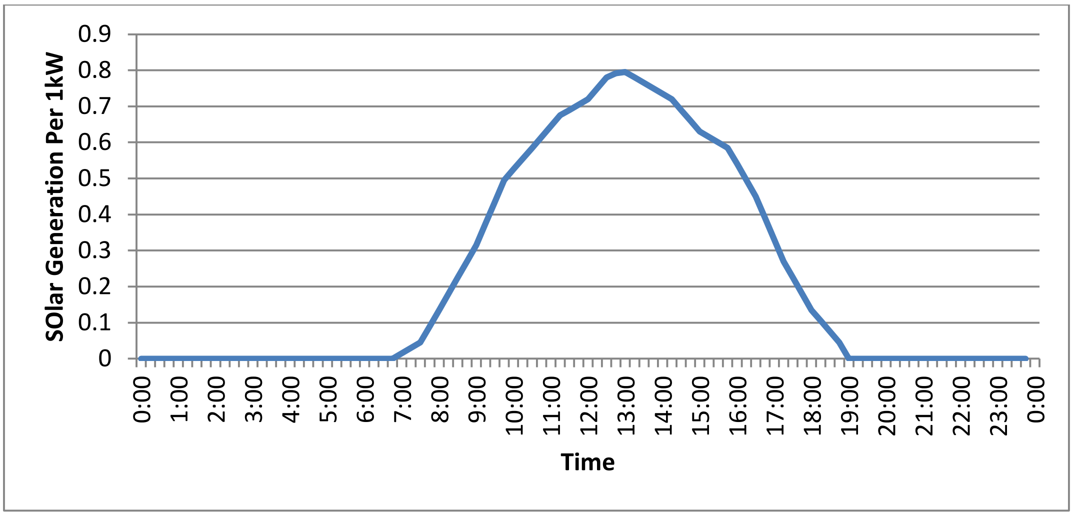


Figure 5.4 Unit Solar Load Curve

When unit solar generation curve is taken as S_t, single phase solar generation curve can be defined as below.

For single phase solar PV/ Inverter system

$$[Soalr\ Load\ Curve_{single\ ph}] = \frac{C_{Panel} x SG_{per\ 1kW,month}}{billing\ cycle\ days}\ X\ S_t \tag{5-6}$$

For three phase solar PV/ Inverter system

$$[Soalr\ Load\ Curve_{single\ ph}] = \frac{C_{Panel} x SG_{per\ 1kW,month}}{billing\ cycle\ days\ x\ 3}\ X\ S_t \tag{5-7}$$

As same as creating pole node load curves, all solar generation at each nodes at each phases were added up to obtain the pole node solar generation curve.

CHAPTER 5

6. SIMULATION RESULTS

6.1. Case Studies and Results

Five case studies were carried out on the selected 250kVA transformer service area by simulating present actual situation, further expected situation and proposed smart grid type arrangement. These case studies are as listed below.

a. Simulation for system without rooftop solar
b. Simulation for preset existing system
c. Simulation for rooftop solar additions of 250kW
d. Simulation for rooftop solar additions of 250kW with batteries with smart grid control
    i. For peak mitigation
    ii. For self-sustaining the network

Following output curves obtained from simulations are presented as results.

a. Load curve of the transformer
b. Daily voltage curve
    i. In feeders starting points,
    ii. In feeder ends
    iii. In feeder mid points
c. Total line loss curve of the feeders
d. Transformer loss curve
e. Battery charging and discharging curve
f. Battery storage curve

6.1.1. Transformer with only the loads and without Rooftop Solar

Before the introduction of rooftop solar PV, conventional distribution transformer service areas were available only with loads. Before study the effect of adding the rooftop solar in to the network, the hypothetical state of the transformer service area was simulated without rooftop solar installations.

For the simulation, only the load curves available at the selected date was considered assuming the total consumption of the customers were supplied by utility grid. The results are presented in Figure 6.1 - Figure 6.5. In this case only a typical uni-directional power flow is available in the LV network vary with the customer loads.

No significant neutral voltage increase presented throughout the day but the line voltage reached beyond the allowable limit during night time. Maximum demand of the transformer is present at 23:00 hrs and the day time load is around half of the night peak.

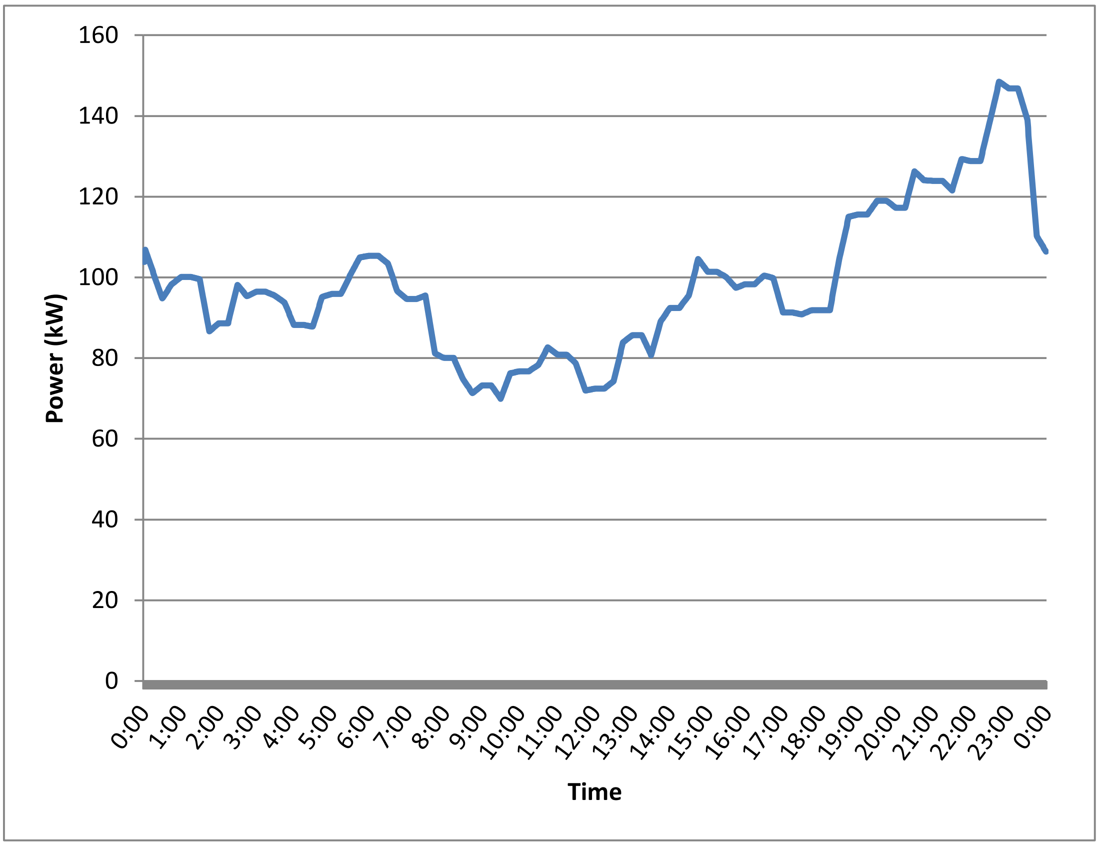


Figure 6.1 Transformer Load Curve without Rooftop Solar

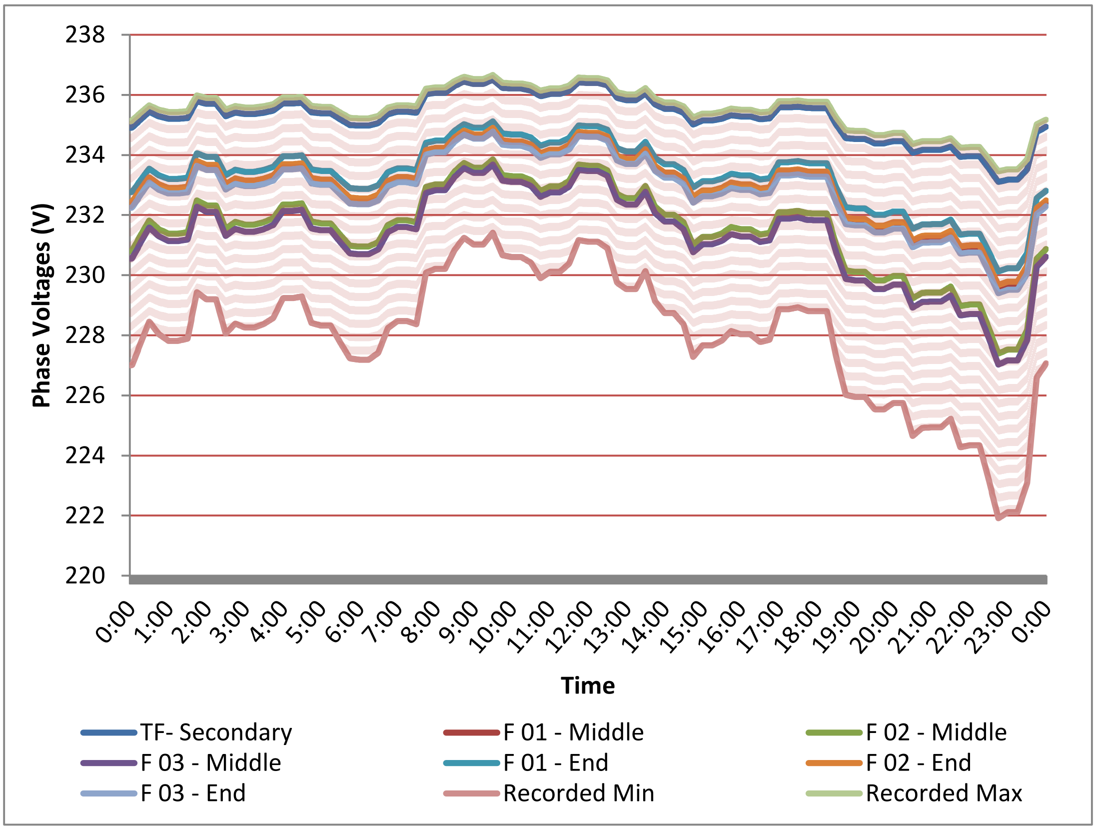


Figure 6.2 Phase Voltages of Feeders without Solar

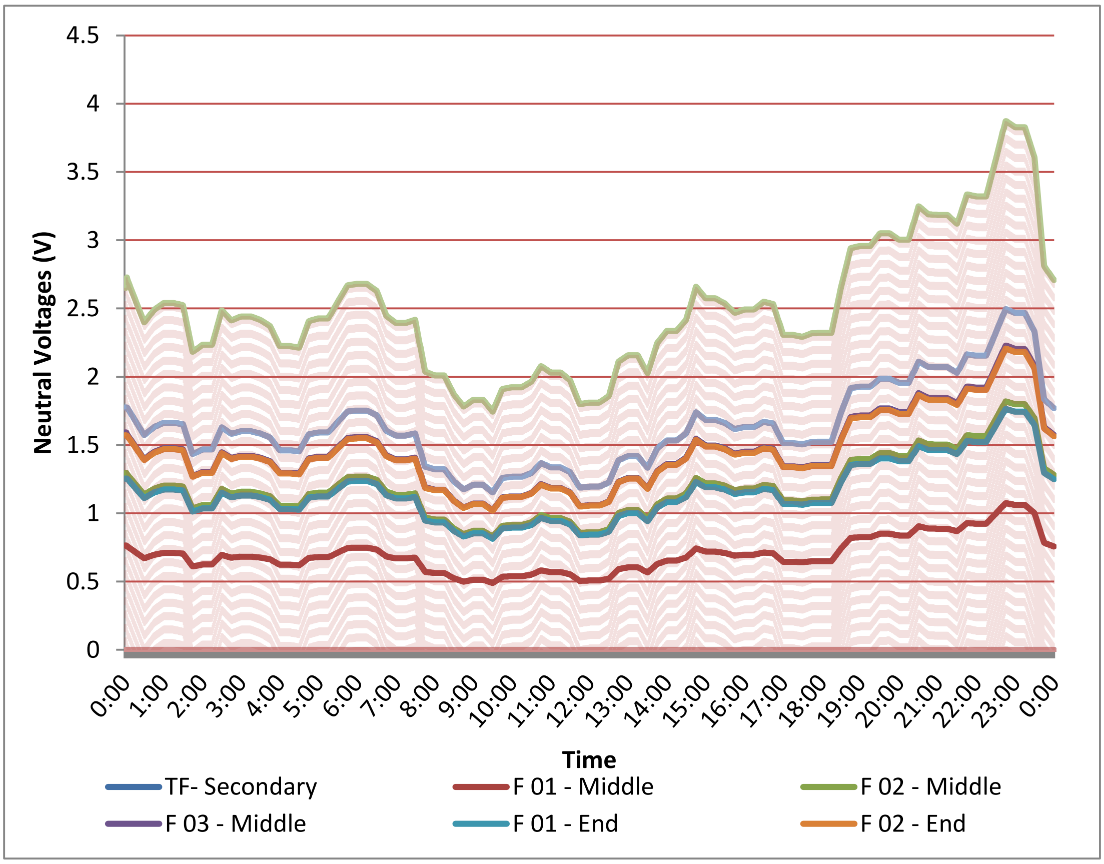


Figure 6.3 Neutral Voltages of Feeders without Solar

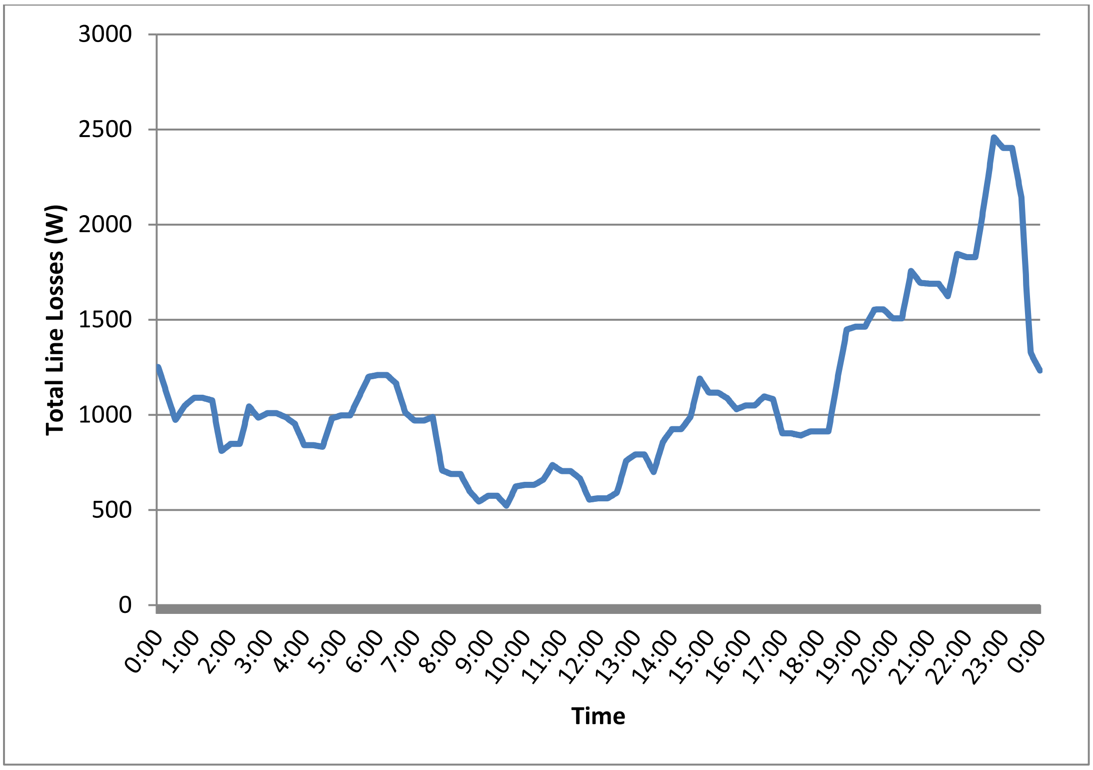


Figure 6.4 Total Line Losses of Feeders without Solar

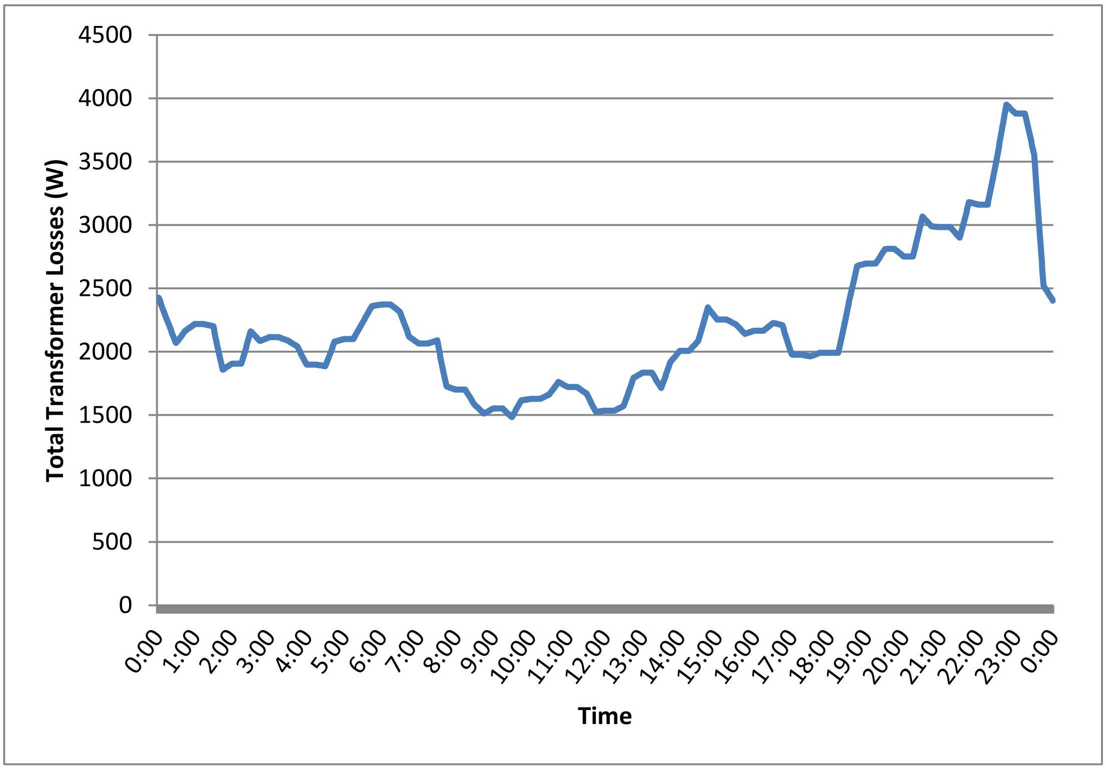


Figure 6.5 Transformer Loss without Solar

6.1.2. Transformer with Actual Loads and Actual Rooftop Solar - Present Actual Network

Existing transformer service area with present rooftop solar installations and actual loads were simulated for the load profile data obtained for the date 07/07/2017. At present in the selected 250 kVA transformer service area there are 342 customers with 24 rooftop solar installations with the total capacity of 120 kW.

The graphical representations of results of the simulation for the complete day are shown in Figure 6.6 - Figure 6.10 below.

For the validation of the model simulation result of the transformer load curve and the actual transformer load curve obtained from the LECO transformer meter for the same day is shown in Figure 6.6.

It can be seen that with addition of 120 kW of rooftop solar, transformer load curve has changed in day time making a large valley. This is due to the utilization of solar PV generation in LV network by loads with reducing the contribution from grid during day time. At the peak energy generation on day noon, transformer power flow has been reversed from LV side to MV due to excess generation inside transformer service area.

Phase voltages of the feeders were in 240 V range rated voltage value and the significant neutral voltage rise was available due to unbalanced solar PV generation during day time. Clear reduction of line losses and transformer losses was seen and no changes were available in night time.

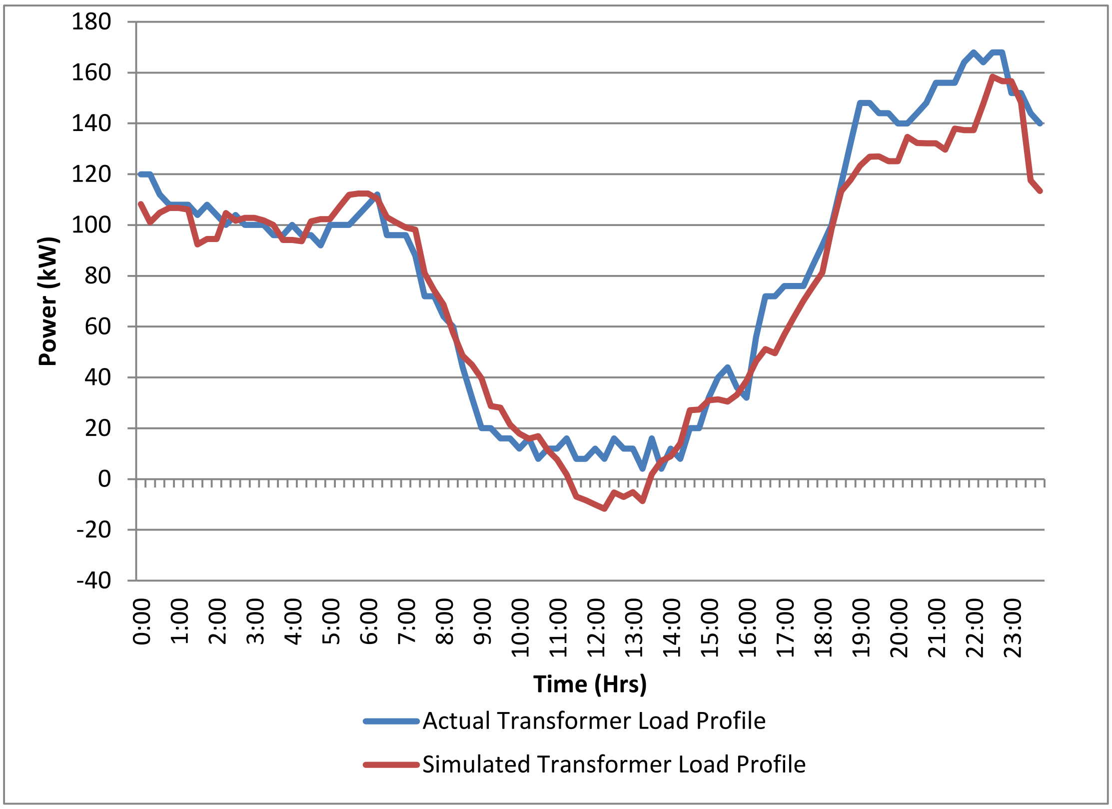


Figure 6.6 Transformer Load Curve with Rooftop Solar

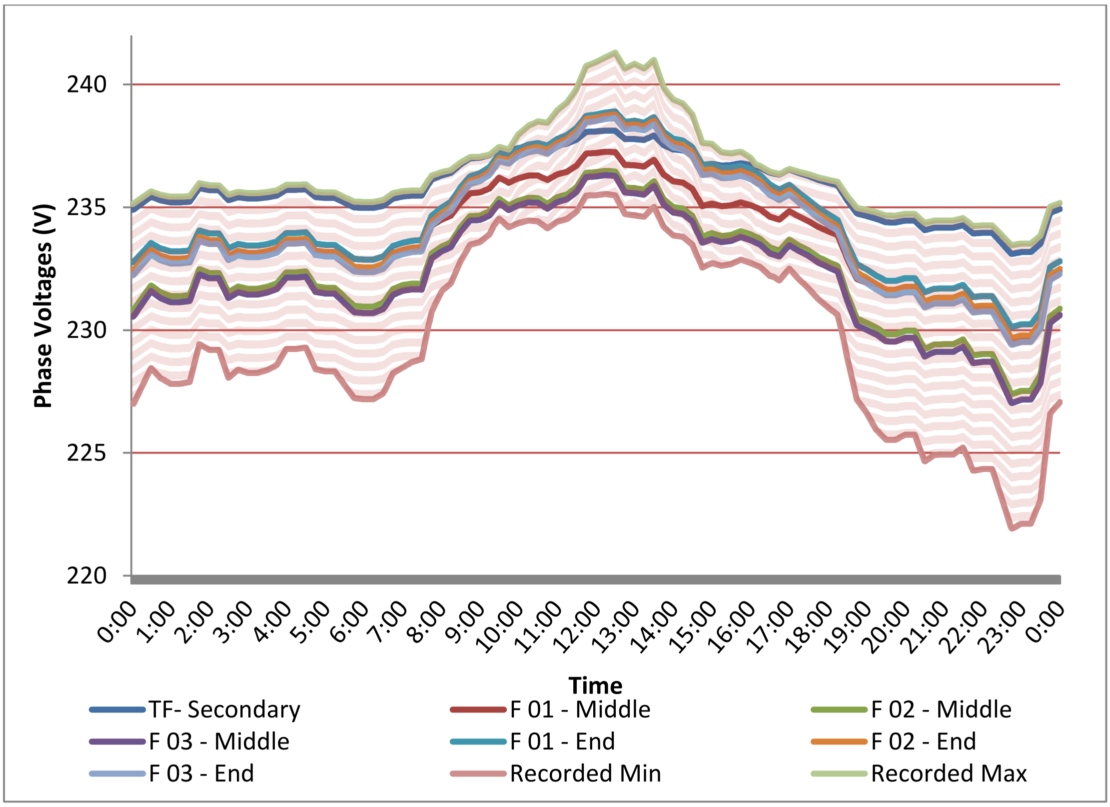


Figure 6.7 Phase Voltages of Feeders with Rooftop Solar

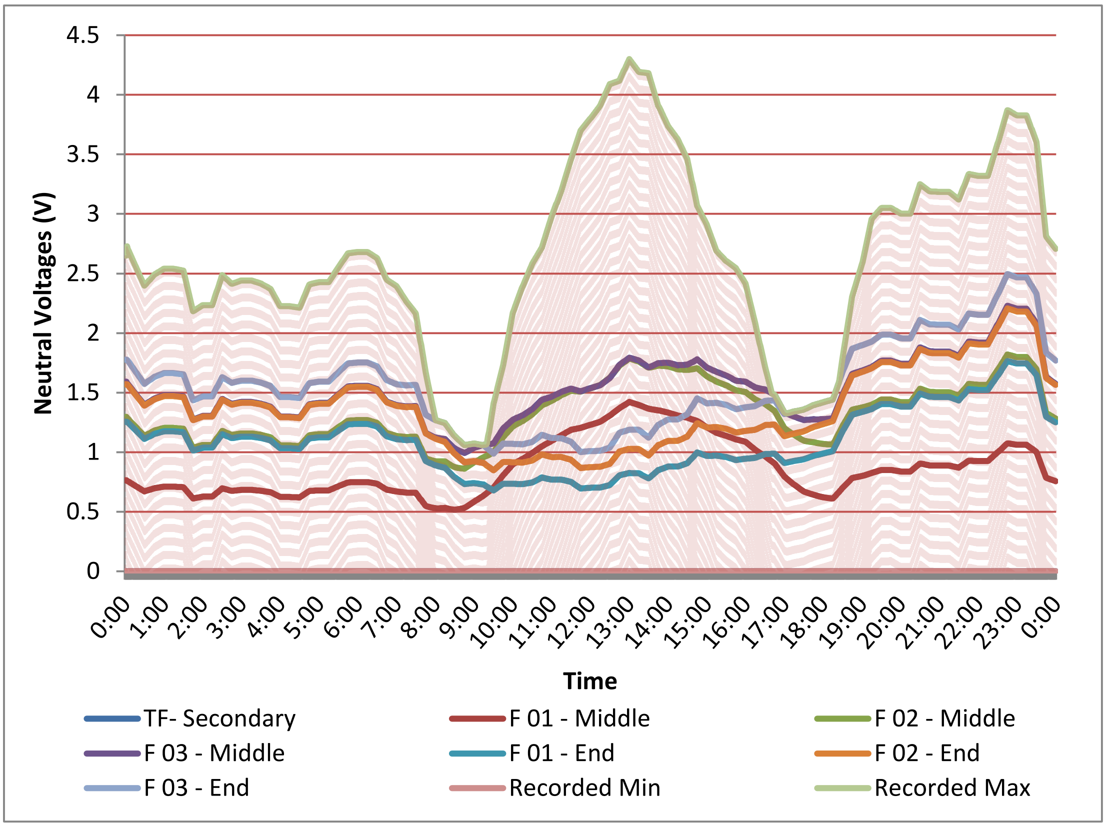


Figure 6.8 Neutral Voltages of Feeders with Rooftop Solar

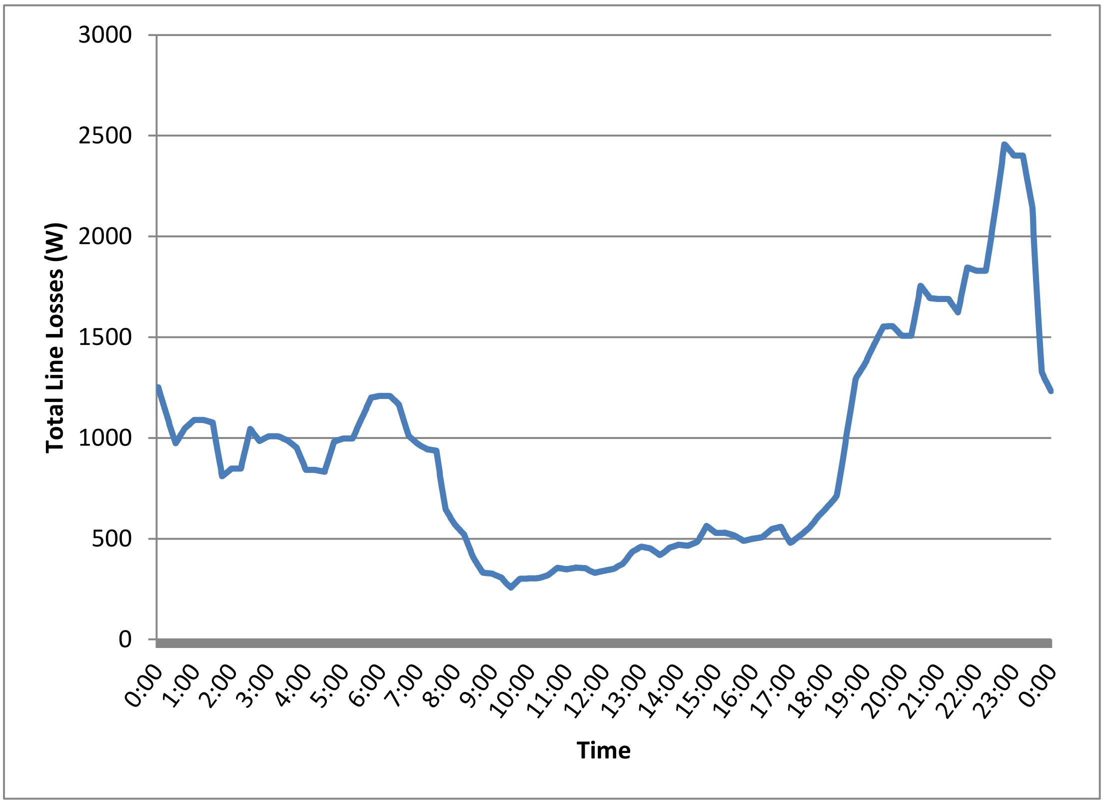


Figure 6.9 Total Line Losses of Feeders with Rooftop Solar

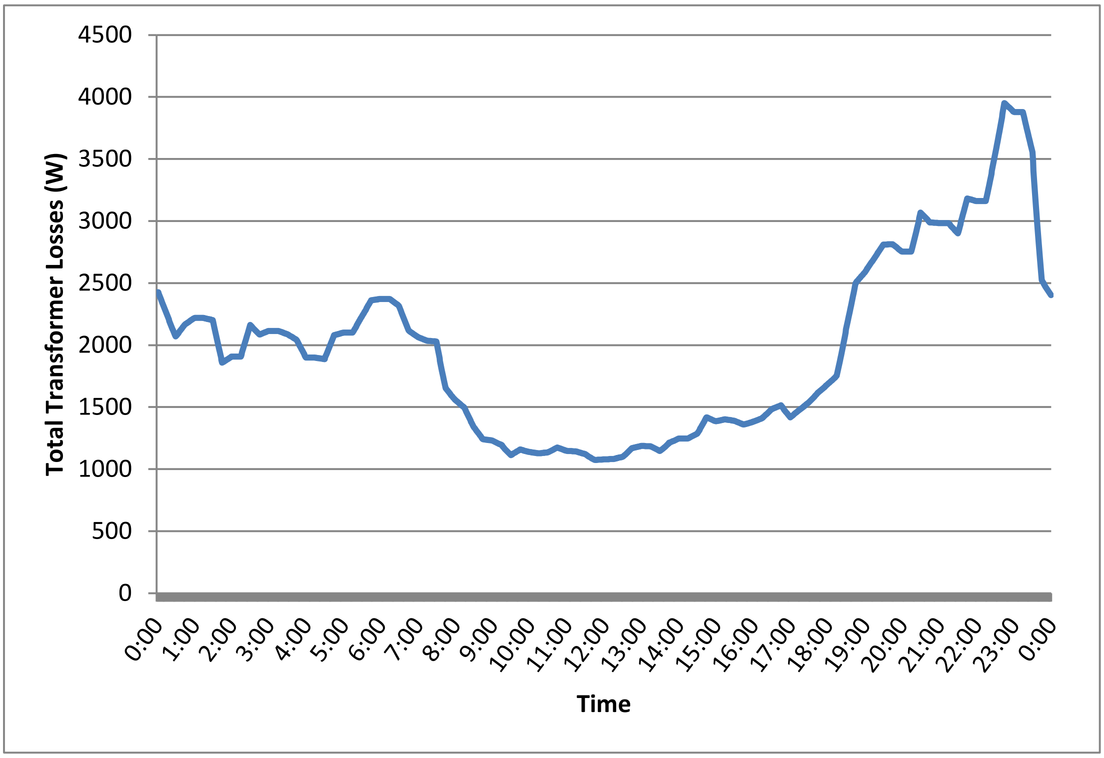


Figure 6.10 Transformer Loss with Rooftop Solar

6.1.3. Transformer with Actual Loads and 250 kW of Rooftop Solar – Future Expected Network

Maximum rooftop PV installations for a transformer service area can be limited to transformer capacity by assuming the maximum reverse power flow without loads available have to be limited to transformer capacity.

This is the maximum allowable export limit through transformer LV side to MV. This situation can be hypothetically occurred at mid-day noon with no loads available and if the total sum of installed rooftop solar PV capacities are equal to the transformer capacity.

Considering the above limitation, 120 kW of present available solar PV capacities were increased virtually up to 250 kW by manually adding small solar PV models distributed along three feeders randomly to study the future expected scenario.

Graphical representations of results of the simulation for the complete day are shown in Figure 6.11- Figure 6.15.

With the increase of rooftop solar capacities, significant amount of energy exports were available during day time. But with this high generation, phase voltages of the feeders exceeded the allowable upper limits with high neutral currants presented in the neutral conductor. Line losses and transformer loss were also increased due to highly increased reverse power flow through the LV network.

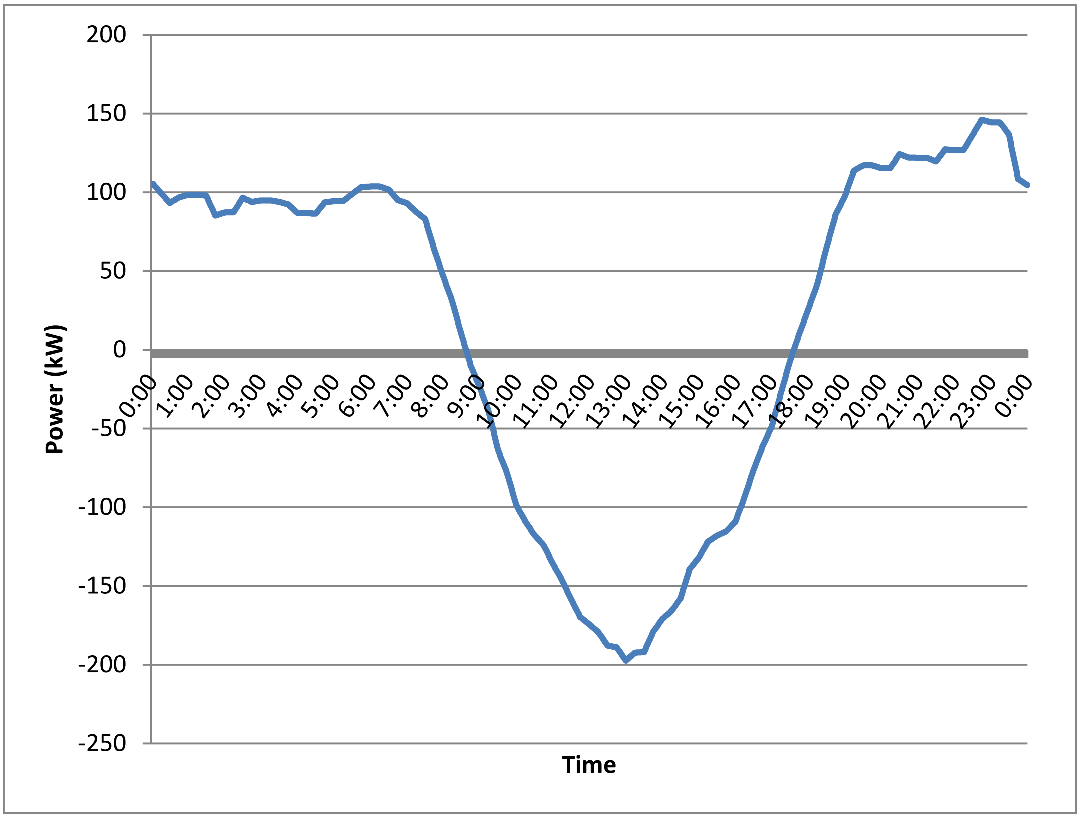


Figure 6.11 Transformer Load Curve with 250 kW of Rooftop Solar

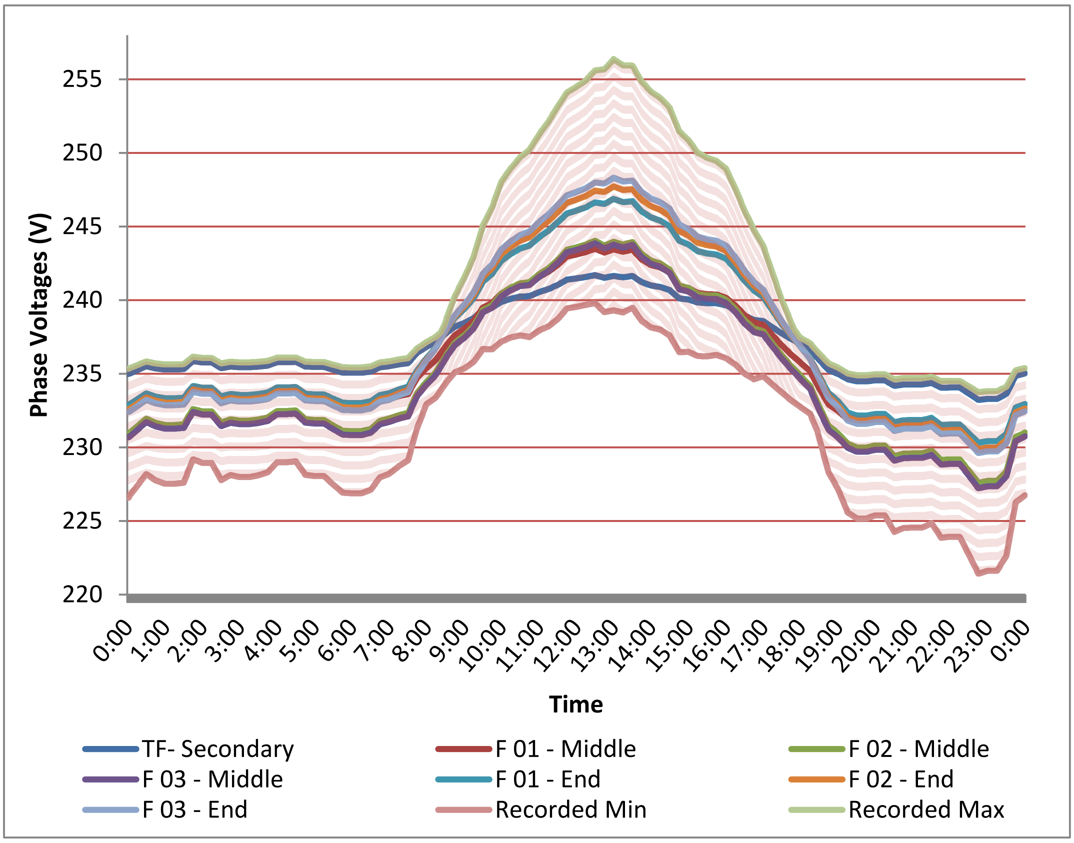


Figure 6.12 Phase Voltages of Feeders with 250 kW of Rooftop Solar

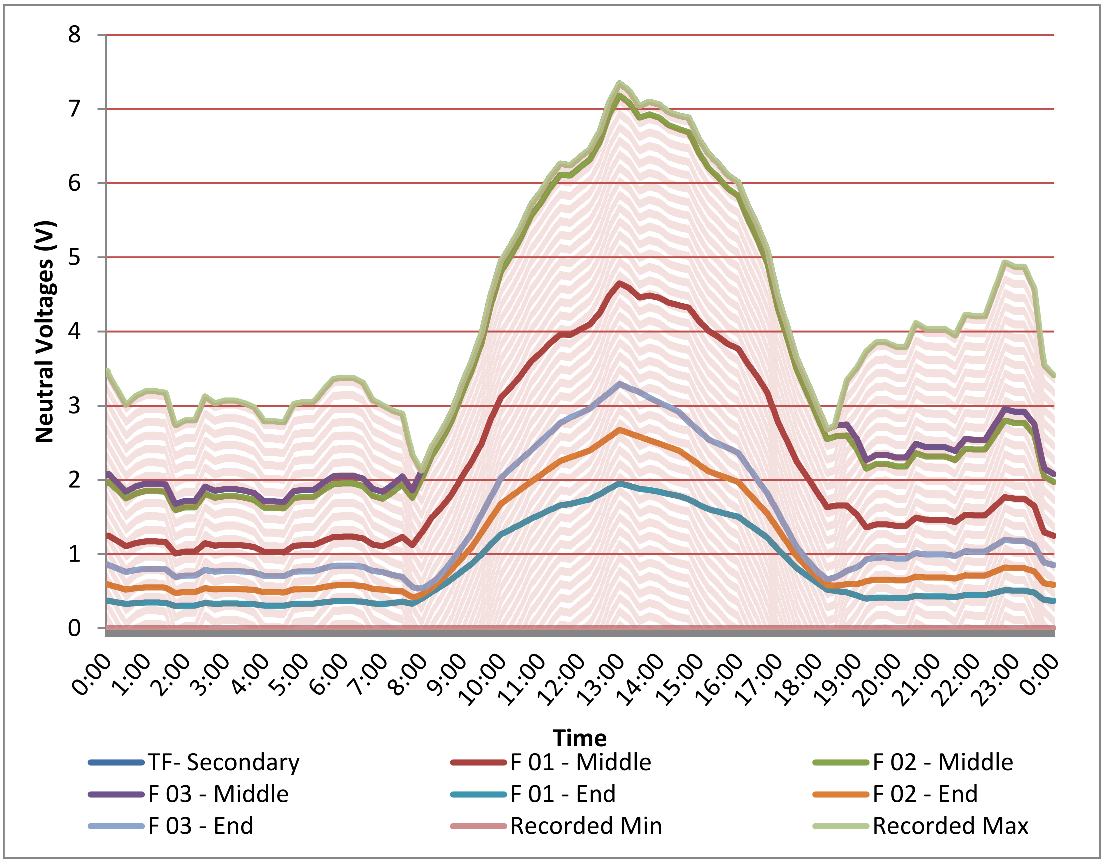


Figure 6.13 Neutral Voltages of Feeders with 250 kW of Rooftop Solar

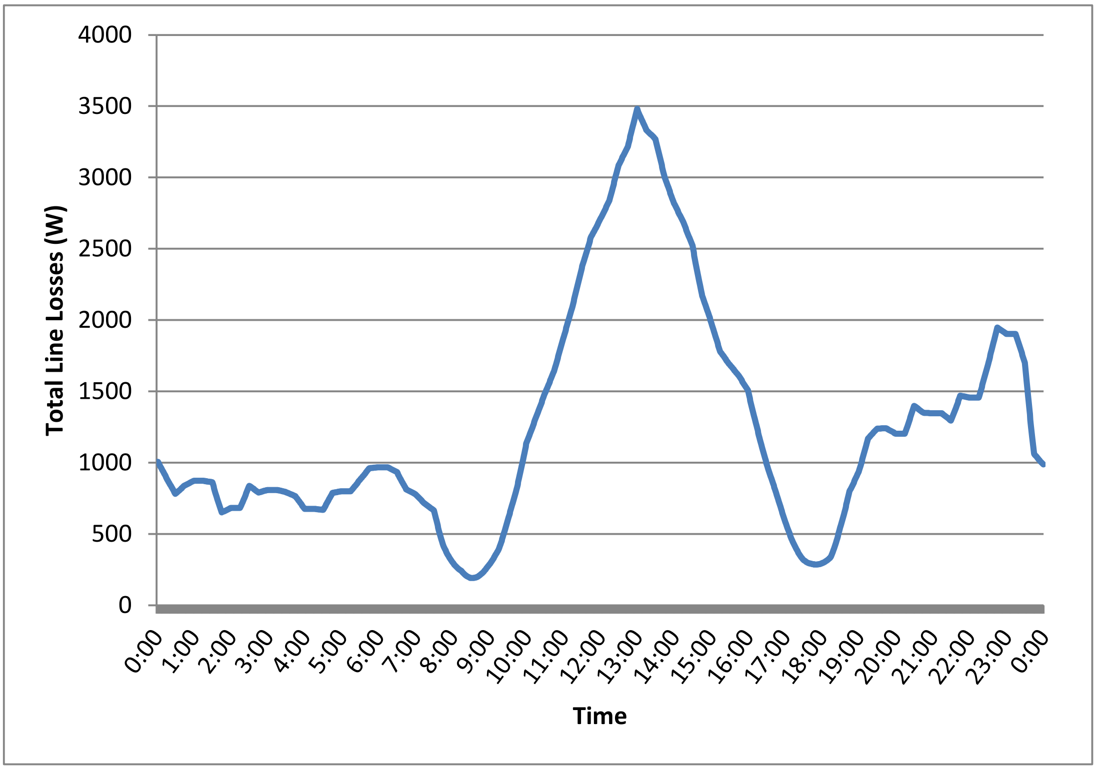


Figure 6.14 Total Line Losses of Feeders with 250 kW of Rooftop Solar

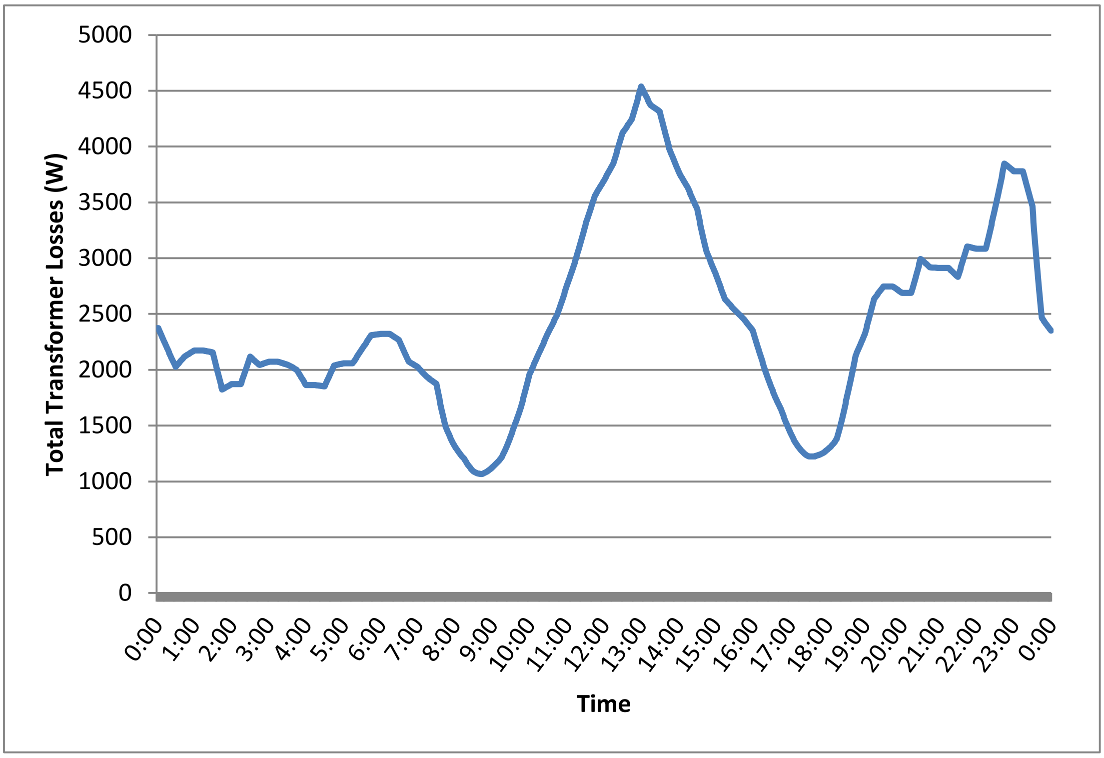


Figure 6.15 Transformer Loss with 250 kW of Rooftop Solar

6.1.4. Transformer with Actual Loads, 250 kW of Rooftop Solar and Batteries for Peak Mitigation in a Smart Grid

In this case, smart grid controlled transformer service area is considered. In this simulation distributed batteries were added equally in several points distributed along the feeders. The objective was to completely mitigate the nighttime peak occurred between 18:30 hrs to 21:30 hrs.

Number of minimum battery backups required was counted by considering the installations of TESLA Wall E2 batteries to active the objective defined above. Centralized battery controller was designed to control battery operation.

Using battery controller, batteries were charged in the day time when the excess generation was available in LV side. Charging rate was defined to mitigate the reverse power flow through the transformer. Hence the excess electricity generated inside transformer area was saved in battery backups to utilize in the night.

In the night time peak where the average electricity generation cost is very high for centralized generation, the total electricity consumption in the transformer service area was entirely provided by discharging the batteries. This was achieved by controlling the battery discharging to stop the imports through the transformer from the main grid during the peak time.

Entire peak mitigation was achieved by having 30 numbers of 13.2 kWh TESLA Wall E 2 battery packs installed in seven locations in three feeders.

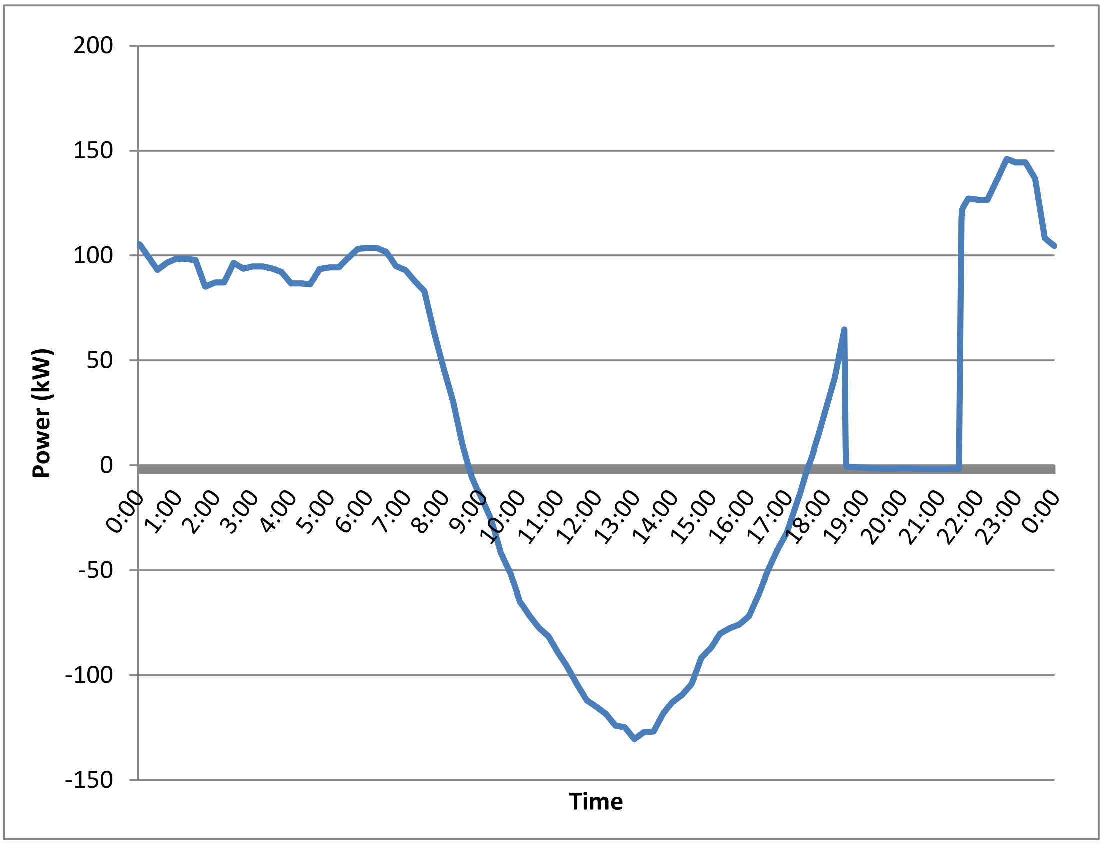


Figure 6.16 Transformer Load Curve with 250 kW of Rooftop Solar and Batteries for Peak Mitigation

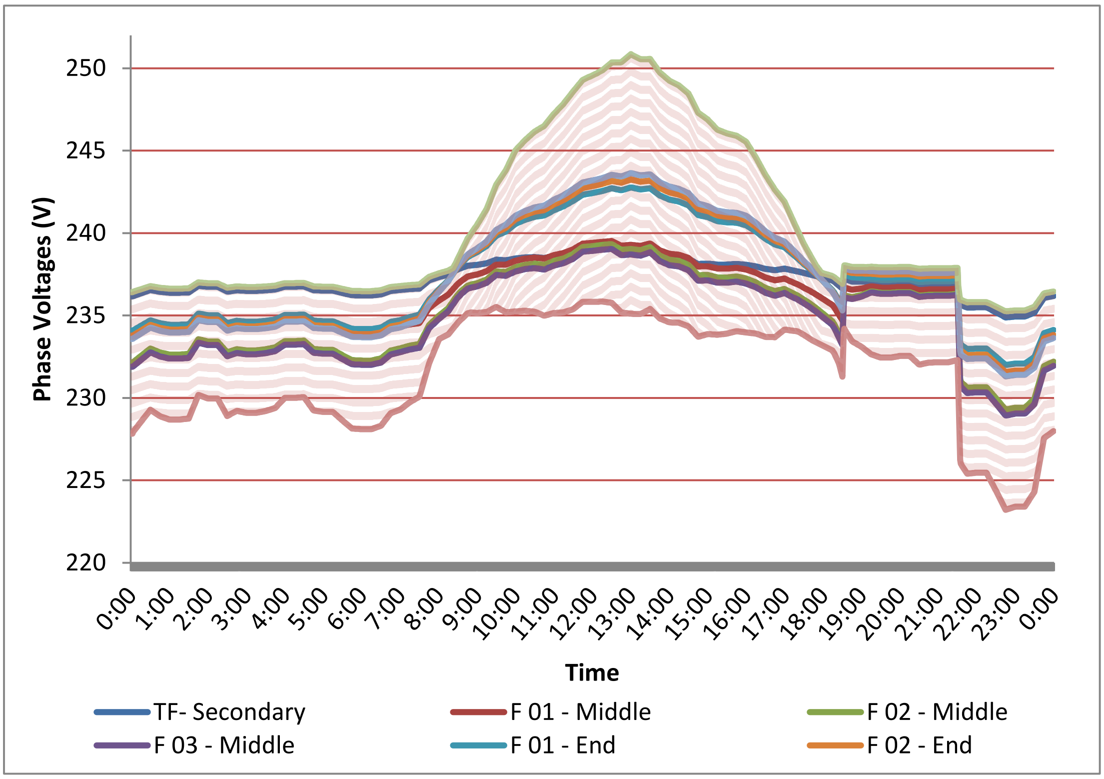


Figure 6.17 Phase Voltages of Feeders with 250 kW of Rooftop Solar and Batteries for Peak Mitigation

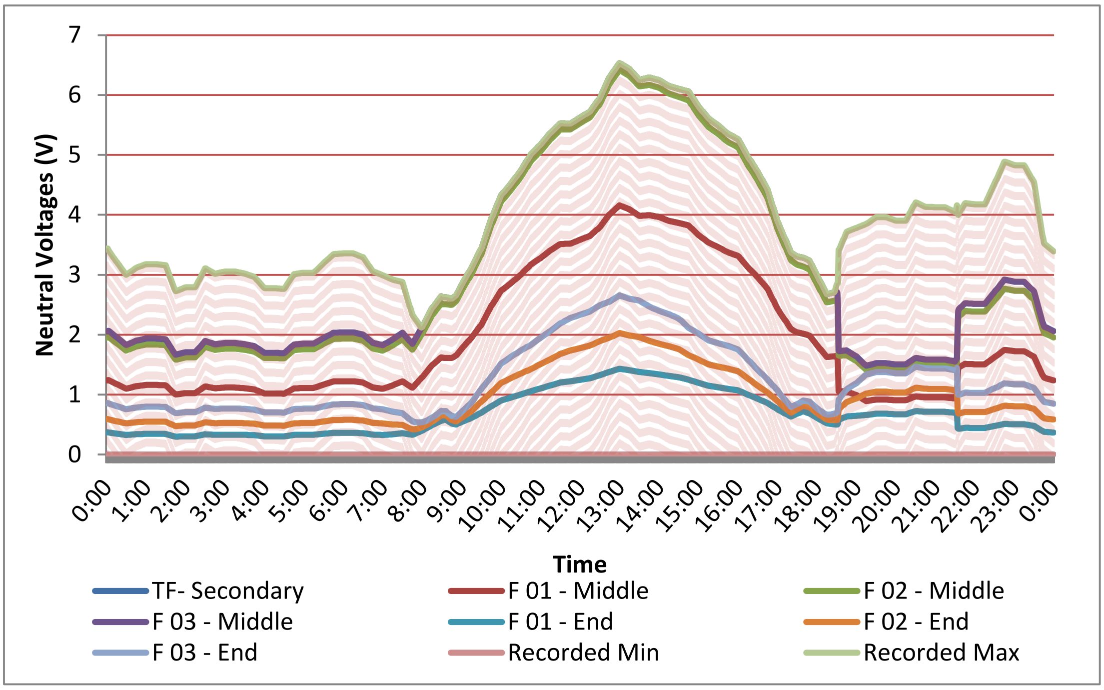


Figure 6.18 Neutral Voltages of Feeders with 250 kW of Rooftop Solar and Batteries for Peak Mitigation

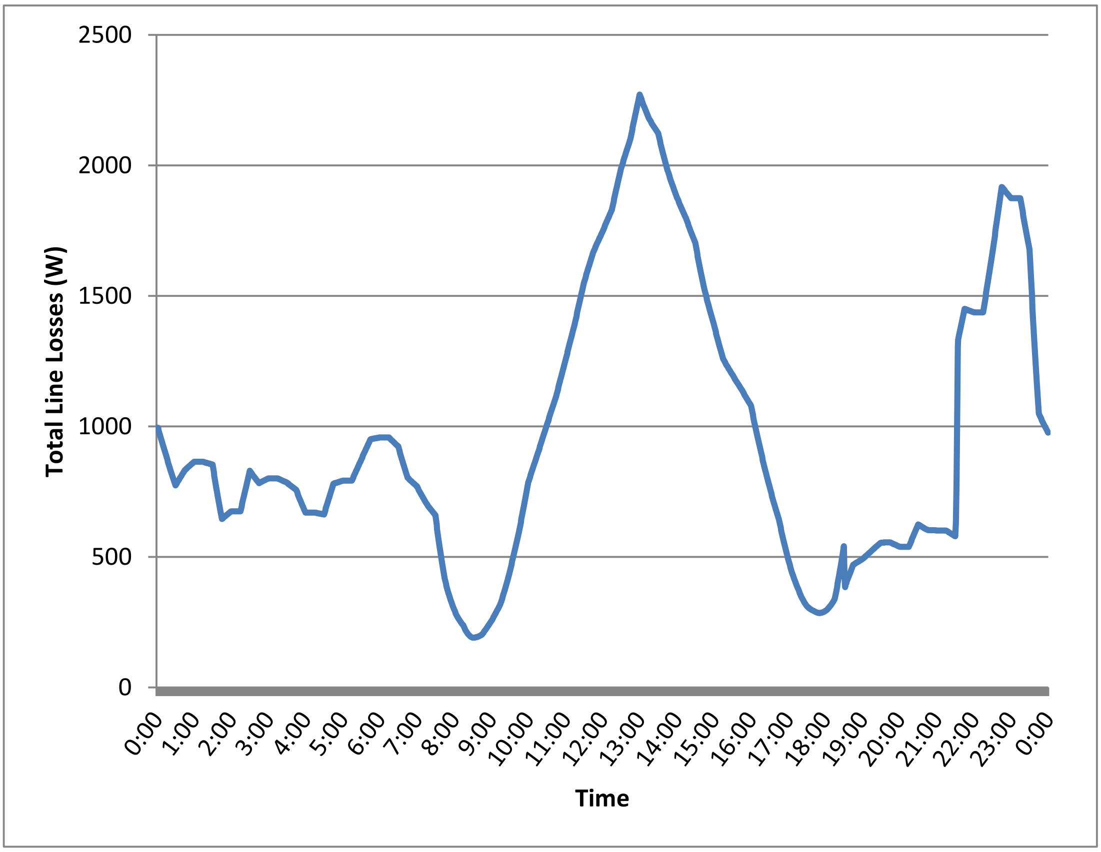


Figure 6.19 Total Line Losses of Feeders with 250 kW of Rooftop Solar and Batteries for Peak Mitigation

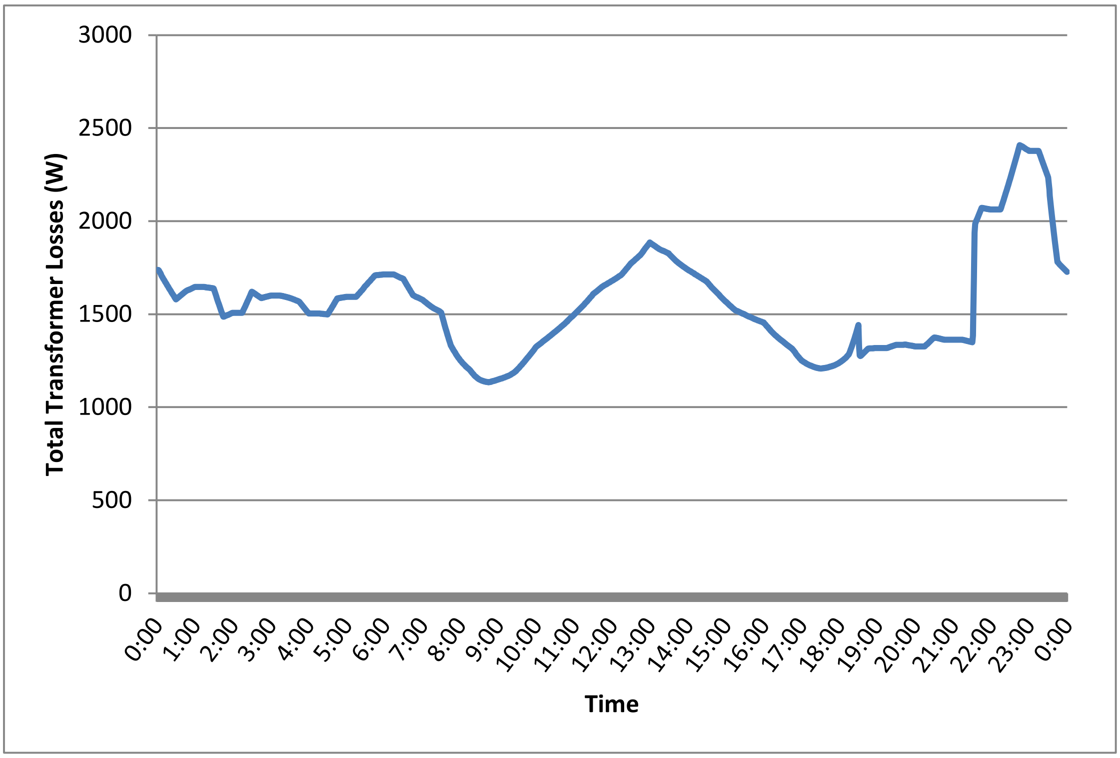


Figure 6.20 Transformer Loss with 250 kW of Rooftop Solar and Batteries for Peak Mitigation

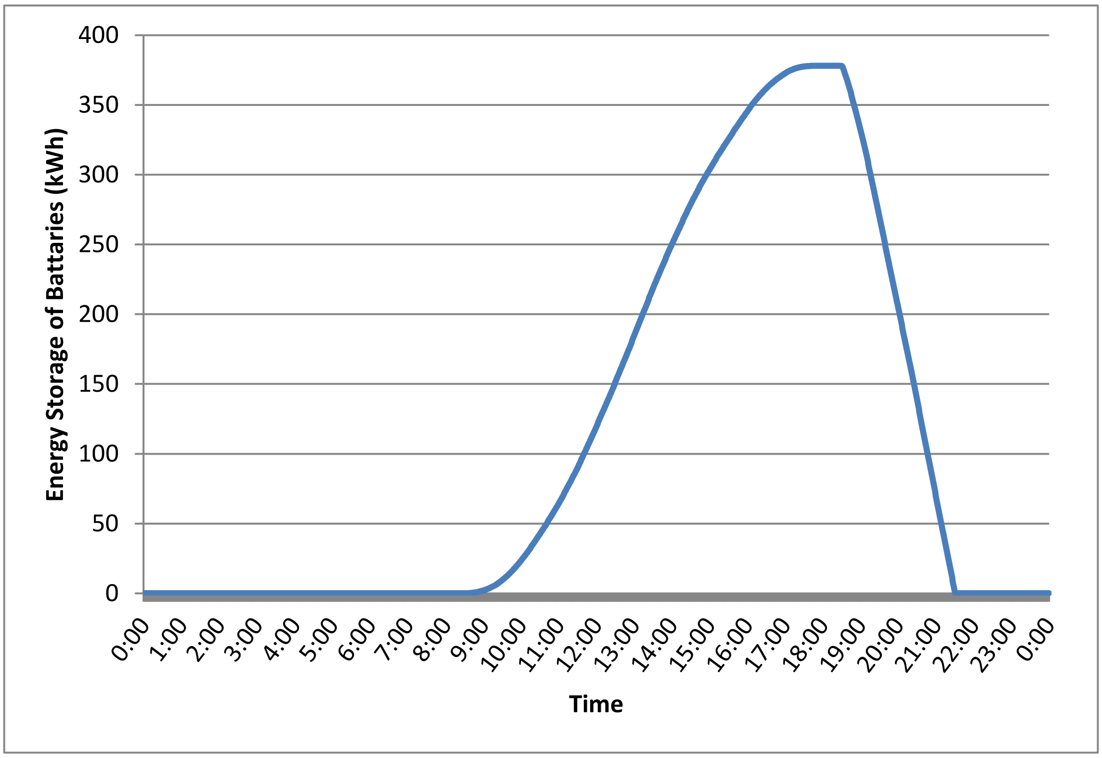


Figure 6.21 Variation of Energy Storage in Batteries with 250 kW of Rooftop Solar and Batteries for Peak Mitigation

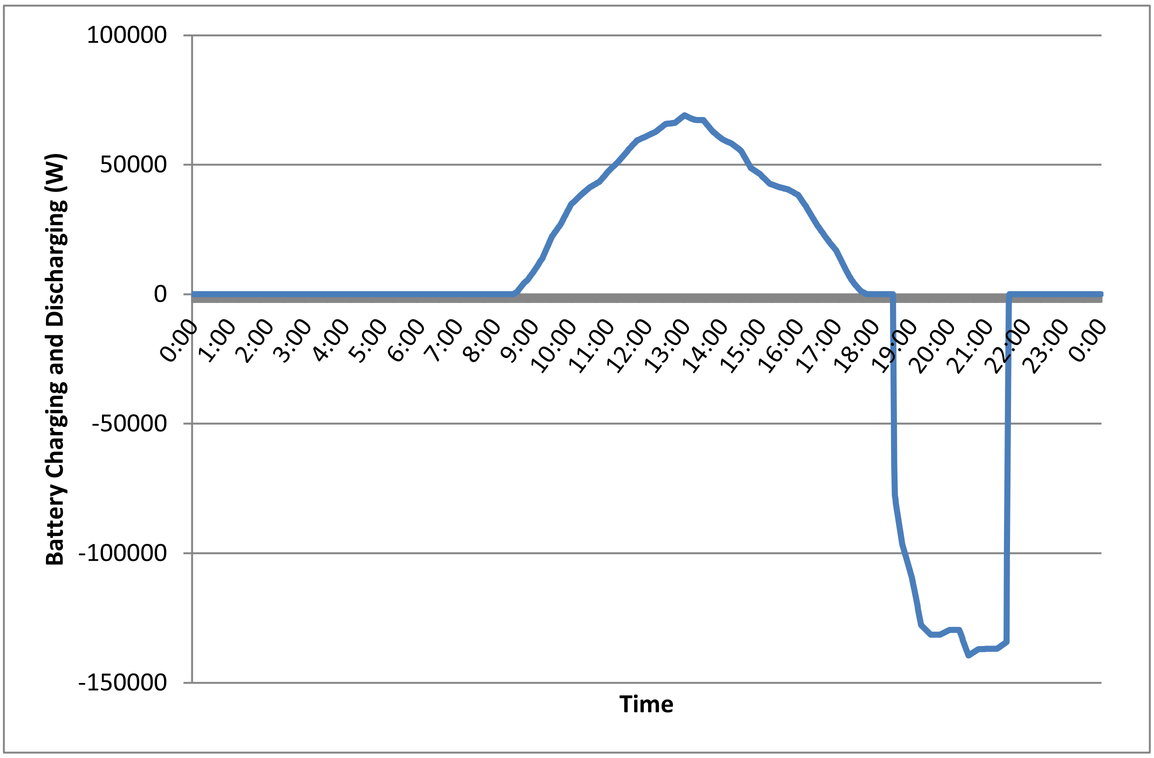


Figure 6.22 Battery Charging Discharging Curve with 250 kW of Rooftop Solar and Batteries for Peak Mitigation

6.1.5. Transformer with Actual Loads, 250 kW of Rooftop Solar and Batteries as Self Sustaining Smart Grid

The ultimate achievement of having distribution transformer service area based smart grid is to become self-sustain by the rooftop solar PV available inside the transformer service area and adequate battery backups for night time consumption.

In this case, entire rooftop solar generation was utilized inside the transformer area without exporting through transformer during daytime by charging the batteries using excess solar PV generation.

Stored energy was discharged during night time and morning without using the grid energy at that time slots by maintaining the power flow through transformer to zero. With 250kW of rooftop solar, 100% self-sustaining cannot be achieved due to entire night and morning demand were larger than the excess solar generation stored in batteries during daytime.

Grid power was required for limited time in night time and this time slot was selected in mid night to further reduce the impact on the grid.

Self-sustaining of smart grid operation was achieved by having 82 numbers of 13.2 kWh TESLA Wall E 2 battery packs installed in seven locations in three feeders.

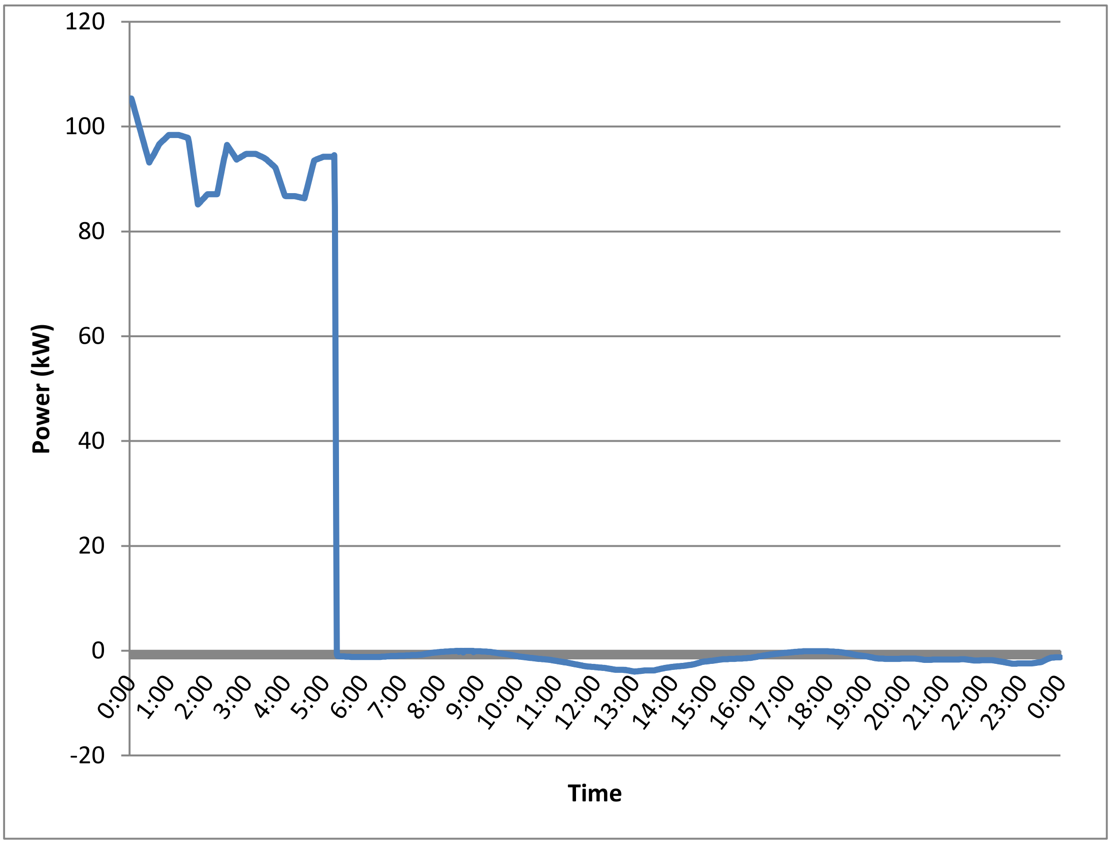


Figure 6.23 Transformer Load Curve with 250 kW of Rooftop Solar and Batteries as Self Sustaining Smart Grid

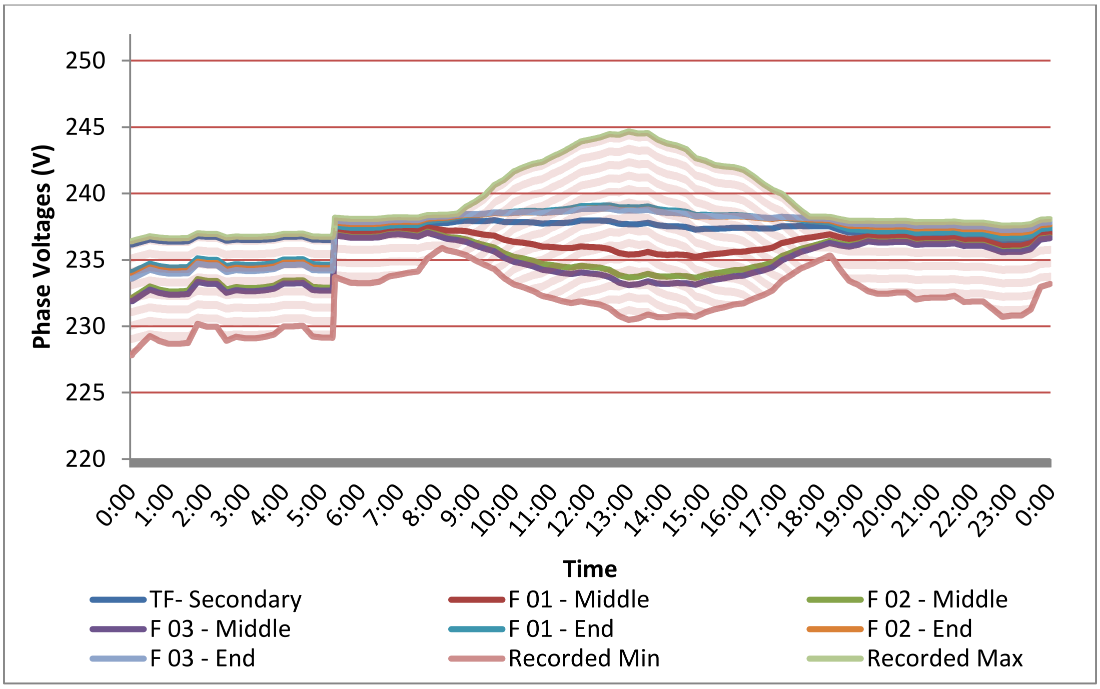


Figure 6.24 Phase Voltages of Feeders with 250 kW of Rooftop Solar and Batteries as Self Sustaining Smart Grid

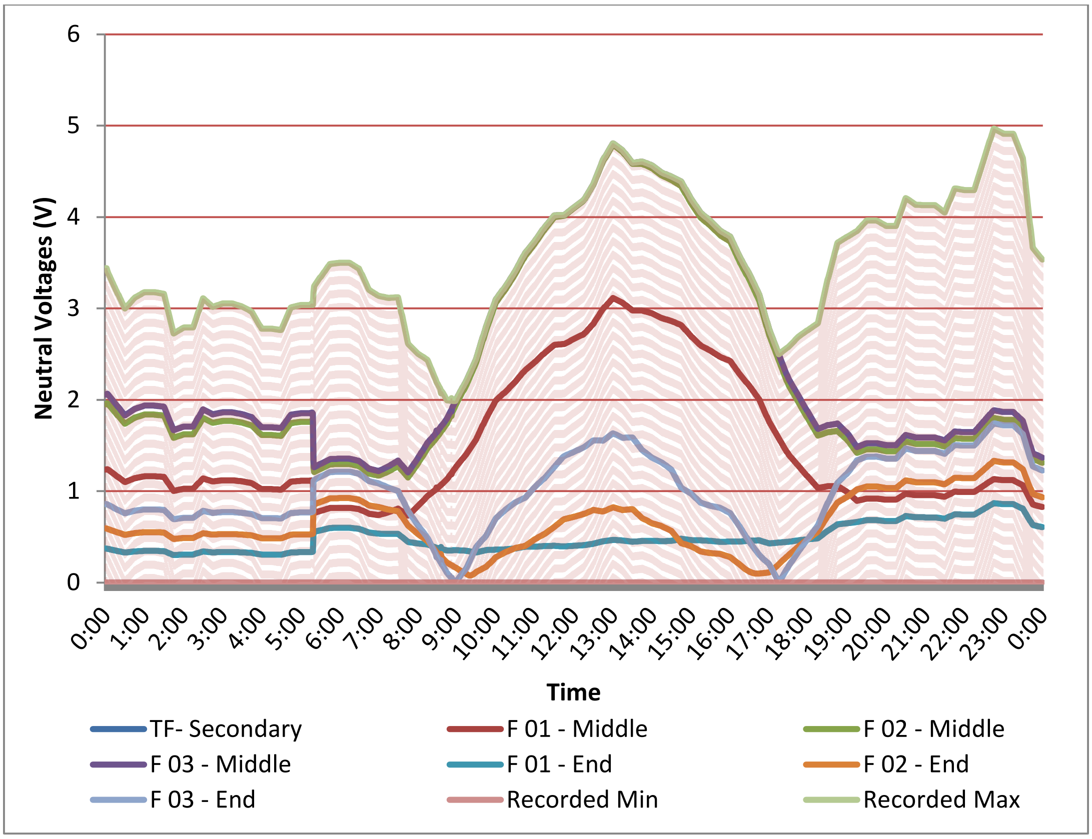


Figure 6.25 Neutral Voltages of Feeders with 250 kW of Rooftop Solar and Batteries as Self Sustaining Smart Grid

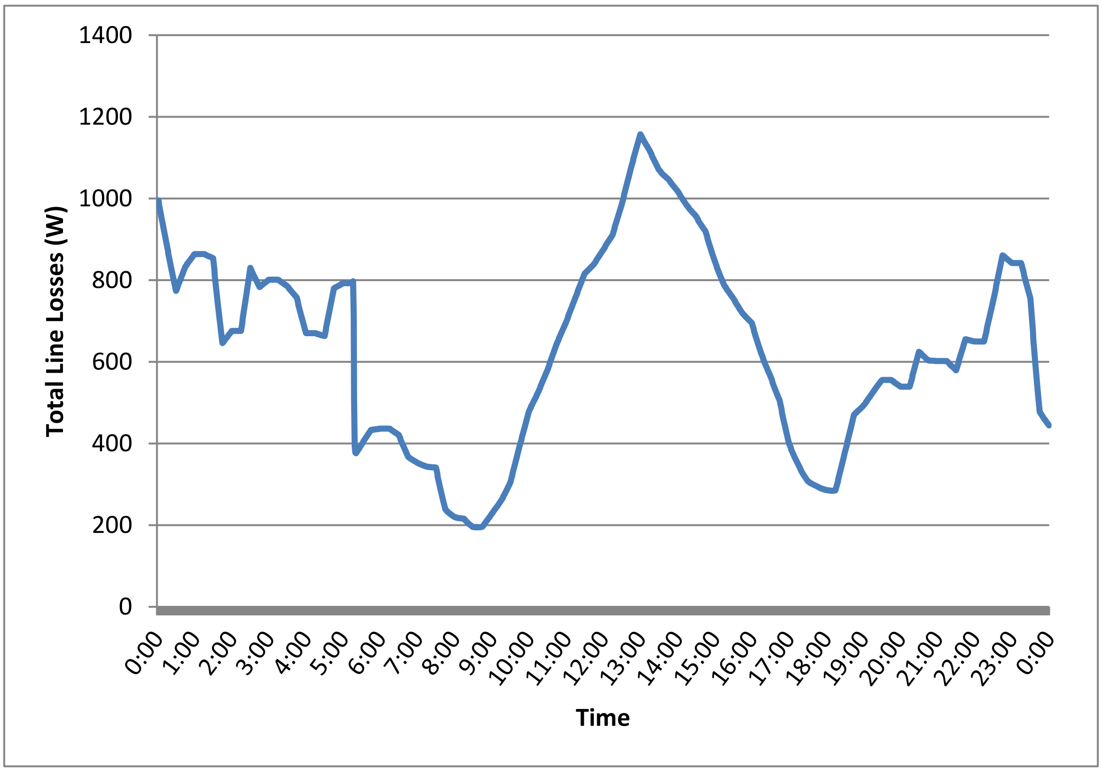


Figure 6.26 Total Line Losses of Feeders with 250kW of Rooftop Solar and Batteries as Self Sustaining Smart Grid

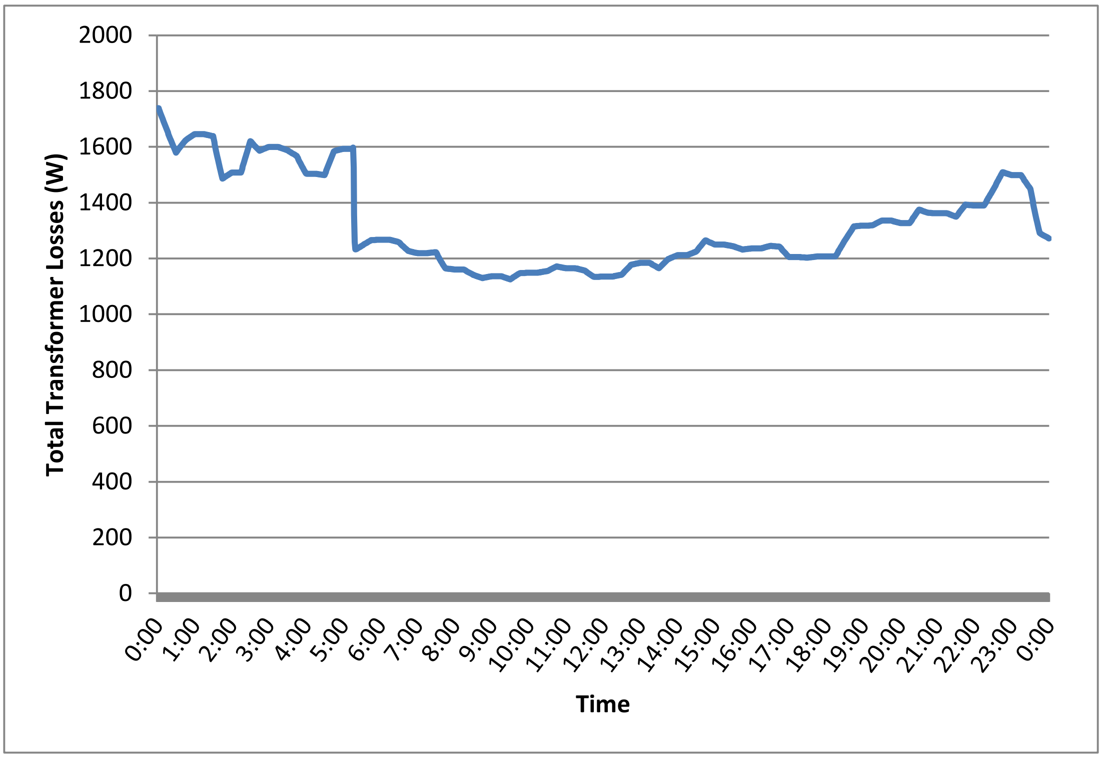


Figure 6.27 Transformer Loss with 250kW of Rooftop Solar and Batteries as Self Sustaining Smart Grid

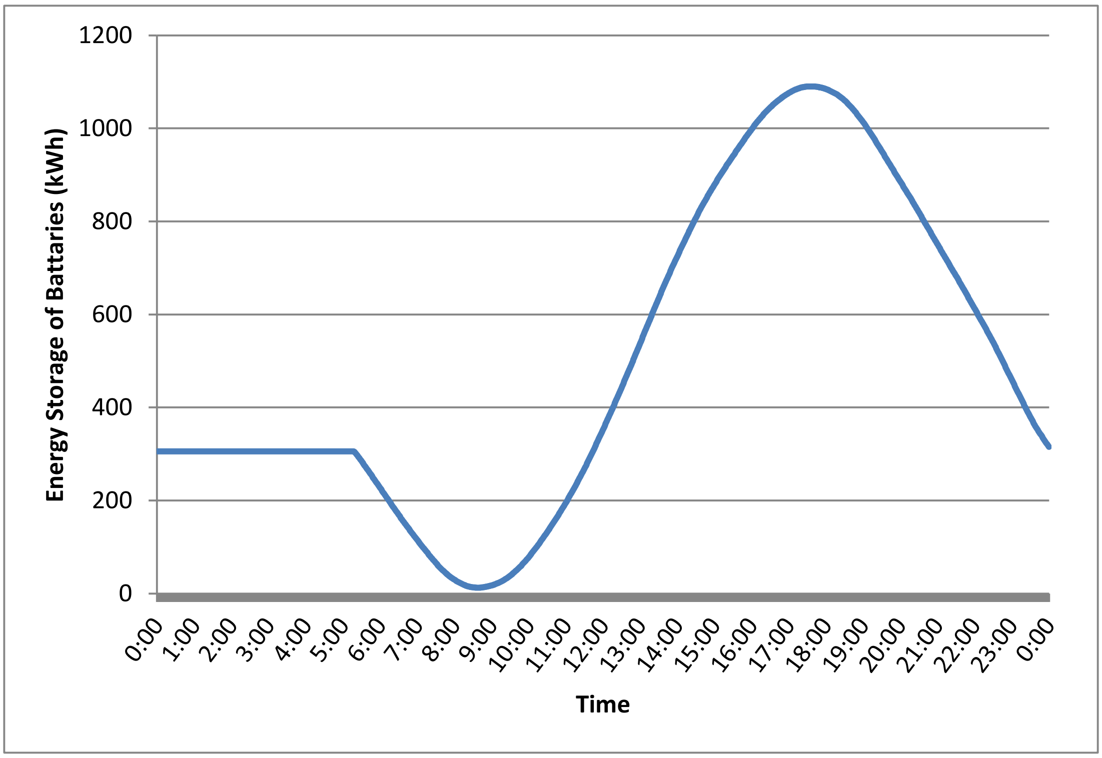


Figure 6.28 Variation of Energy Storage in Batteries with 250kW of Rooftop Solar and Batteries as Self Sustaining Smart Grid

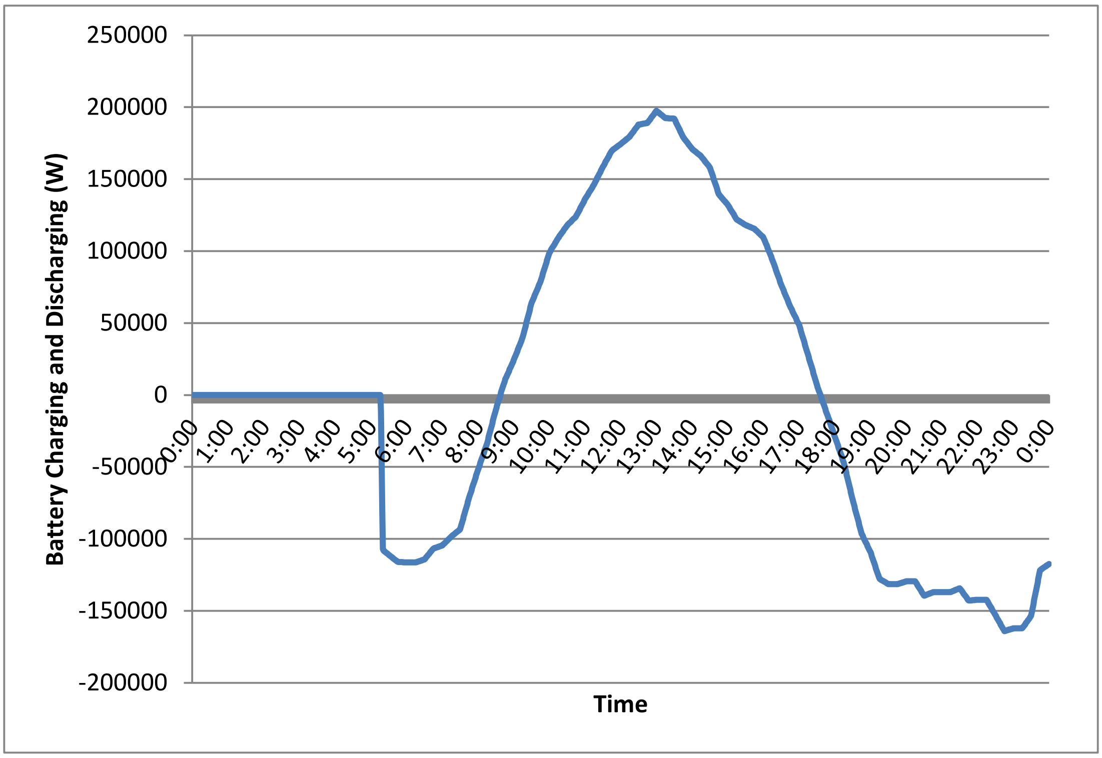


Figure 6.29 Battery Charging Discharging Curve with 250kW of Rooftop Solar and Batteries as Self Sustaining Smart Grid

4. Summary

In 6.1.1 when only the loads were available in the transformer service area without solar PV, LV network was in acceptable condition except the slight voltage reduction beyond allowable limit at the night time due to higher domestic consumption at night peak.

6.1.2 presented the behavior of actual transformer service area available today. Due to day time excess solar PV generation inside the transformer service area, line losses and transformer losses were reduced with the reduction of energy imports from the grid. Feeder voltage drops reduced during day time with the reduction of line currents. Slight increase of neutral voltage was presented due to unbalanced installations of single phase solar PV units, but it was not considerably high.

6.2.3 was the further expected situation of the transformer service area with installed rooftop solar PV capacity reaching up to the transformer capacity In this case, significant increase in feeder voltages were available during day time, exceeding the allowable upper limit with high neutral voltages. Very high line losses presented in day time due to the large unbalanced backward power flow in LV feeders. Even with the advantage of high power export to the grid, it is questionable to operate this kind of network with increased losses and exceeding voltage levels.

To mitigate the issues occurred in 6.2.3, proposed smart grid operation for future expected transformer service area is presented with battery storage and smart grid control. The size of the storage capacity was defined to obtain the specific outcome of each case.

In 6.2.4, fraction of daytime excess solar energy generation was stored in 30 TESLA batteries to completely avoid the night time peak. In this case, day time power export has reduced, hence the day time voltage came back to allowable range. Entire night time peak demand of the transformer service area was supplied by discharging the batteries without grid support.

6.2.5 Presented the self-sustaining distribution transformer with 82 TESLA batteries to completely store the daytime excess solar generation. But it can be seen that even after storing all the excess solar generation in day time the entire night time energy requirement cannot be achieved.

The comprehensive summary on all five simulations are tabulated in Table 4.1.

6.2. Limitation of the Study

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

a. Due to non-availability of customer data, assumptions had to be made on connected phase of the single phase customers, connected phase of the single phase solar inverters and load curves of some customers.

   Utilities may require these data in near future at least for urban transformer service areas.

b. Loads, rooftop solar PVs and batteries were modeled as constant current sources in the research. The actual modeling of each can be improved the results.

c. Controlling algorithms and mechanisms are not developed in detail for the smart grid operation. The development of detailed smart grid operating algorithms for proposed smart grid type distribution transformer operation would be an interesting future study.

d. Only the technical feasibility was considered in this study and the feasibility study of having smart grid type distribution transformers in economic and environmental basis will be a feature study area.

Table 4.1 Summary of All Simulations

Case		**Case 6.1.1**	**Case 6.1.2**	**Case 6.1.3**	**Case 6.1.4**	**Case 6.1.5**
Description		**Only with Actual Loads**	**Actual Loads + 120kW Solar (Present Network)**	**Actual Loads + 250kW Solar (Future Network)**	**Actual Loads + 250kW Solar + 30 Batteries for Peak Mitigation (Smart Grid 1)**	**Actual Loads + 250kW Solar + 82 Batteries for Self Sustaining (Smart Grid 2)**
Loads		Actual Loads	Actual Loads	Actual Loads	Actual Loads	Actual Loads
Rooftop Solar		-	120kW	250kW	250kW	250kW
No of TESLA WALL E2 Batteries (13.2kWh)		-	-	-	30	82
Total Energy Storage	kWh				396.00	1,082.40
Total Customer Energy Usage per day	kWh	2,309.70	2,309.70	2,309.70	2,309.70	2,309.70
Tot Solar Generation	kWh	-	629.60	2,006.90	2,006.90	2,006.90
Total Transformer Energy Imports	kWh	2,360.23	1,738.95	1,446.73	1,108.25	495.24
Total Transformer Energy Exports	kWh		(14.48)	(1,077.91)	(713.51)	(28.72)
Total Transformer Energy Loss	kWh	53.16	47.20	58.71	37.41	31.75
Total Line Loss	kWh	26.13	22.19	30.39	23.20	15.25

Case		**Case 6.1.1**	**Case 6.1.2**	**Case 6.1.3**	**Case 6.1.4**	**Case 6.1.5**
Description		**Only with Actual Loads**	**Actual Loads + 120kW Solar (Present Network)**	**Actual Loads + 250kW Solar (Future Network)**	**Actual Loads + 250kW Solar + 30 Batteries for Peak Mitigation (Smart Grid 1)**	**Actual Loads + 250kW Solar + 82 Batteries for Self Sustaining (Smart Grid 2)**
Total LV Network Loss		**79.29**	**69.38**	**89.10**	**60.61**	**47.00**
Total Battery Roundtrip Loss	kWh	-	-	-	41.84	117.85
Total Losses	**kWh**	**79.29**	**69.38**	**89.10**	**102.45**	**164.85**
Recorded Maximum Transformer Load	kW	148.49	148.49	146.00	145.94	105.38
Recorded Minimum Transformer Load	kW	69.88	(11.02)	(197.48)	(130.47)	(3.97)
Recorded Maximum Voltage in Feeders	V	236.66	241.30	🟥 256.36	250.85	244.67
Recorded Minimum Voltage in Feeders	V	🟥 221.92	🟥 221.92	🟥 221.41	🟥 223.21	227.83
Recorded Maximum Neutral Voltage in Feeders	V	3.87	4.30	🟥 7.35	🟥 6.53	4.97

🟥 Beyond Allowable Limits

7. Conclusion

High penetration of rooftop solar PV in urban LV feeders have changed the load flow of the LV network and the conventional operation pattern of the distribution transformer. The related effects have made quality and loss issues in the network that Sri Lankan utilities have to address urgently.

These issues have to be studied carefully, since more rooftop solar installations are continuously adding in to the distribution network. Accurate modeling of modern LV distribution network in Sri Lankan context is required with accurate system data in analyzing the behaviors of the distribution transformer service areas.

In this study, concept of having distribution transformer service area based smart grid is presented for mitigating the issues related to larger additions of solar rooftop PV in single distribution transformer service area. Analysis has been carried out to urban distribution transformer service area to study the behavior of future expected urban distribution transformer with rooftop solar, loads, batteries and centralized controlling mechanism.

Case studies presented with study results proves that the addition of rooftop solar PV with storage capacities in distribution transformer based smart grids have the potential of mitigating quality and loss issues occur due to large number of rooftop solar PV additions. Further, in such operation, solar PV generation can be utilized in more efficient manner inside the service area itself with reducing the grid burden and being independent.

Depending on the required outcome, battery capacity requirement has to be decided by simulating the model considering the daily operational cycle. Finally, it can be concluded that the future Sri Lankan urban distribution transformers have the potential of operating with distributed rooftop solar and battery storages as individual smart grids which beneficial to utility, grid and customer.

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