USE OF ON-LOAD TAP CHANGERS IN DISTRIBUTION TRANSFORMERS FOR ENHANCED RENEWABLE ENERGY INTEGRATION AND ACQUISITION : CASE STUDY

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Degree of Master of Science in Electrical Installations

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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(Prof. W.D.A.S. Wijayapala)

ABSTRACT

The increasing integration of rooftop solar PV systems into low-voltage (LV) distribution networks has introduced significant voltage regulation challenges. This study focuses on a real-world distribution transformer within the Sri Lankan electricity distribution network, where high solar penetration has led to persistent overvoltage issues across multiple feeders. Using OpenDSS modeling and field data, a range of mitigation strategies was analyzed, including power factor correction, parallel feeder installation, and fixed tap setting adjustments.

Simulation results revealed that traditional approaches such as manual tap changes were either insufficient or impractical for sustained voltage control. While power factor correction helped reduce peak voltages, it also increased system losses and required deviations from grid standards. Parallel feeder installations, although technically viable, were cost-prohibitive and lacked demand justification.

The study identifies the adoption of On-Load Tap Changers (OLTC) as the most effective solution. OLTCs offer real-time voltage regulation without the need for major infrastructure changes or policy modifications. The selected OLTC solution, which uses vacuum-based switching, was found to be cost-efficient, operationally reliable, and thermally robust, making it highly suitable for addressing the identified voltage issues.

This thesis concludes that OLTC technology provides a scalable and sustainable pathway to enhance hosting capacity and ensure voltage stability in LV networks with high solar PV penetration.

Keywords: On-Load Tap Changer (OLTC), voltage regulation, solar PV integration, distribution transformer, hosting capacity, renewable energy integration, overvoltage mitigation.

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LIST OF ABBREVIATIONS

Abbreviation	Description
LECO	Lanka Electricity Company Private Limited
CEB	Ceylon Electricity Board
LV	Low Voltage
MV	Medium Voltage
GIS	Geographic Information System
DPV	Distributed Photovoltaic
DC	Direct Current
AC	Alternating Current
OLTC	On-Load Tap Changer
DG	Distributed Generation
THD	Total Harmonic Distortion
NMD	Network Monitoring Device
kW	Kilowatt
kVA	Kilovolt-ampere
TF	Transformer
PS	Pre-Stressed
RC	Reinforced Concrete
PFC	Power Factor Correction

CHAPTER 1

1 INTRODUCTION

The global shift toward integrating renewable energy into power grids has been accelerating, and Sri Lanka is following this trend. A significant portion of renewable energy additions to the grid comes from distributed photovoltaic (DPV) systems, which are primarily connected at the distribution level. Over the past ten years, both the Ceylon Electricity Board (CEB) and Lanka Electricity Company (LECO) have seen a substantial increase in PV installations across their medium voltage (MV) and low voltage (LV) distribution networks.

Traditionally, distribution systems in Sri Lanka have been designed as radial networks intended for one-way power flow from the substation to end users. However, the integration of DPVs introduces reverse power flows, making the system operation more complex. As the number of DPV connections continues to grow, this can result in various power quality challenges, including voltage fluctuations and violations of network performance limits.

Such issues can hinder the ability of existing distribution infrastructure to support higher levels of solar PV integration. Despite these technical limitations, electricity distribution utilities are under increasing pressure from government bodies, regulatory authorities, and the public to modernize the grid and implement necessary upgrades that would enable the safe and efficient accommodation of greater DPV penetration.

With the rising penetration of DPVs, it has become essential to upgrade the distribution network using modern technological solutions. This includes incorporating advanced monitoring systems, automated voltage regulation, adaptive protection schemes, and real-time control mechanisms. These upgrades are vital not only to maintain power quality and network stability but also to enhance the grid's flexibility and readiness for future energy demands. The implementation of smart grid technologies and intelligent energy management systems can significantly improve the capacity of the network to integrate distributed renewable energy resources effectively. This thesis explores the challenges posed by high DPV penetration and investigates potential technological approaches to enhance the distribution network's capability to accommodate these systems sustainably.

1.1 Problem Statement

The rapid integration of rooftop solar photovoltaic (PV) systems into Sri Lanka's national distribution network, particularly under initiatives such as *Soorya Bala Sangramaya,* has introduced both opportunities and operational challenges for electricity utilities. While the environmental and economic advantages of distributed PV systems are clear, the existing low-voltage and medium-voltage distribution networks originally designed for unidirectional power flow are facing significant strain under increasing bidirectional energy flows.

Sri Lanka's distribution infrastructure comprises primarily overhead 33 kV and 11 kV medium-voltage lines and 400 V/230 V low-voltage lines, with underground systems limited to certain urban pockets. The lack of defined technical limits has led to unregulated solar penetration, particularly in densely populated regions like Kotte, Nugegoda, and Negombo, where transformers managed by LECO have recorded rooftop PV capacities exceeding 50% of their rated values.

The growing number of customer-owned rooftop systems, which can operate both as loads and sources, has created several operational issues. The following sections discuss the most frequently encountered issues in such scenarios, based on current research and field observations.

1. **Local Voltage Rise (Overvoltage):**

   One of the most commonly encountered challenges in distribution networks with high solar PV integration is the occurrence of local voltage rise. This typically happens when a solar PV system is installed at a specific point in the network, potentially causing the voltage at that location to exceed normal levels. The extent of this increase is influenced by the voltage regulation settings of the associated equipment. In Sri Lanka, the recommended voltage tolerance for low-voltage networks is ±6% of the nominal voltage. However, this limit may sometimes be exceeded by individual rooftop PV system owners in an attempt to maximize their energy output.

2. Increased Power Losses

Traditional distribution networks were originally designed under the assumption that electricity would consistently flow from centralized power plants to end users. However, with the widespread adoption of distributed generation systems such as rooftop solar, this assumption is no longer valid. Homes and businesses equipped with solar panels can alternate between consuming electricity from the grid and injecting excess power back into it. This bidirectional power flow can lead to increased losses in low-voltage (LV) distribution networks, presenting operational challenges for utility providers.

3. Voltage Unbalance and Transients in Solar Installations

Voltage imbalance is a concern that emerges when single-phase solar systems are unevenly distributed across the phases in a three-phase network. If solar arrays are not properly connected across all phases, it can result in unequal voltage levels, leading to unbalanced system conditions. The severity of this issue escalates as more single-phase systems are added.

Additionally, transients caused by the rapid variability of solar radiation are another challenge. Solar panels react almost instantaneously to changes in irradiance, and because they are sensitive to a broader spectrum than visible light, fluctuations can occur even on clear days due to atmospheric particles or pollutants. Without adequate voltage regulation mechanisms, these fluctuations can generate fast voltage transients that disrupt system stability.

4. Harmonic Distortion

Solar inverters, which are essential for converting direct current (DC) from solar panels into alternating current (AC), are inherently non-linear devices. Their operation can introduce harmonic distortion into the power system. As these inverters often operate at high switching frequencies to improve efficiency, they can produce high-order harmonics, which may negatively impact power quality and sensitive equipment connected to the grid.

5. **Stability Challenges**

   Because solar generation depends on sunlight, it is inherently intermittent; no power is produced at night or during unfavorable weather conditions. As a result, utilities must maintain standby capacity to ensure a consistent power supply during these periods. This requirement for backup generation introduces additional operational costs and complexity for the utility.

6. **Protection Coordination Difficulties**

   Conventional protection schemes in distribution systems are designed based on a radial topology with unidirectional current flow. The integration of distributed generation disrupts this model by introducing variable and reverse power flows. This dynamic environment complicates the coordination of protection devices, potentially compromising system reliability and fault detection.

Without clearly defined technical and regulatory boundaries, the unchecked expansion of rooftop solar PV threatens to compromise power quality, system reliability, and the long-term sustainability of the network. There is a pressing need to evaluate the technical limits of PV integration based on empirical data and system performance indicators such as overvoltage issues. This research examines the technical challenges associated with high levels of distributed photovoltaic (DPV) integration and evaluates viable technological solutions such as automatic OLTC to strengthen the distribution network’s capacity for accommodating systems. The study includes a case analysis based on real-world data to ensure practical relevance and applicability.

1.2 Project Objectives and Scope

1.2.1 Objective of the study

The primary objective of this study is to identify an effective and practical solution to address the prevalent issue of overvoltage in distribution networks, through the application of modern technology specifically, the implementation of on-load tap changers (OLTCs) in distribution transformers within the Sri Lankan context.

The specific objectives of this study are:

- To examine current techniques for enhanced solar PV integration and their limitations.
- To analyze and simulate the application of On-Load Tap Changers in reducing overvoltage problems associated with solar PV integration.
- To evaluate the cost-effectiveness of the proposed On-Load Tap Changers.

1.2.2 Scope of the study

This research focuses on identifying an effective and practical solution to mitigate the widespread issue of overvoltage in radial, low-voltage distribution networks in Sri Lanka, with specific emphasis on the application of modern technology namely, the deployment of on-load tap changers (OLTCs) in distribution transformers.

The study is based on real-world data obtained from the Lanka Electricity Company (LECO), which operates extensively in highly urbanized regions of the country. The initial analysis was conducted using data from existing distribution transformers within the LECO service area. For the detailed case study, the Negombo area was selected as the focus region due to its representative characteristics and operational challenges.

Transformers within the selected area were categorized into six distinct scenarios based on key operational parameters, and the transformer representing the worst-case scenario was chosen for in-depth investigation. Both the selected transformer and its associated low-voltage feeders were modeled for simulation and analysis.

For modeling and simulation, OpenDSS was used in conjunction with MATLAB to accurately represent network behavior under various conditions. The study also includes a comparison of current practices employed to manage overvoltage issues. In addition, alternative methods and advanced technological approaches including OLTC-based solutions were explored and evaluated.

Through simulations on the modeled test feeders, the research aims to determine the most immediately applicable and technically viable solution to mitigate overvoltage problems in Sri Lanka's distribution networks.

1.3 Thesis Organization

This section provides an overview of the thesis structure. A brief summary of the content covered in each chapter is presented below. Additional details, including simulation models and results from various analyses conducted during the research, are included in the appendices.

- Chapter 1 – This chapter outlines the evolution of solar photovoltaic (PV) systems. It also presents the problem statement, research motivation, scope, objectives, and the methodology adopted for the study.
- Chapter 2 – A comprehensive review of existing literature was carried out to understand the current state of knowledge and previous research related to the subject of this study. Particular emphasis was placed on the use of on-load tap changers (OLTCs) in transformers as a means of mitigating overvoltage issues. Additionally, alternative methods for addressing overvoltage and other challenges arising from high levels of distributed photovoltaic (DPV) integration were also explored.
- Chapter 3 – This chapter presents the impact analysis conducted to identify voltage-related issues in the distribution network. Based on customer complaints and recorded voltage deviations, a transformer with significant voltage irregularities was selected for detailed study. The analysis revealed consistent overvoltage conditions in three of its connected feeders.
- Chapter 4 – This chapter compares the current practices employed to mitigate overvoltage issues in distribution networks. It also investigates proposed methods, including the application of modern technologies such as on-load tap changing (OLTC), as potential solutions. The effectiveness and practicality of these approaches are analyzed and discussed in detail.
- Chapter 5 – This chapter presents the research conducted on the selected test feeder, including a detailed explanation of the modeling approach and the features of the OpenDSS simulation tool. The results and observations derived from the case study are also discussed.

- Chapter 6 – This chapter presents the conclusions drawn from the research and discusses the recommendations derived from the findings, as well as the study's limitations and directions for future work.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

Research into the integration of distributed generation (DG) systems particularly rooftop solar panels within electricity distribution networks has addressed issues such as reverse power flow, voltage regulation, system stability, total harmonic distortion (THD), and transformer performance and aging. This study, however, concentrates on developing a practical and effective strategy for mitigating the pervasive problem of overvoltage in radial, low voltage distribution networks in Sri Lanka. Specifically, it evaluates the use of on-load tap changers (OLTCs) in distribution transformers as a modern technological solution.

2.2 Impact of High PV Penetration on Electrical Distribution Networks

Overvoltage represents a key operational challenge for utilities managing high levels of distributed solar PV. Although Sri Lankan distribution codes recommend that feeder voltages remain within ±6% of nominal, many rooftop installations are configured with higher trip thresholds to maximize energy export. In areas of dense PV penetration, this practice can push feeder voltages beyond acceptable limits, not only reducing the output of some systems but also creating overvoltage conditions for neighboring customers. Additionally, the variable nature of solar irradiance introduces further voltage fluctuations, compounding power quality concerns.

High levels of PV generation can exceed local load demand, reversing the intended power flow direction and triggering reverse power flow. This condition significantly influences voltage regulation within the network, often leading to overvoltage scenarios, particularly during midday hours, when solar generation peaks and consumption is low. [1]

Reverse power flow has been observed to increase transformer loadings and introduce voltage rise in low-voltage (LV) networks. Analytical and simulation-based investigations reveal that as PV output surpasses local consumption, the surplus energy is injected back into the upstream network, causing voltage levels to rise above nominal values. This phenomenon is accentuated in radial distribution systems where impedance toward the substation amplifies voltage deviations. [1]

Data from real-world LV feeders demonstrate that overvoltage becomes prominent at PV penetration levels exceeding 20–30%, depending on the feeder's loading profile and electrical characteristics. [2] In extreme cases, voltages at customer endpoints can exceed regulatory limits, potentially leading to equipment malfunctions and disconnection of PV inverters due to protection trips.

Effective voltage regulation is essential to mitigate adverse DG effects on power quality. Techniques such as on-load tap changers, voltage regulators, and STATCOMs are used to stabilize voltage levels. [3] Additionally, smart inverters provide dynamic voltage support and reactive power management, help maintain voltage within acceptable limits, enhancing grid stability. [4]

High DG penetration impacts power quality, causing voltage fluctuations, harmonics, and flicker due to the intermittent nature of solar power which emphasizes the need for effective voltage regulation to maintain stability [5] and improper voltage regulation could lead to widespread voltage sags or swells, affecting both utility equipment and consumer appliances. [6]

Backfeeding complicates the coordination of protection devices like fuses, circuit breakers, and relays, which are designed for unidirectional power flow. Backfeeding could lead to delayed or nuisance tripping of protection devices, compromising network stability and safety. [7] Also backfeeding increases fault current contribution, potentially causing improper functioning of protection devices.

2.3 On-Load Tap Changers to Mitigate Overvoltage Issues

To address overvoltage issues resulting from high PV penetration, On-Load Tap Changers (OLTCs) are increasingly implemented as part of a dynamic voltage control strategy. OLTCs operate by adjusting transformer winding ratios in real time, maintaining voltage within permissible limits despite the variability introduced by PV systems.

Control strategies for OLTC operation include decentralized voltage regulation using local measurements at the transformer’s secondary terminals. These strategies leverage power flow and voltage data to adjust tap positions based on predicted voltage behavior, without requiring centralized communication systems. Case studies involving Monte Carlo simulations have shown that such control systems can prevent overvoltage and increase PV hosting capacity by dynamically maintaining voltage compliance across all customer nodes. [9]

Moreover, in networks with multiple feeders, OLTC algorithms that prioritize the feeder experiencing the highest voltage deviation have demonstrated effectiveness in mitigating both undervoltage and overvoltage conditions. By differentiating between load induced voltage drops and generation induced rises, these systems adaptively manage tap settings in response to real-time conditions. [10]

Smart meter data integration has also been instrumental in refining OLTC performance. In pilot deployments, such as those in Norway, voltage data from customer endpoints feed into control algorithms that adjust transformer settings proactively. These approaches have proven capable of reducing losses, maintaining voltage within statutory limits, and expanding the network's capacity to accommodate distributed PV systems. [11]

In summary, OLTCs play a vital role in managing overvoltage issues associated with high PV penetration. Their deployment, particularly with advanced control schemes and data-driven decision-making, contributes significantly to enhancing the reliability and flexibility of modern distribution networks.

CHAPTER 3

3 IMPACT ANALYSIS

The area selected for the case study is the LECO Negombo branch area, specifically focusing on the Katunayake feeder. This location was chosen due to its notably high recorded solar PV installation capacity, making it a significant contributor to renewable energy integration in the region. The area features a diversified network architecture with extended branch lines, supporting a range of distribution dynamics. Furthermore, the availability of both customer information and detailed solar PV system data. The region also encompasses a diverse mix of customer categories residential, commercial, and industrial enabling a comprehensive evaluation of system performance under varied consumption patterns.

3.1 Data Collection

1. **Low Voltage Feeder Analysis using Network Monitoring Devices**

Voltage quality along low-voltage (LV) feeders was assessed using data obtained from network monitoring devices (NMDs) installed at transformer points. These devices offered continuous measurements, facilitating the identification of locations exhibiting notable voltage deviations and irregularities.

2. **Transformer Loading Assessment via Remote Meter Reading**

To investigate suspected instances of reverse power flow (backfeeding), transformer loading data was acquired through remote meter reading systems. These readings provided detailed voltage and current profiles, enabling accurate evaluation of loading patterns and the extent of backfeeding at selected distribution transformers.

3. **Evaluation of Upgraded Transformers and Enhanced Feeders**

The study also incorporated analysis of NMD data from transformers and feeder lines that had been upgraded with enhanced cable capacities. This enabled an evaluation of how infrastructure improvements influenced voltage stability and transformer performance under varying load and generation conditions.

4. **Phase-wise Voltage Irregularities**

Phase by phase voltage data from NMDs was used to detect imbalances across the three phase system. This information was crucial in identifying where corrective actions were needed on site to address voltage issues and improve power quality.

3.2 Data Analysis and Observations

As part of the data analysis process, collected datasets were systematically categorized based on transformers into five distinct operational scenarios. The most critical among these is identified as follows:

'*Worst-Case Scenario: Excessive Solar Penetration Leading to Transformer Back feeding'*

Observations:

LV Voltage Fluctuations: Notable voltage irregularities were detected, particularly at the midpoints and terminal sections of low-voltage feeders, indicating instability under certain load and generation conditions.

Degraded Transformer Condition: A number of aging transformers located in these affected zones have exhibited signs of failure. Replacement programs have been initiated where necessary to mitigate associated risks.

Inconsistent Solar Distribution: Although several transformers have not yet experienced substantial solar input, high solar irradiance days intensify stress on the network, pushing some units beyond safe operational limits.

Impact of the Net Plus Extra Scheme: The growth in solar photovoltaic (PV) installations under this incentive scheme has accelerated the number of transformers operating in this high penetration risk category.

Customer Complaints: A surge in voltage related customer complaints has been reported, aligning with areas of known high PV output and load imbalances.

NMD (Network Monitoring Device) Data Patterns: Analysis of consumption data during daytime and evening peak periods revealed significant deviations from expected norms, supporting evidence of network instability.

Transformer Efficiency Losses: Elevated transformer losses have been recorded, indicating diminished efficiency and highlighting the need for targeted technical interventions.

3.3 Feeder Selection

The focus of this case study is the Katunayake feeder, situated in the Seeduwa service area within LECO's Negombo operations. This feeder includes a total of 31 distribution transformers, covering a geographic span of approximately 5 km^2. Within this feeder, there are 69 customers utilizing solar energy.

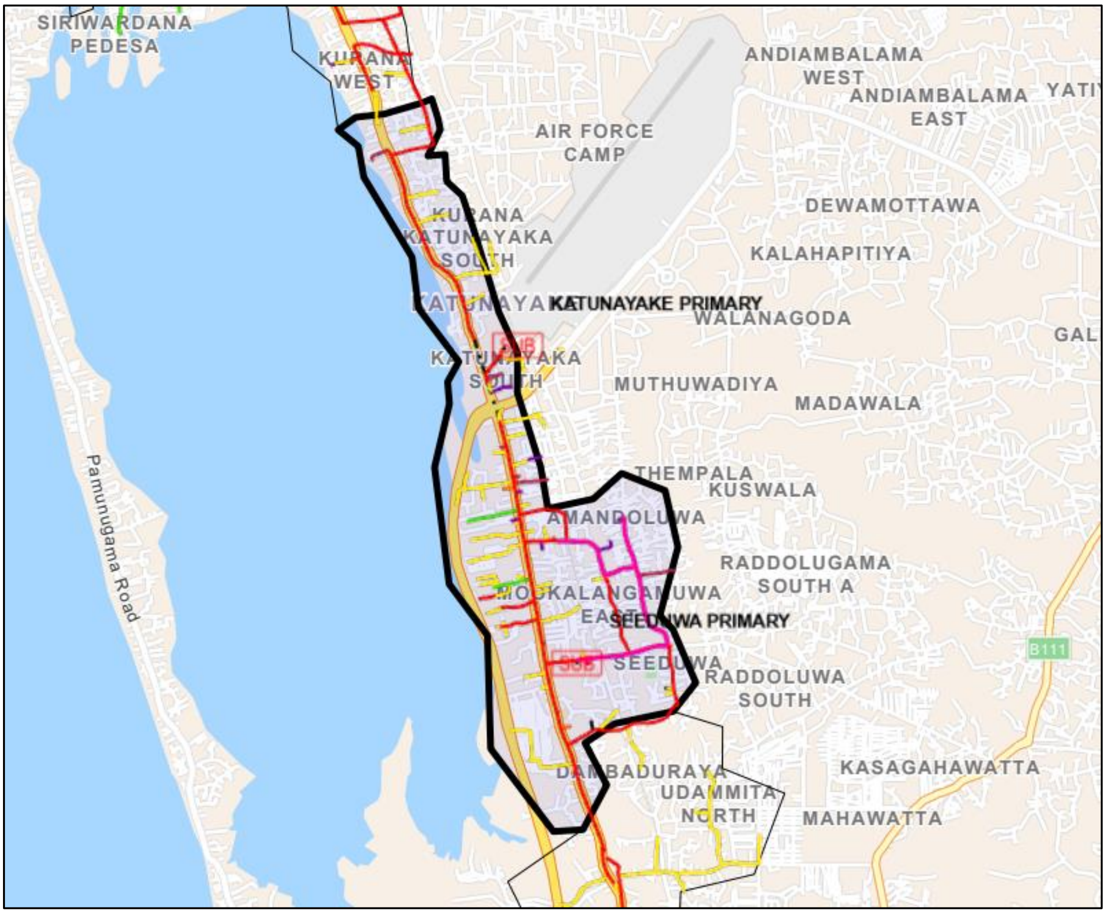


Figure 1: Seeduwa Customer Service Area

3.2.1 Behavior of the Feeder

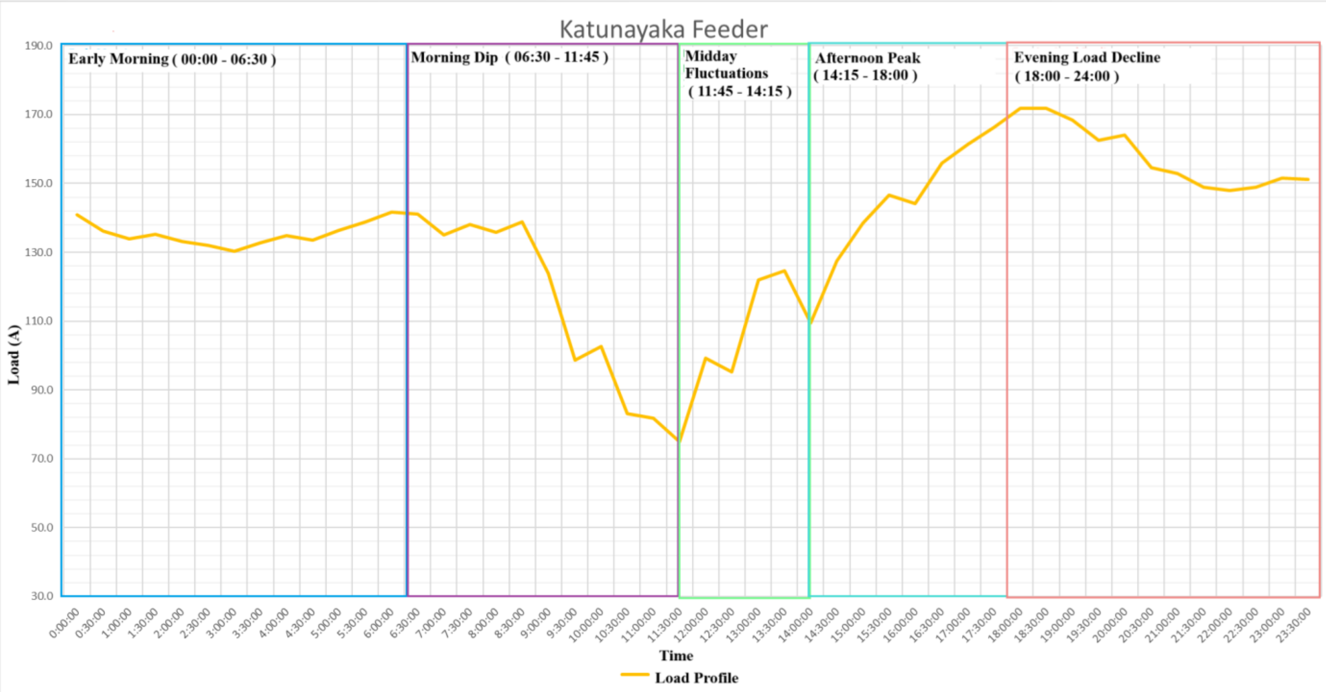


Figure 2: Load curve of the Katunayaka Feeder

This load curve of the Katunayaka Feeder, which includes high solar PV, shows a typical pattern for a system heavily influenced by solar generation. Here's a breakdown of the behavior observed:

1. **Early Morning (0:00 - 6:30)**: The load remains relatively stable but on the lower side, hovering around 130-140 A. This period likely represents nighttime when solar PV is not generating, and the load is primarily from base demand such as residential or industrial activities.
2. **Morning Dip (6:30 - 11:45)**: As the day progresses, there is a significant drop in the load starting around 6:30, reaching its lowest point between 9:30 and 11:45. This corresponds to the peak solar generation hours, where solar PV reduces the net demand on the feeder since local generation offsets a significant portion of the load.
3. **Midday Fluctuations (11:45 - 14:15)**: After the lowest point, the load begins to recover around 11:45, but it shows fluctuations, indicating variability in solar PV

output, possibly due to cloud cover or other intermittent factors affecting solar power production.

4. **Afternoon Peak (14:15 - 18:00)**: From midday to the late afternoon, there is a steady increase in load, reaching its highest point around 16:00-17:00. This rise could be due to the decline in solar PV generation as the sun sets, combined with increased demand as people return home from work or as industrial activities pick up.
5. **Evening Load Decline (18:00 - 24:00)**: After the peak, the load gradually declines in the evening as demand reduces and solar generation is no longer contributing. The feeder stabilizes in the range of 140-150 A in the late evening.

This curve highlights the strong influence of solar PV generation on the net load, particularly the morning dip and afternoon peak. The load curve is characteristic of a system with a high penetration of solar energy, where solar generation reduces net demand during sunny periods, but the load rises sharply when solar generation drops.

3.4 Transformer Selection

Data regarding transformers under Katunayaka feeder, along with the corresponding installed solar PV capacities, were obtained from the LECO system database. Based on this information, transformers were categorized into 6 scenarios and from worst scenario a transformer was selected for the case study. Selection of transformers representing the most critical conditions has been summarized in following table.

Table 1:Transformer Data

Transformer Number	Transformer Capacity (kVA)	Count of Solar Customers	Total Installed Solar Capacity (kW)	Solar Penetration (%)
BZ0451	100	17	124.75	125%
BZ0450	100	10	120	120%
BZ0431	160	7	166	104%
BZ0402	250	14	194	78%
BZ0436	160	12	86	54%

BZ0451 transformer was selected as the case study location based on a combination of technical and data driven considerations. It represents the highest recorded solar photovoltaic (PV) installation capacity within the study area, making it particularly relevant for assessing integration impacts. The feeder also features a diverse and extended network architecture, offering a representative model for distribution system behavior. Moreover, the availability of detailed customer and solar PV system data facilitated a comprehensive and reliable analysis. Transformer details are shown in following table.

Table 2: Transformer Details

Transformer	BZ0451
Primary	Seeduwa Primary Substation
Capacity of the primary	10MVA
Branch	Negombo Branch
Feeder	Katunayaka Feeder
Transformer Capacity	100kVA
Location	613 Dr. Sydney Premathiratne Road, Katunayake
Total Number of Customers	201
Number of feeders	3

Transformer BZ0451 supplies electricity to 201 customers in total. Among them, 17 customers (approximately 8%) have installed rooftop solar PV systems, while the remaining 184 customers (around 92%) are non-solar users. A detailed breakdown of the customer base connected to this feeder is presented in Table 3.

Table 3: Customer details of BZ0451

Customer category	Phase	Number of customers
Domestic	SP	134
Domestic	TP	16
Domestic Net Accounting	SP	8
Domestic Net Accounting	TP	4
Domestic Net Metering	SP	1
General Purpose 1.1	SP	30
General Purpose 1.1 – Net Account	TP	2
General Purpose 1.1 – Net Plus	TP	1
General Purpose 1.1 – Net Metering	TP	1
General Purpose 1.2	TP	4
Total		201

The low-voltage (LV) network layout of the feeder, obtained from the Geographical Information System (GIS), is illustrated in Figure 3.

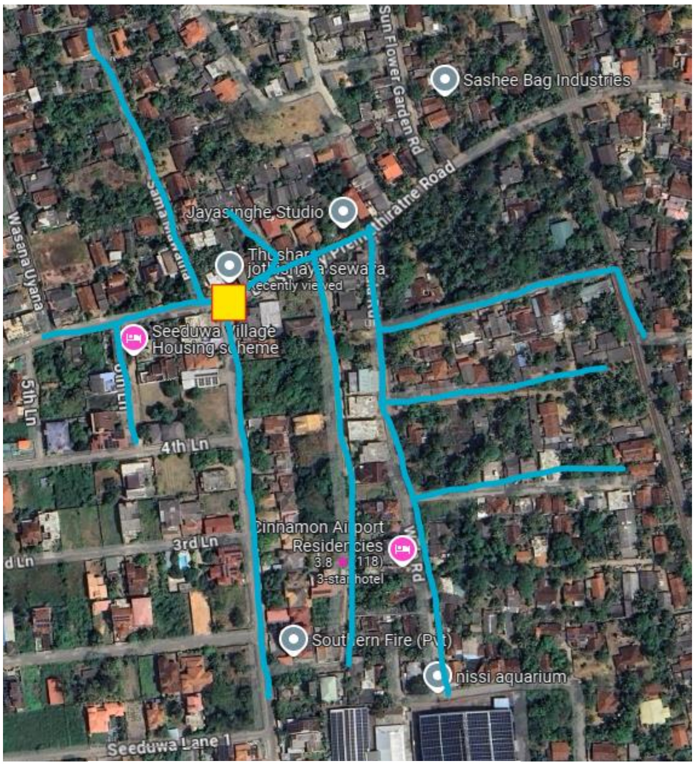


Figure 3: GIS map of BZ0451

	BZ0451 Transformer		Feeders

3.4.1 Behavior of the Selected Transformer (BZ0451)

3.4.1.1 Initial Condition

Transformer was operated with nominal tap position (Tap 2). Transformer had three LV feeders and were constructed with 70mm^2 ABC for Feeder 1, 3 and 50mm^2 ABC for Feeder 2. Feeder wise PV penetration was as follows.

Table 4: Feeder wise Solar PV Penetration

Feeder	Solar Installed Capacity (kW)
F1	37.25
F2	51.50
F3	36

The figure below presents the variation in demand at the distribution transformer level during the period from April 21 to April 27, 2023. This week was selected as it experienced high solar generation alongside regular human activity patterns, with no public holidays occurring within the time frame.

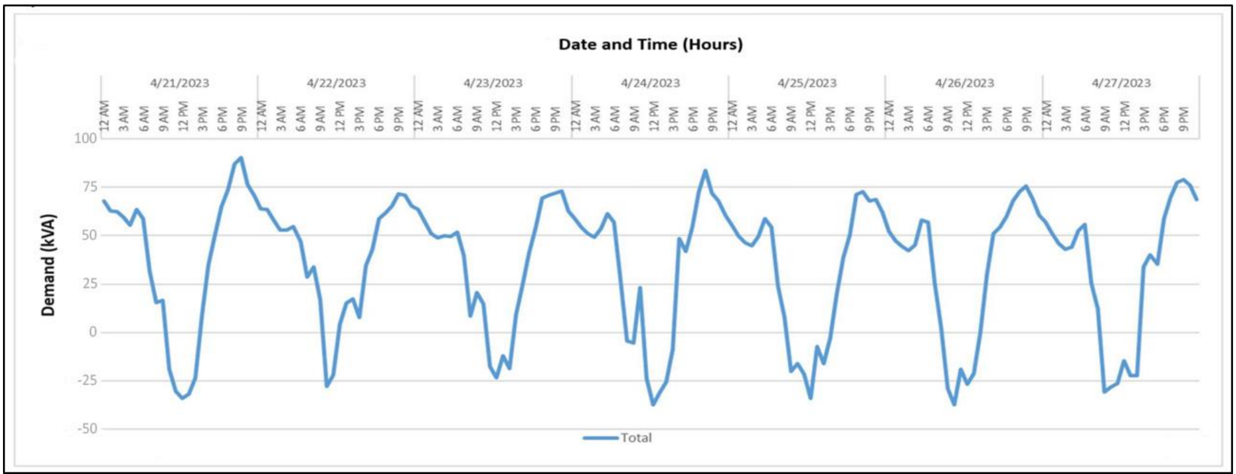


Figure 3: Behavior of the Selected Transformer

Transformer had a nighttime load of 80-90kVA during 8:00pm to 9:00pm and a daytime export demand of 30-35kVA.

3.4.1.2 Thermal loading levels and total fault contribution criteria

Table 5: Table of Thermal Loading Levels and Total Fault Contribution Criteria

Criteria	**PV Penetration Level**	**PV Penetration Level (Extreme minimum)**
Feeder selection overloading limit	F1-37.25kW F2-51.50kW F3-36kW	<112.23kVA for 100kVA TF with 50sqmm ABC <140.63kVA for 100kVA TF with 70sqmm ABC
Total fault contribution limit	F1-37.25kW F2-51.50kW F3-36kW	<96.92kVA limit for 100kVA

Transformer PV penetration	Max. reverse power flow through transformer 34kVA	<100kVA for 100kVA TF

Therefore, PV penetration in the LV network was within the limits of feeder, transformer thermal limits and total fault current contribution criteria.

3.4.1.3 Voltage Criteria

The following graphs indicates the transformer node voltage details, phase-wise voltage measurement details and voltage unbalance details acquired from April 21-27, 2023.

1. Transformer Secondary Node

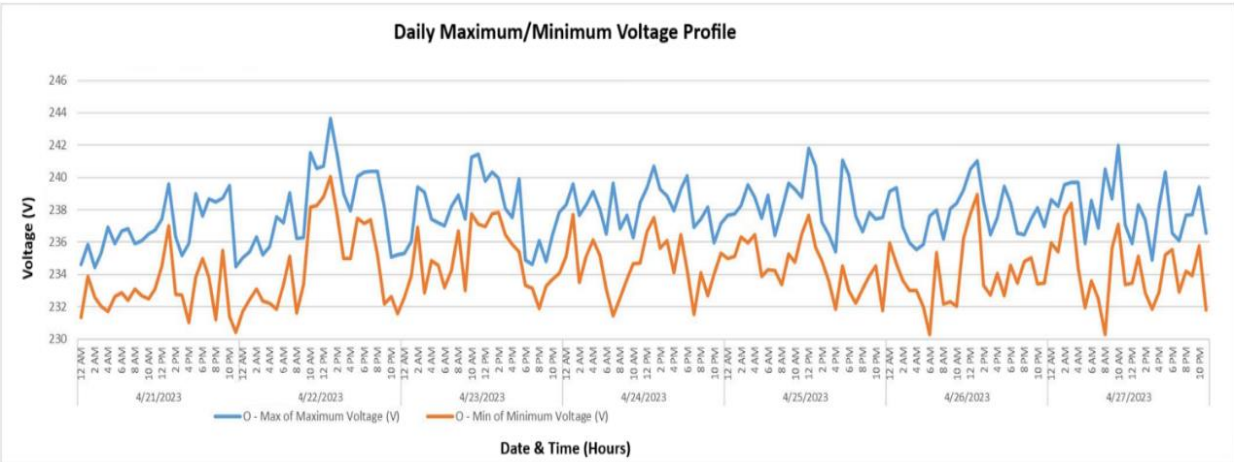


Figure 4: Transformer Node Voltage Details

The secondary voltage of the transformer is operating mostly on the 234V-240V range. The voltage unbalance is below 1%.

2. LV Feeder 1

The following graph illustrate the daily voltage fluctuations, both maximum and minimum recorded at monitored nodes associated with Feeder 1 during the observation period from April 21 to April 27, 2023.

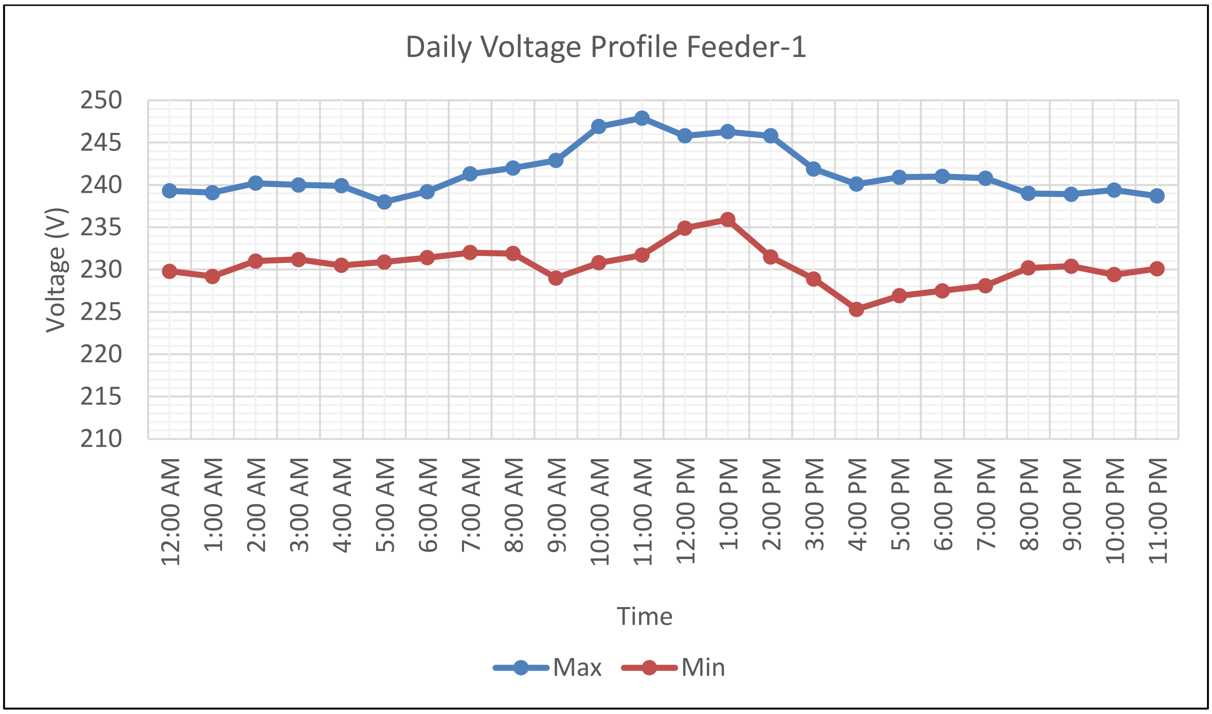


Figure 5: Feeder 1- Voltage Fluctuations

The highest recorded voltage, 246 V, was observed at monitoring point SK11/7/8. This node is supplied by a total of 20.25 kW of solar PV capacity, with a nearby pole contributing 17 kW. Voltage at this location exceeded the upper threshold limit between 10:00 a.m. and 2:00 p.m. The lowest voltage measurement, 225.3 V, was also recorded at SK11/7/8, occurring around 4:00 p.m. Despite these fluctuations, all monitored node voltages remained within the acceptable lower voltage threshold. Additionally, voltage unbalance across all monitored points was maintained within the 3% permissible limit.

3. LV Feeder 2

Observation period from April 21 to April 27, 2023.

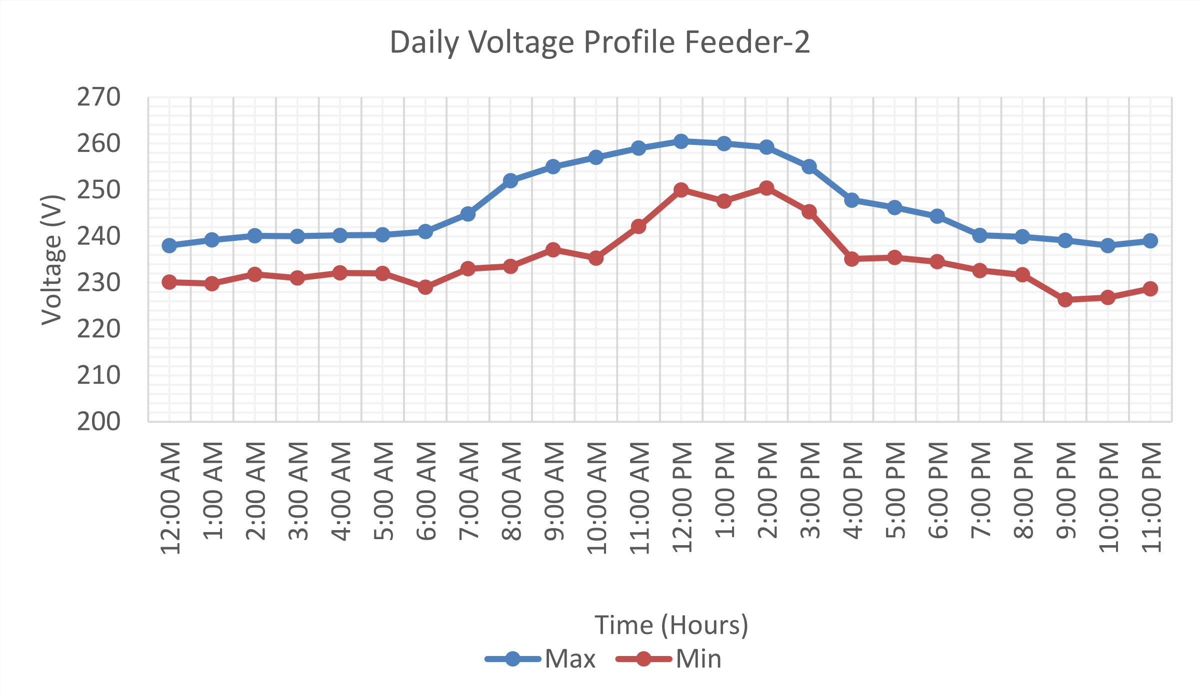


Figure 6: Feeder 2- Voltage Fluctuations

An overvoltage of 259 V was recorded at the feeder's far-end node, identified as SK11/7-1E, which is supported by two solar PV systems with capacities of 7.38 kW and 6.6 kW. Additionally, the mid-feeder node SK11/7-1B also exhibited overvoltage conditions. Despite these instances, all monitored nodes remained within the acceptable lower voltage threshold, with the minimum recorded value being 226.3 V. Voltage unbalance across all monitored locations was maintained below the 3% allowable limit.

4. LV Feeder 3

Observation period from April 21 to April 27, 2023.

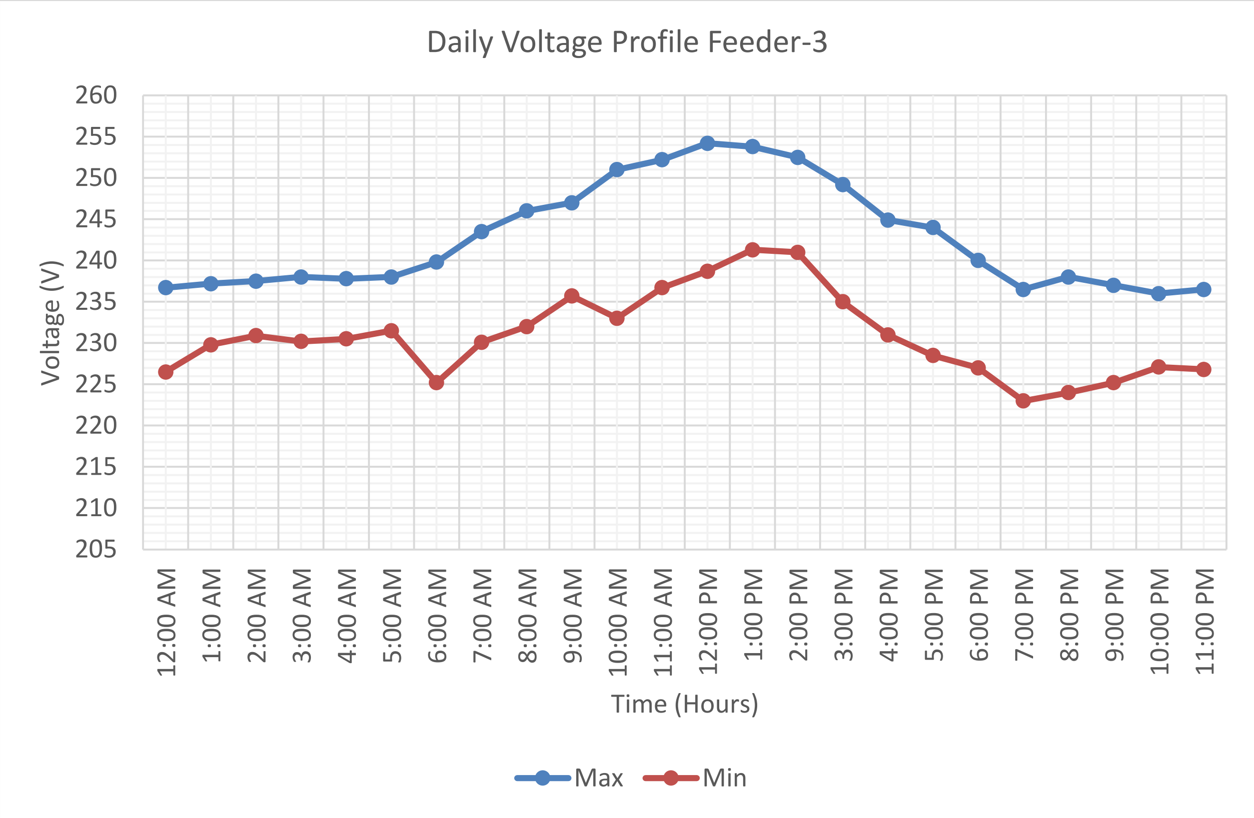


Figure 7: Feeder 3- Voltage Fluctuations

An overvoltage of 254.2 V (15-minute average) was observed at the far end of the feeder, specifically at node SK11/10/6D, which is connected to a single phase solar PV system. All monitored nodes remained within the acceptable lower voltage threshold, with the minimum recorded value being 223 V. Voltage unbalance across all monitored locations was maintained below the 3% allowable limit.

3.5 Summary of the Impact Analysis

Table 6: Summary of the Impact Analysis

Performance Criteria	Network Status	Decisions
Transformer Thermal Limit for PV	Within limits	-
Feeder Thermal Loading	All feeders are within limits	-
Total Fault Contribution of PV	All feeders are within limits	-
Overvoltage	All Feeders operate above the limits	Mitigation Required
	- F1 - 246V	
	- F2 - 259V	
	- F3 - 245.2V	
Low-Voltage	All feeders are within limits	-
Voltage Unbalance	F1, F2 & F3 feeders are within limits.	-

Overvoltage was the violated criteria for this LV network.

The following chapter explores the existing methods employed to address such challenges and evaluates their relevance to the specific issues identified in the case study.

CHAPTER 4

4 ANALYSIS OF PREVAILING MITIGATION STRATEGIES

4.1 Introduction

The integration of rooftop solar photovoltaic (PV) systems into low-voltage (LV) distribution networks presents a range of operational challenges, particularly in relation to voltage regulation. This chapter examines the prevailing techniques currently adopted by distribution utilities to address voltage issues associated with increasing levels of distributed solar generation. Each method is analyzed for its effectiveness in the context of the selected case study: BZ0451 Transformer in Katunayaka feeder under the Seeduwa primary substation.

4.2 Distribute solar customers evenly across all three phases in the feeder

One common mitigation strategy involves ensuring an even distribution of solar PV connections across all three phases of the feeder. This is typically done to minimize voltage imbalance and prevent localized overvoltage. Network monitoring tools are used to identify any uneven phase loads, after which connections may be reassigned to improve balance. The procedure of the process as follows.

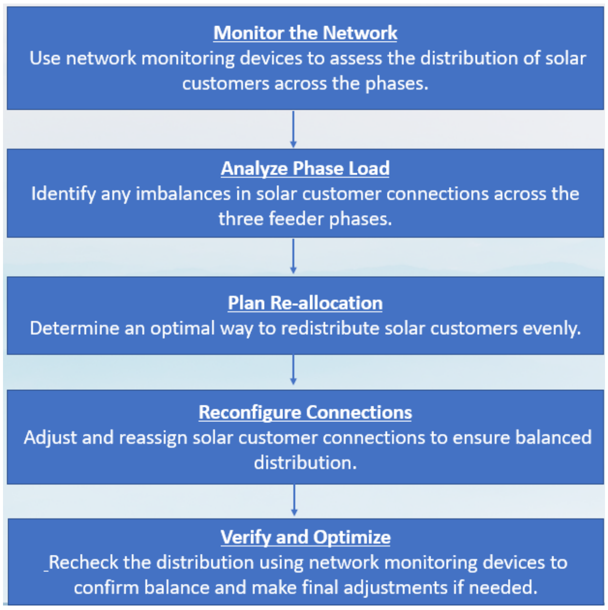


Figure 8: Procedure of the Process

In the context of the selected transformer (BZ0451), however, this method has already been fully applied. Solar customers have been appropriately distributed across the three phases of the feeder to achieve the best possible balance as follows.

Table 7: Phase-wise Solar Integration

Phase	Feeder 1 (37.25 kW)	Feeder 2 (51.5 kW)	Feeder 3 (36 kW)
1	12.42	17.6	12
2	12.42	17	11
3	12.42	16.9	13

Despite this, voltage deformities especially overvoltage continue to occur across the network. Therefore, this practice cannot be considered a viable solution for the current issue, as the phase distribution is already optimized and further adjustment would yield no significant improvement. The persistence of voltage rise under balanced conditions indicates that phase balancing alone is insufficient to manage the impact of high solar integration in this scenario.

4.3 Installation of Parallel Feeders

Another method employed to address voltage regulation challenges is the use of parallel feeders. By installing an additional conductor alongside the existing feeder and linking them through coordinated connections, utilities aim to reduce line impedance, improve voltage profiles, and enhance overall system redundancy. The procedure of the process as follows.

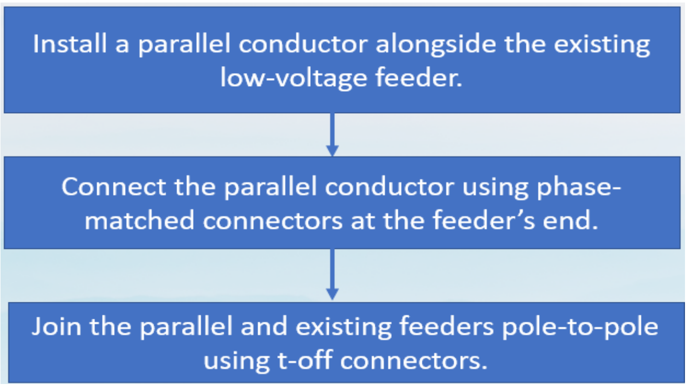


Figure 9: Installation of Parallel Feeders Procedure

4.3.1 Financial Analysis

A financial analysis was carried out for the implementation of a parallel feeder. All cost estimations were based on figures provided in the LECO Standard Cost Manual 2025. Due to existing infrastructure constraints, it was necessary to replace 9-meter RC poles with 9-meter PS poles. For the purpose of this analysis, only 18 poles out of a total of 66 were included in the cost calculation. As the objective of this infrastructure upgrade is to enhance hosting capacity and address overvoltage issues, a 70 sqmm bundled conductor was selected. Given that all three feeders connected to the selected transformer are experiencing overvoltage problems, the total feeder length considered for the analysis was 1,750 meters. The financial analysis is as follows.

Table 8: Financial Analysis of the Parallel Feeder Installation

Description	Cost (LKR)
70 Sqmm bundle conductor (1750m)	1,412,250.00
Several pole replacements 9m RC to 9m PS poles-18 (Tot. poles 66)	1,503,162.00
Labour + Overhead	902,492.00
Total Cost	**3,817,904.00**

This configuration helps reduce impedance, minimize voltage drops, and improve system redundancy. However, it requires careful planning to maintain proper phase alignment and avoid issues such as phase imbalance or harmonic distortion. Additionally, the added infrastructure may lead to increased maintenance needs, and its effectiveness may be limited in congested or widely spread distribution networks.

4.4 Power Factor Correction (PFC) and Inverter-Based Reactive Power Control

In modern distribution networks, especially those with significant solar PV integration, utilities are increasingly exploring power factor correction (PFC) as a method for voltage regulation. This approach leverages inverter-based technologies such as Volt-Var and Watt-Var control schemes to dynamically adjust reactive power in response to real-time voltage fluctuations at the local level. These functions enable solar inverters to actively participate in grid support by injecting or absorbing reactive power, helping to stabilize voltage profiles without the need for manual intervention.

Although not yet implemented in Sri Lanka’s distribution systems, these techniques are gaining attention globally due to their decentralized and scalable nature. Unlike conventional grid equipment, smart inverters can perform reactive power adjustments independently, based on pre-programmed control curves that respond to local voltage measurements. This allows voltage support to be provided exactly where and when it is needed, potentially deferring the need for costly infrastructure upgrades. The relevance and practical applicability of this method to the specific conditions observed in the case study area will be discussed in detail in the following chapter.

4.5 Adjusting Transformer Fixed Tap Positions

In the current distribution system, most transformers like the one examined in this study are designed for traditional load conditions and remain equipped with fixed tap positions, typically at Tap 2. These manual off-load tap changers usually provide five tap levels within a +2.5% to -7.5% voltage adjustment range. While a single tap reduction can lower voltage by approximately 2.75 V (2.5%) to provide headroom against overvoltage, this approach depends on the minimum voltage across the network remaining within acceptable limits (above 216.2 V). If the minimum voltage exceeds 222 V, tap changes may be implemented without further reinforcement.

However, these fixed tap settings are increasingly unsuitable due to the rapid growth in solar PV installations. Feeders now often experience voltage rise during peak solar generation periods, a condition that fixed tap transformers cannot adequately address. The lack of adaptability in fixed tap systems means they are ineffective at responding to the fluctuating voltage patterns introduced by variable solar output overvoltage during midday generation peaks and undervoltage during evening demand periods or under cloud cover.

In the case study scenario, adjusting the tap to position 1 alone was insufficient to bring voltage levels within the acceptable range, suggesting a need for additional tap positions. However, fixed tap positions are not a viable solution, as voltage rise is a time-specific issue linked to solar production hours. During other times, the voltage profile remains within normal limits, making manual tap adjustment throughout the day impractical.

Manually altering taps requires deploying technical teams, which is both time consuming and operationally inefficient. Such practices may also lead to inconsistent service quality and potential supply disruptions. Therefore, to address these dynamic voltage challenges and support the integration of renewable energy, the deployment of automatic On-Load Tap Changers (OLTCs) is recommended. OLTC equipped transformers can respond in real-time to voltage fluctuations, maintaining stability and improving overall network reliability. The relevance and practical applicability of OLTCs to the specific conditions observed in the case study area will be examined in detail through simulation analysis in the following chapter.

4.6 Automatic On-Load Tap Changer

Automatic OLTCs are used to regulate transformer output voltage under load by switching between winding taps. Vacuum switch OLTCs offer a cost-effective solution and are well-suited for low-voltage grid applications where budget constraints are a concern. Additionally, the system under study frequently experiences reverse power flow during periods of high solar generation, which results in elevated transformer temperatures. This condition can accelerate wear in thyristor-based OLTCs due to their sensitivity to thermal stress. In contrast, vacuum-based systems are more robust under such conditions, making them a better fit for sustained and stable operation.

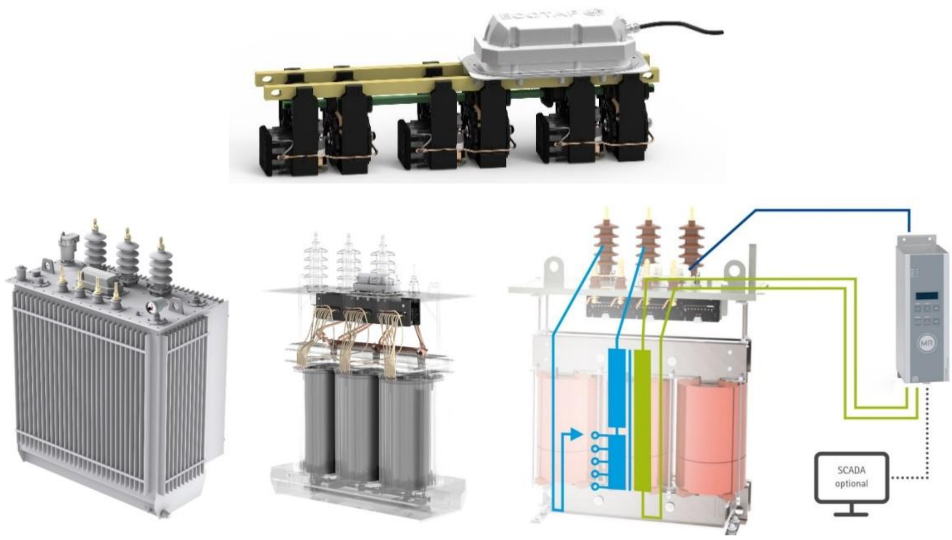
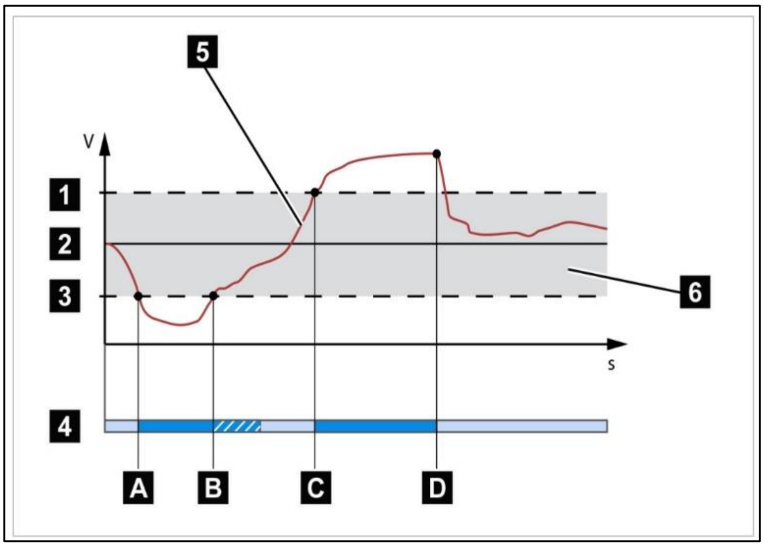


Figure 10: Automatic OLTC and Its Assembly

4.6.1 Operation of the On-Load Tap Changer



No.	Description	
1	+ B%	Upper limit
2	$U_{desired}$	Desired value
3	- B%	Lower limit
4	T (sec)	Set delay time
5	U_{actual}	Measured voltage
6	B%	Tolerance bandwidth

Figure 11: Operation of the On-Load Tap Changer

A: U_{actual} is outside the bandwidth. Delay time T starts

B: U_{actual} is back within the bandwidth before delay time T is complete.

C: U_{actual} is outside the bandwidth. Delay time T starts.

D: U_{actual} is still outside the bandwidth when delay time T is complete. Tap-change operation is initiated.

In Automatic OLTC, the system continuously monitors the transformer's output voltage and adjusts tap positions only when necessary. The motor drive unit does not take remedial action if the measured voltage (U_{actual}) stays within the specified tolerance range (bandwidth). Furthermore, if the voltage returns to the permissible range after a specified time delay (T1), no tap change will be initiated, even in the event of a brief voltage departure.

4.6.2 Algorithm for Tap Changer Operation under Varying Conditions

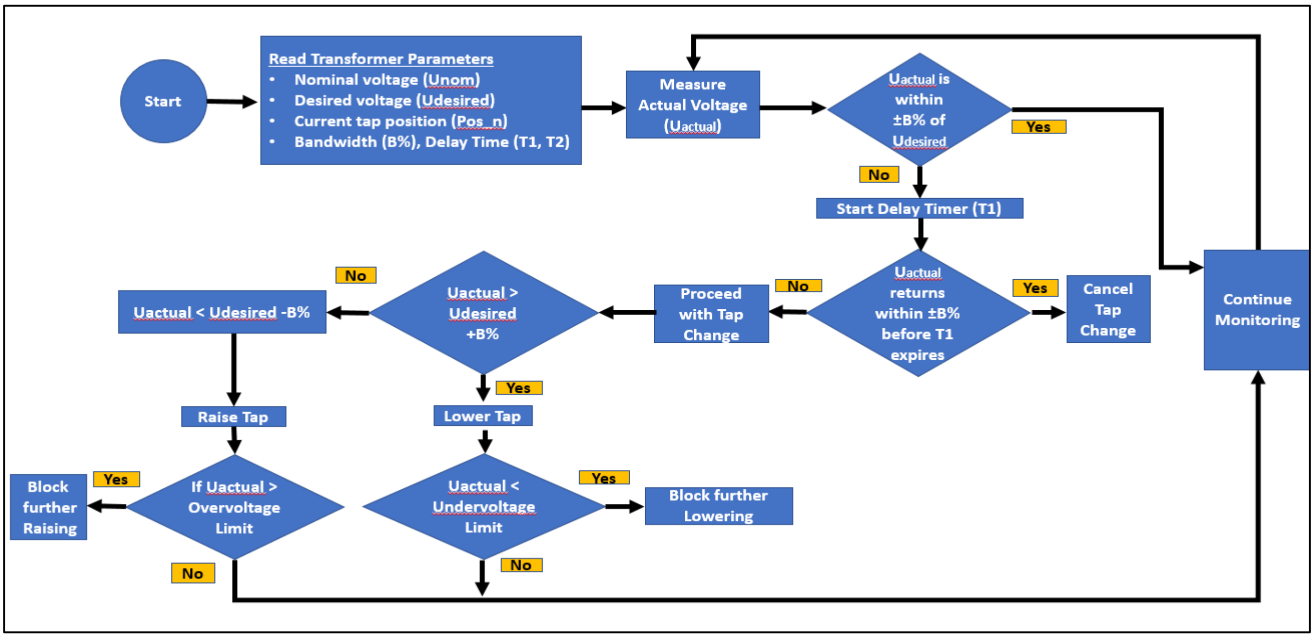


Figure 12: Algorithm for Tap Changer Operation under Varying Conditions

4.6.3 Practical Limitations

In automatic voltage regulation systems, tap changes are generally controlled using a single voltage reference point and are effective within a predefined voltage bandwidth. However, this approach becomes less reliable when a transformer supplies multiple feeders with varying voltage profiles. For instance, after a tap adjustment based on the reference point, the feeder experiencing overvoltage may return to acceptable levels, while another feeder may subsequently drop below the minimum voltage threshold, resulting in undervoltage. This imbalance highlights a key limitation of using a single reference point in systems with diverse feeder conditions.

4.6.4 Financial Analysis

A financial evaluation was conducted based on a commercially available product, the ECOTAP VPD, developed by Maschinenfabrik Reinhausen (MR), which has been successfully deployed in distribution networks worldwide. This compact device can be integrated into existing distribution transformers with minor structural modifications, preserving the original transformer core. Cost projections were derived using data from the LECO Standard Cost Manual 2025 to ensure alignment with local budgeting practices.

Table 9: Financial Analysis for the Automatic OLTC

Description	Amount (LKR)
Cost of the automatic tap changer (Euro 5000)	1,567,364.41
Cost of the transformer (100kVA)	1,849,490.00
Total	**3,416,854.41**

4.7 Summary of Analysis of Prevailing Mitigation Strategies

An evaluation of various mitigation strategies revealed several key insights. Attempts to redistribute solar customers across phases proved ineffective, as the existing phase balancing was already optimized. Although installing a parallel feeder could enhance hosting capacity, it was not economically viable compared to the proposed alternative, especially since there was no demand-side requirement for new grid infrastructure. Power factor correction helped reduce peak voltages but failed to consistently maintain voltages within the permissible range and slightly increased system losses. Fixed tap changers were found unsuitable due to their inability to accommodate significant voltage fluctuations between daytime solar peaks and nighttime lows, and manual adjustments were deemed impractical. In contrast, on-load tap changers (OLTCs) offered continuous, automated voltage control, effectively mitigating both overvoltage and undervoltage conditions, and thus emerged as the most practical and reliable solution.

CHAPTER 5

5 SIMULATION AND RESULT ANALYSIS

5.1 Modeling and Development of the Test Feeder

The Open Distribution System Simulator (OpenDSS) was used for modeling the distribution network. As a comprehensive simulation tool designed for electric utility distribution systems, OpenDSS supports detailed analysis of electrical behavior under various conditions. In this study, it was integrated with MATLAB to develop a generalized model. The test feeder model was constructed using OpenDSS scripting, based on actual data related to transformers, distribution lines, connected loads and rooftop solar PV systems. A steady state analysis was then carried out under a defined loading condition to evaluate system performance.

5.1.1 Modeling of Selected LV Transformer

The BZ0451 is a 100kVA 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.
- 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.BZ0451 windings=2 buses=(Sourcebus, loadbus) conns=(delta, wye)
kvs=(11, 0.4) kvas=(100, 100) %Rs=(1.41, 1.03) %loadloss=1.516 %Noloadloss=0.2237
```

5.1.2 Modeling of Selected LV Feeders

For LV feeders, LECO uses Aerial Bundled Conductors (ABC), which are four core aluminum twisted conductors with a neutral conductor as a messenger cable. Extruded cross-linked thermosetting polyethylene (XLPE) is used to insulate each core, and the cores are twisted together using a right hand lay. The following table lists the conductor data for the ABC conductors that were used.

Table 10: Aerial 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	mm^2	70	50	70	50
2	Neutral / messenger conductor	mm^2	50	35	50	35
3	Conductor Resistance (20°C)					
	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°C)					
	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

The following figure shows the feeder distribution, lengths, and all four types of ABC cables for the chosen test feeder.

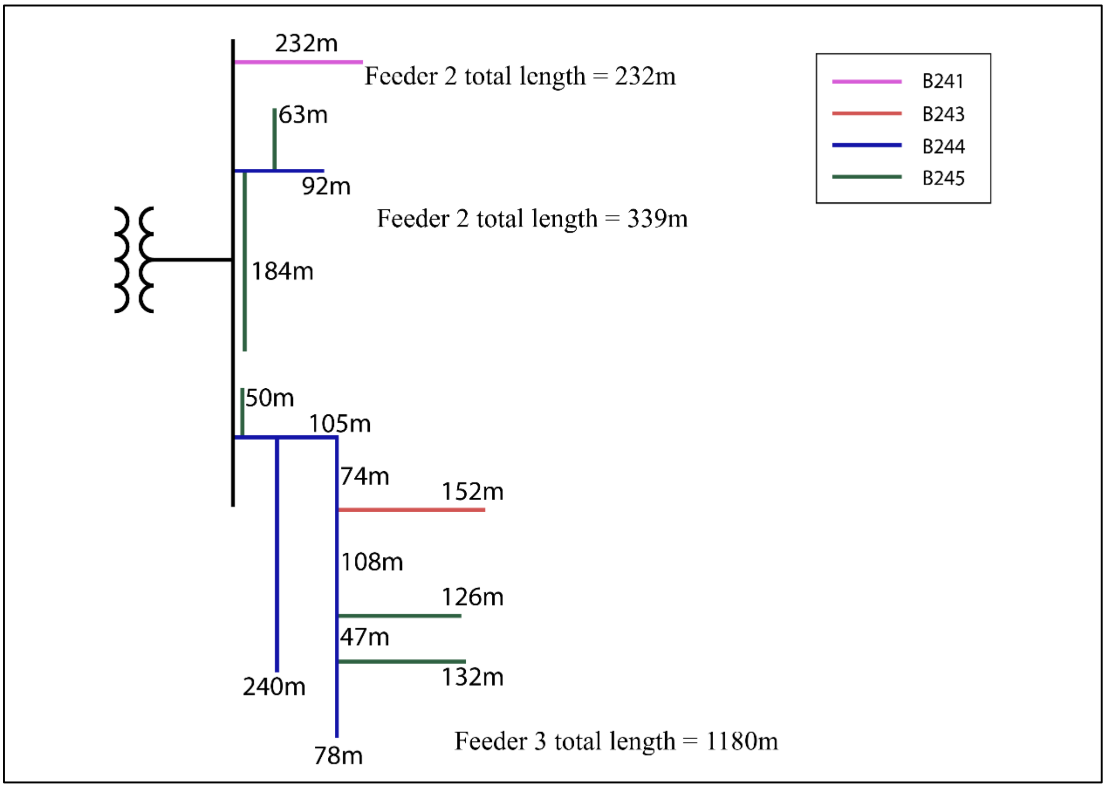


Figure 13: Single Line Diagram of BZ0451

The OpenDSS general library's Line code object was utilized to model the LV feeder. Properties of the line code 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.

LECO feeders- Sample code

```
!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
```

The distance between two poles was defined as a line segment. The line's two endpoints were then regarded as nodes. The bounded pole names were used to identify each line section. The line segment's attributes were defined as follows.

- 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

Line segment in Feeder 1- Sample code

```
!F1

new line.SK11/7_SK11/7/1      bus1=SK11/7      bus2=SK11/7/1    length=0.037  phases=4  units=km  LineCode=LVB244
new line.SK11/7/1_SK11/7/2    bus1=SK11/7/1    bus2=SK11/7/2    length=0.024  phases=4  units=km  linecode=LVB244
new line.SK11/7/2_SK11/7/3    bus1=SK11/7/2    bus2=SK11/7/3    length=0.024  phases=4  units=km  linecode=LVB244
new line.SK11/7/3_SK11/7/4    bus1=SK11/7/3    bus2=SK11/7/4    length=0.023  phases=4  units=km  linecode=LVB244
new line.SK11/7/4_SK11/7/5    bus1=SK11/7/4    bus2=SK11/7/5    length=0.024  phases=4  units=km  linecode=LVB244
new line.SK11/7/5_SK11/7/6    bus1=SK11/7/5    bus2=SK11/7/6    length=0.025  phases=4  units=km  linecode=LVB244
new line.SK11/7/6_SK11/7/7    bus1=SK11/7/6    bus2=SK11/7/7    length=0.025  phases=4  units=km  linecode=LVB244
new line.SK11/7/7_SK11/7/8    bus1=SK11/7/7    bus2=SK11/7/8    length=0.024  phases=4  units=km  linecode=LVB244
new line.SK11/7/8_JD112K      bus1=SK11/7/8    bus2=JD112K      length=0.033  phases=4  units=km  linecode=LVB244
```

5.1.3 Modeling of Selected Transformer Loads

The customers connected to each pole of an LV distribution feeder are known as loads. Consequently, the pole can be thought of as a node, and this model has 66 nodes in total. Single-phase or three-phase loads are both possible. The sum of all customer loads linked to that node is the total load that is visible to the LV feeder at the connected node's point.

Customers that are single phase and three phase may be mixed together in a single pole node. Nevertheless, taking into account the sum of all loads, the final load in a pole node can be expressed as a three phase balance load.

To determine the loads at each node, actual customer energy usage was taken from the LECO system database. To disperse the loads for nodes, a diversity factor was established for every tariff type.

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

Dn – Diversity factor of each category

Xn – Number of customers of each category

Load per node,

Load per node = Σ (D_nX_n) x Demand to be modeled

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

Table 11: 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

The load models were created using the OpenDSS library's load object. In essence, its nominal kW and PF or kW and kVar define it. It is believed that loads are three-phase balanced. The following are the load object's properties.

- 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 of Feeder 1 loads.

```
!F1

new load.SK11/7          bus1=SK11/7     phases=3        kV=0.4  kW=5.4   pf=0.95
new load.SK11/7/1        bus1=SK11/7/1   phases=3        kV=0.4  kW=1.66  pf=0.95
new load.SK11/7/2        bus1=SK11/7/2   phases=3        kV=0.4  kW=2.51  pf=0.95
new load.SK11/7/3        bus1=SK11/7/3   phases=3        kV=0.4  kW=1.54  pf=0.95
new load.SK11/7/4        bus1=SK11/7/4   phases=3        kV=0.4  kW=0.83  pf=0.95
new load.SK11/7/5        bus1=SK11/7/5   phases=3        kV=0.4  kW=1.9   pf=0.95
new load.SK11/7/6        bus1=SK11/7/6   phases=3        kV=0.4  kW=3.11  pf=0.95
new load.SK11/7/7        bus1=SK11/7/7   phases=3        kV=0.4  kW=17    pf=0.95
new load.SK11/7/8        bus1=SK11/7/8   phases=3        kV=0.4  kW=20.25 pf=0.95
new load.JD112K          bus1=JD112K     phases=3        kV=0.4  kW=1.33  pf=0.95
```

5.1.4 Modeling of Solar PV under Selected Transformer

The PVSystem object in the OpenDSS library was used to indicate the total solar additions on each pole. The properties listed below were utilized.

- 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

```
!PV System

New PVSystem.SK11/7       phases=3   bus1=SK11/7       kV=0.4   kVA=5.4    irrad=0.8   Pmpp=5.4    pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/7/7     phases=3   bus1=SK11/7/7     kV=0.4   kVA=17     irrad=0.8   Pmpp=17     pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/7/8     phases=3   bus1=SK11/7/8     kV=0.4   kVA=20.25  irrad=0.8   Pmpp=20.25  pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT


New PVSystem.SK11/7       phases=3   bus1=SK11/7       kV=0.4   kVA=15     irrad=0.8   Pmpp=15     pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/7-1A    phases=3   bus1=SK11/7-1A    kV=0.4   kVA=5.2    irrad=0.8   Pmpp=5.2    pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/7-1B    phases=3   bus1=SK11/7-1B    kV=0.4   kVA=6.5    irrad=0.8   Pmpp=6.5    pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/7-1C    phases=3   bus1=SK11/7-1C    kV=0.4   kVA=10.4   irrad=0.8   Pmpp=10.4   pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/7-1E-1  phases=3   bus1=SK11/7-1E-1  kV=0.4   kVA=5      irrad=0.8   Pmpp=5      pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/7-1E    phases=3   bus1=SK11/7-1E    kV=0.4   kVA=14     irrad=0.8   Pmpp=14     pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT


New PVSystem.SK11/9/8     phases=3   bus1=SK11/9/8     kV=0.4   kVA=5      irrad=0.8   Pmpp=5      pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/9/10    phases=3   bus1=SK11/9/10    kV=0.4   kVA=2.3    irrad=0.8   Pmpp=2.3    pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/10/6    phases=3   bus1=SK11/10/6    kV=0.4   kVA=3.7    irrad=0.8   Pmpp=3.7    pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/10/6    phases=3   bus1=SK11/10/6    kV=0.4   kVA=4.2    irrad=0.8   Pmpp=4.2    pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
New PVSystem.SK11/10/6D   phases=3   bus1=SK11/10/6D   kV=0.4   kVA=4.3    irrad=0.8   Pmpp=4.3    pf=1   effcurve=Efficiency   P-TCurve=JAP_PvsT
```

5.2 Simulation and Results

Modeled BZ0451 Transformer has simulated under six scenarios and listed as below.

1. Scenario 1: Simulation for actual feeders of the transformer (base case)
2. Scenario 2: Simulation to determine hosting capacity in the base case
3. Scenario 3: Simulation for voltage control through power factor correction (PF-0.95) applied to base case
4. Scenario 4: Simulation for voltage control through power factor correction (PF-0.9) applied to base case
5. Scenario 5: Simulation for voltage control through power factor correction (PF-0.85) applied to base case
6. Scenario 6: Simulation of base case with tap position set to tap 3.

5.2.1 Scenario 1: Simulation for actual feeders of the transformer (base case)

In this scenario, the transformer and its associated feeders were modeled to reflect existing field conditions. A baseline simulation was conducted to evaluate the current operational performance without any corrective measures applied. For analysis, the points within the feeders that exhibited the most critical voltage deviations were selected. Specifically, both the lowest and highest recorded voltage values across the feeders were considered to capture the full extent of voltage variation. The results are presented in the following figure.

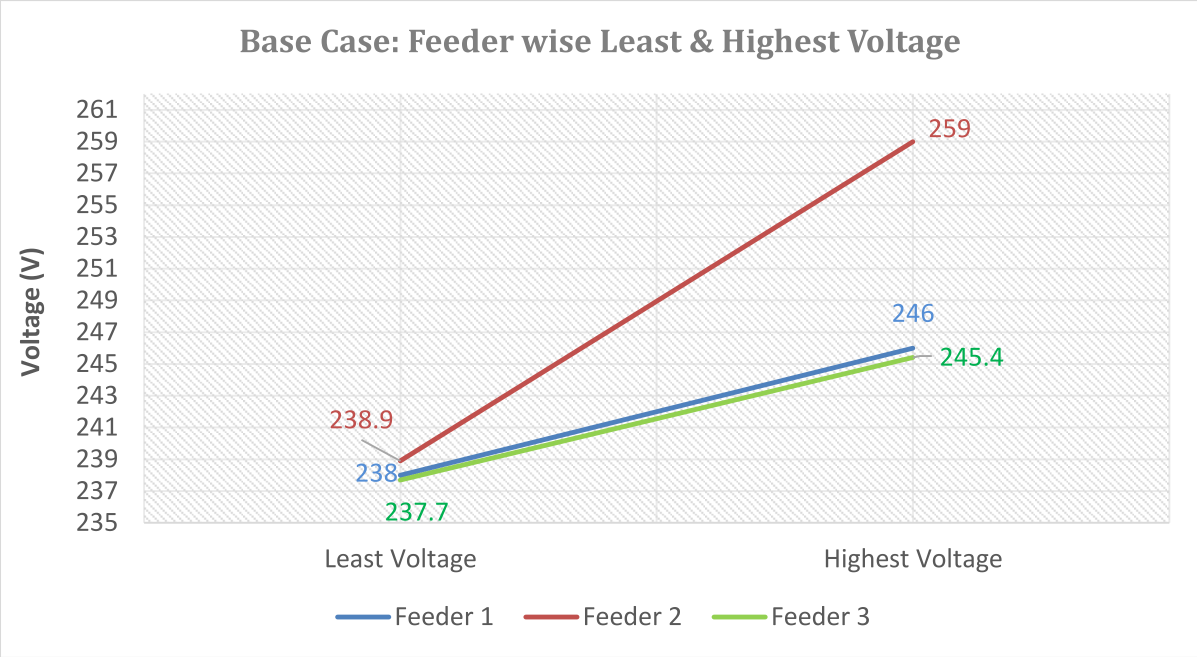


Figure 14: Feeder wise Least & Highest Voltages for the Base Case

Across the three feeder segments analyzed under existing solar integration levels, the voltage profiles showed significant variation. Current through Transformer was 128.4 A. In Feeder 1, which has a total of 37.25 kW of connected solar PV capacity, the voltage ranged from 238 V (lowest) to 246 V (highest). In Feeder 2, with 51.5 kW of solar integration, the minimum voltage recorded was 238.9 V, while the maximum reached 259 V, indicating a higher degree of overvoltage risk. Feeder 3, hosting 36 kW of solar capacity, exhibited a voltage range between 237.7 V and 245.4 V. These results underscore the influence of varying solar penetration levels on voltage fluctuation within the low voltage network.

5.2.2 Scenario 2: Simulation to determine hosting capacity in the base case

In this scenario, the transformer and feeder network were simulated using the same configuration as the base case. The objective was to estimate the solar PV hosting capacity that the system can accommodate without exceeding acceptable voltage limits. A trial-and-error approach was adopted, where the base case solar generation levels were incrementally reduced. This process continued until the maximum observed voltage across the network dropped below 243.8 V, which was set as the upper threshold for acceptable voltage performance. The resulting data, illustrating the adjusted conditions and voltage behavior, is presented in the following figure.

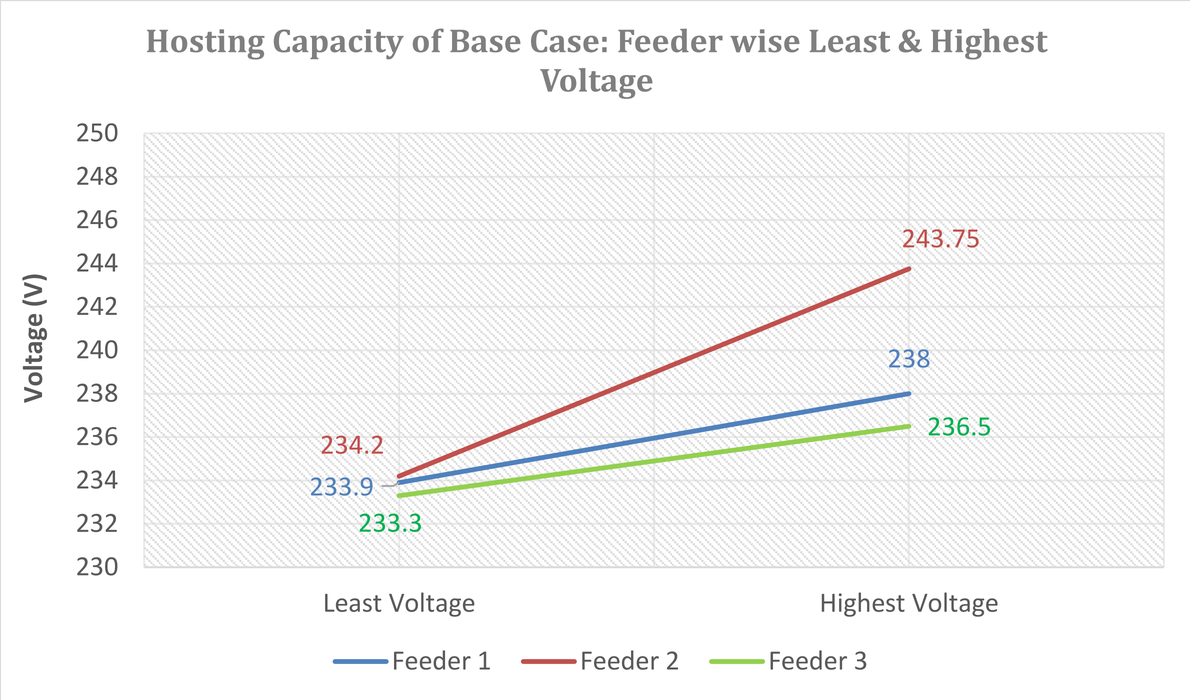


Figure 15: Hosting Capacity of Base Case (Feeder wise Least & Highest Voltage)

Following the reduction of solar generation in the base case, the resulting voltage levels across the feeders were observed to fall within acceptable limits. In Feeder 1, the voltage ranged from a minimum of 233.9 V to a maximum of 238 V. For Feeder 2, the voltage values varied between 234.2 V and 243.75 V. In Feeder 3, the recorded voltage spanned from 233.3 V to 236.5 V. Under these conditions, the current flowing through the transformer was approximately 49.2 A.

Based on these observations, the maximum solar PV capacity that the system can host without exceeding the allowable voltage threshold was determined to be 68.6 kW. This represents approximately 55% of the original total solar capacity modeled in the base case. The full solar PV penetration level in the transformer under initial conditions was 124.75 kW.

5.2.3 Scenario 3: Simulation for voltage control through power factor correction (pf-0.95) applied to base case

In this simulation scenario, the transformer feeders were modeled based on the base case configuration, with a modification to the power factor settings of the solar inverters.

Specifically, the solar PV systems were configured to operate at a lagging power factor of 0.95 to support voltage regulation through reactive power control.

A series of trial-and-error simulations were conducted, during which solar generation levels were gradually reduced. This iterative process continued until the maximum recorded voltage in the network dropped below the target threshold of 243.8 V. The outcome of this analysis provides insights into the effectiveness of power factor correction as a voltage control measure under high solar penetration conditions. The simulation results are presented in the following figure.

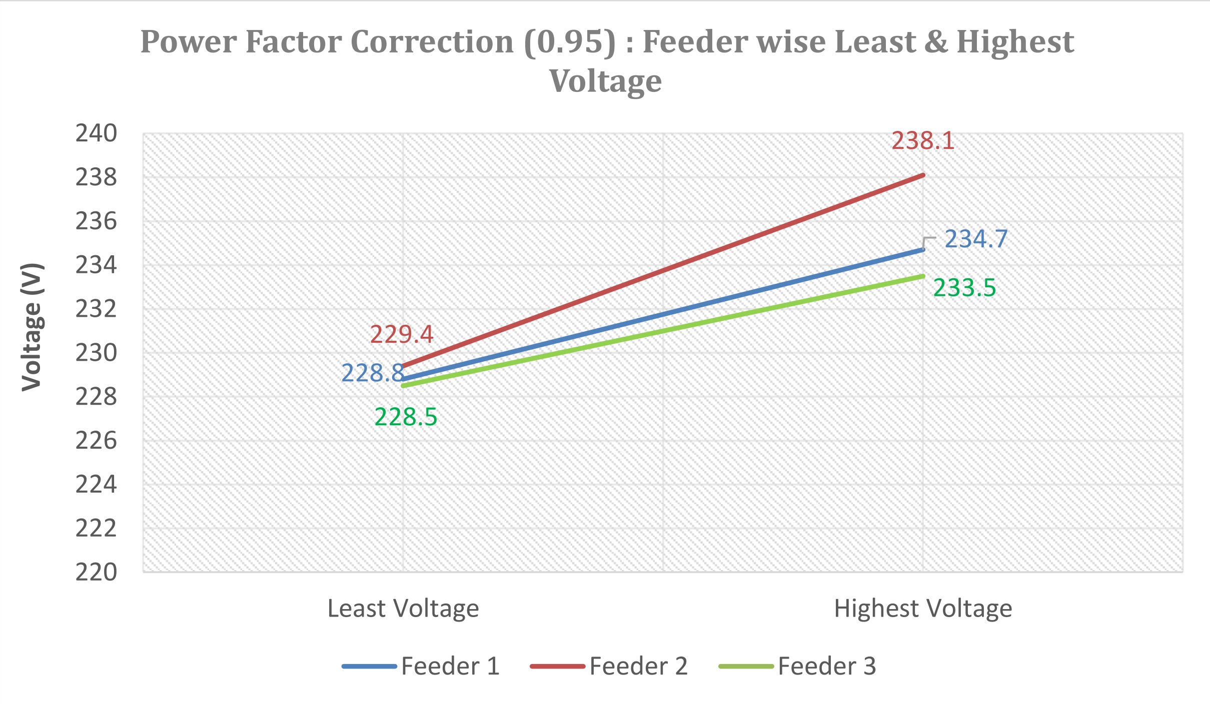


Figure 16: Power Factor Correction (0.95) (Feeder wise Least & Highest Voltage)

Following the application of lagging power factor correction at 0.95, voltage levels across all three feeders were observed to remain within the acceptable operational range. In Feeder 1, the voltage varied from a minimum of 228.8 V to a maximum of 234.7 V. For Feeder 2, the voltage ranged between 229.4 V and 238.1 V, while Feeder 3 recorded voltages from 228.5 V to 233.5 V. Under these conditions, the measured current through the transformer was approximately 96.4 A.

Based on the simulation results, the maximum solar PV hosting capacity that can be supported without violating the voltage threshold was found to be 93.5 kW, which accounts for approximately 75% of the total base case solar capacity. The full solar PV penetration level modeled in the transformer was 124.75 kW.

5.2.4 Scenario 4: Simulation for voltage control through power factor correction (pf-0.9) applied to base case

As same as the above scenario, the base case feeder model was adjusted by configuring solar inverters to operate at a 0.9 lagging power factor to aid in voltage control through reactive power control. A trial-and-error method was used to gradually reduce solar generation until the maximum voltage observed in the network fell below 243.8 V. The simulation results demonstrate the potential of power factor correction to improve voltage stability under high levels of solar PV integration. The outcomes are illustrated in the figure below.

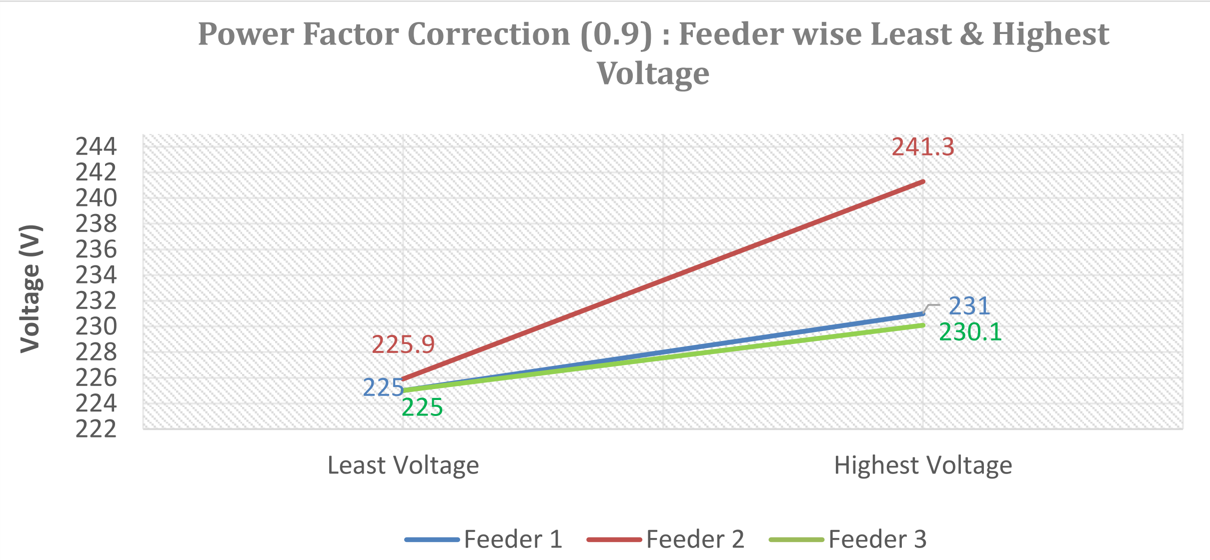


Figure 17: Power Factor Correction (0.9) (Feeder wise Least & Highest Voltage)

Under the power factor correction scenario, voltage levels across the feeders remained within acceptable limits. In Feeder 1, the voltage ranged from 225 V to 231 V. Feeder 2 exhibited a broader range, with the minimum voltage recorded at 225.9 V and the maximum at 241.3 V. In Feeder 3, voltages varied between 225 V and 230.1 V. During this condition, the transformer current was approximately 109.8 A.

The simulation results indicate that the maximum solar PV hosting capacity that can be supported without exceeding voltage thresholds is 99.8 kW, which represents 80% of the total installed solar capacity modeled in the base case. The total PV penetration level across the transformer remains at 124.75 kW.

5.2.5 Scenario 5: Simulation for voltage control through power factor correction (pf-0.85) applied to base case

In this simulation, the feeder model from the base case was adapted by setting the solar inverter lagging power factor to 0.85, enabling improved reactive power control. Through a series of iterative simulations, solar generation was reduced until the maximum network voltage dropped below 243.8 V. The results highlight the enhanced voltage regulation achieved with a lower power factor under high solar penetration. The corresponding outcomes are shown in the figure below.

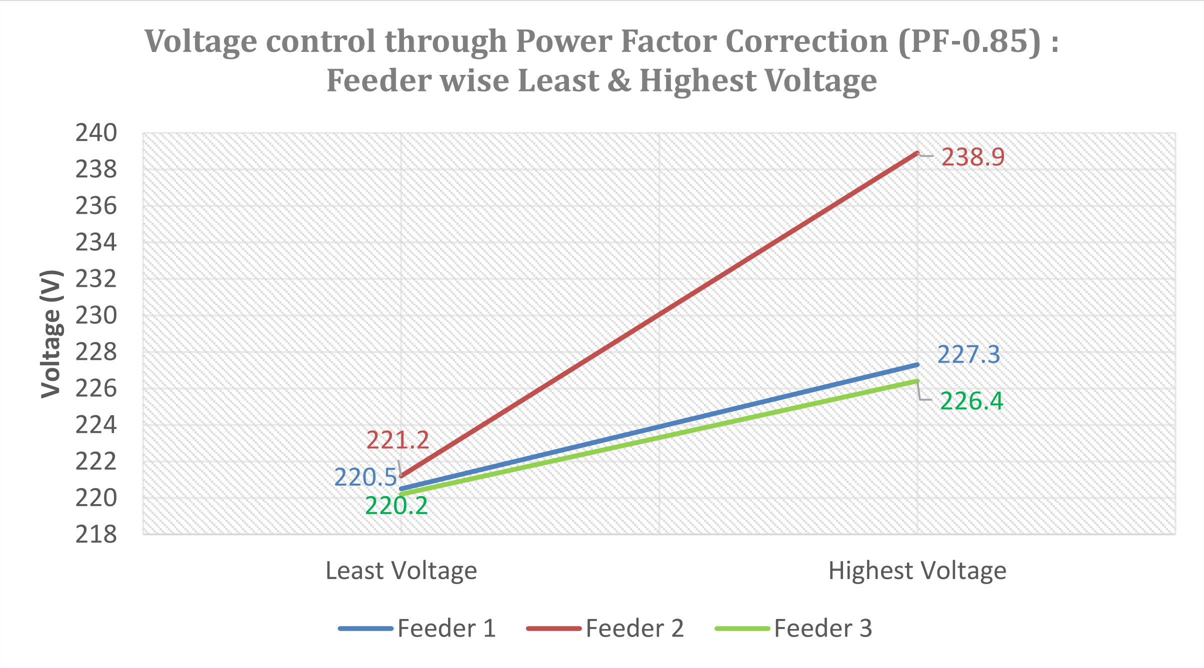


Figure 18: Power Factor Correction (0.85) (Feeder wise Least & Highest Voltage)

Under the adjusted lagging power factor setting of 0.85, voltage levels across all three feeders remained within acceptable operating limits. In Feeder 1, the voltage ranged from 220.5 V to 227.3 V. Feeder 2 recorded a minimum voltage of 221.2 V and a maximum of 238.9 V, while Feeder 3 ranged from 220.2 V to 226.4 V. During this condition, the transformer current was approximately 144.57 A.

The simulation results indicate that the entire installed solar PV capacity 124.75 kW can be accommodated without exceeding voltage thresholds. This corresponds to 100% of the total base case solar capacity, demonstrating that configuring inverters to operate at a 0.85 power factor can effectively enable full hosting capacity without voltage violations.

5.2.6 Scenario 6: Simulation of base case with tap position set to tap 3

In this scenario, the transformer feeders were modeled using the base case configuration, with a modification to the transformer's tap position, which was adjusted to Tap 3 (11.825 kV). A series of trial-and-error simulations were then performed, where the solar generation levels were gradually reduced. This process continued until the maximum recorded voltage across the network dropped below the specified threshold of 243.8 V. The simulation aimed to evaluate the effectiveness of tap adjustment in managing voltage levels under high solar PV penetration. The corresponding outcomes are shown in the figure below.

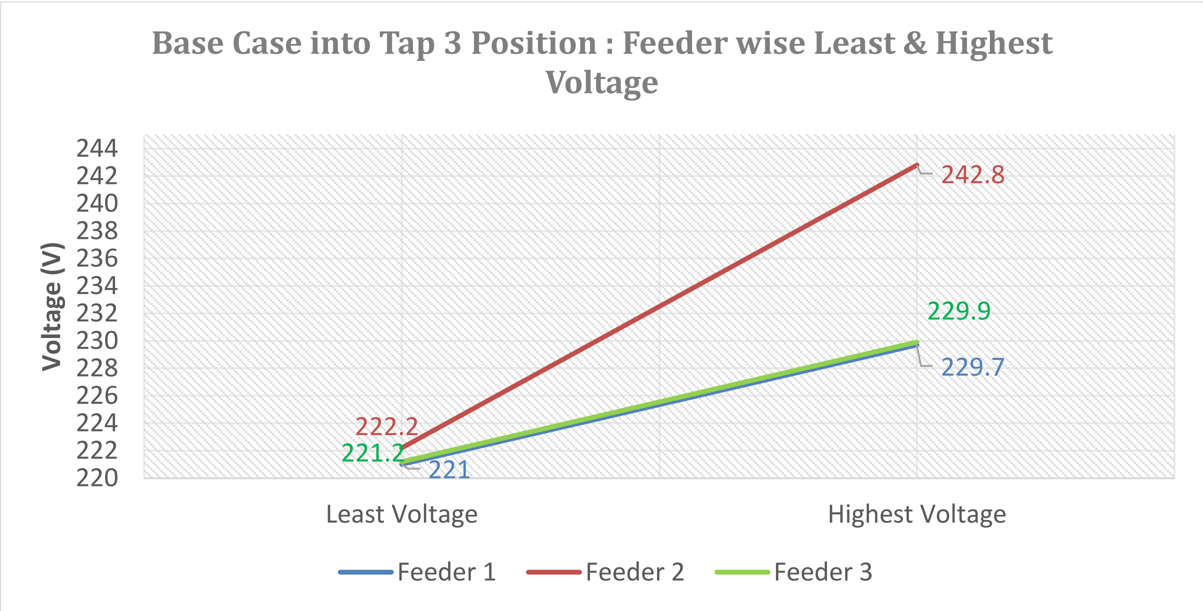


Figure 19: Base Case into Tap 3 Position (Feeder wise Least & Highest Voltage)

Under the Tap 3 position configuration, voltage levels across all feeders were brought within acceptable operational limits. In Feeder 1, the voltage ranged from 221 V to 229.7 V. Feeder 2 recorded a minimum of 222.2 V and a maximum of 242.8 V, while Feeder 3 showed values between 221.2 V and 229.9 V. During this scenario, the current measured through the transformer was approximately 136.8 A.

These results indicate that the system, under this tap setting, can accommodate the full solar PV penetration level of 124.75 kW without violating voltage thresholds. This demonstrates the potential of tap adjustment as a practical approach for managing voltage rise in high PV penetration scenarios.

5.2.7 Summary of the Results

Table 12: Summary of the Results

	Base Case	Hosting Capacity of the Base case	Power Factor Correction to the Base Case (PF 0.95)	Power Factor Correction to the Base Case (PF 0.9)	Power Factor Correction to the Base Case (PF 0.85)	Base Case into Tap 3 Position
Transformer Current through LV side (A)	128.4	49.2	96.4	109.8	144.57	136.8
Hosting capacity (kW)	-	68.6	93.5	99.8	-	-

Scenario 1: In the base case simulation, the low-voltage (LV) side current of the transformer was recorded at 128.4 A, corresponding to a total installed solar PV capacity of 124.75 kW. This remains within the transformer's rated output current of 139.3 A, indicating that the system is operating within its design limits under current conditions.

Scenario 2: The simulation determined that the base case can support a maximum of 68.6 kW of solar PV without violating voltage thresholds, which represents 55% of the total installed capacity. At this hosting level, the LV-side current was approximately 49.2 A.

Scenario 3: When solar inverters were configured to operate at a lagging power factor of 0.95, the system was able to accommodate up to 93.5 kW of solar capacity 75% of the total installed PV without voltage threshold violations. At this capacity, the transformer current was measured at 96.4 A, reflecting a 36% improvement in hosting capacity compared to Scenario 2.

Scenario 4: Further improvement was observed at a lagging power factor of 0.9, applied to inverters where the hosting capacity increased to 99.8 kW (representing 80% of the total installed capacity). Under these conditions, the current through the transformer was 109.8 A, showing a 45% increase in hosting capacity relative to the base case limit.

Scenario 5: When the power factor was reduced to 0.85, the full installed solar capacity of 124.75 kW was modeled. However, this configuration resulted in the transformer current of 144.57A exceeding its rated limit of 139.3, indicating that the existing transformer windings are **not suitable** for sustained operation under these conditions.

Scenario 6: With the transformer tap position adjusted to Tap 3, the system successfully accommodated the full installed solar PV capacity of 124.75 kW. The current measured on the LV side was 136.8 A, which remains within the rated output of the transformer. Thus, the existing transformer windings are deemed **suitable** for this configuration.

5.3 Results Analysis

A comprehensive results analysis was carried out across six simulation scenarios. The evaluation focused on determining the solar PV hosting capacity in each case, observing how it increased under different control strategies, and comparing the maximum current through the transformer for each scenario.

5.3.1 Solar Hosting Capacity Across Scenarios

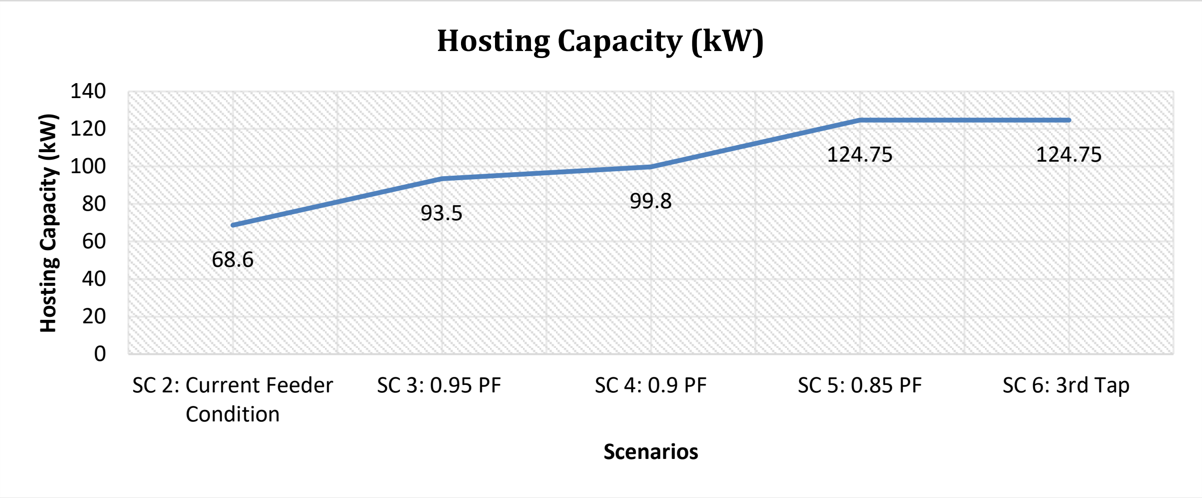


Figure 20: Solar Hosting Capacity across Scenarios

This graph illustrates the solar PV hosting capacity supported under each scenario. Scenario 1 (base case) accommodates only 68.6 kW, which is 55% of the total installed capacity. Scenarios 3 and 4, which implement power factor corrections of 0.95 and 0.9, respectively, show progressive increases in hosting capacity reaching up to 99.8 kW in Scenario 4. Scenario 5 (PF = 0.85) and Scenario 6 (Tap 3 position) both enable the full hosting of 124.75 kW, indicating these are the only configurations capable of fully integrating the existing solar PV capacity.

5.3.2 Transformer Current under each Scenario

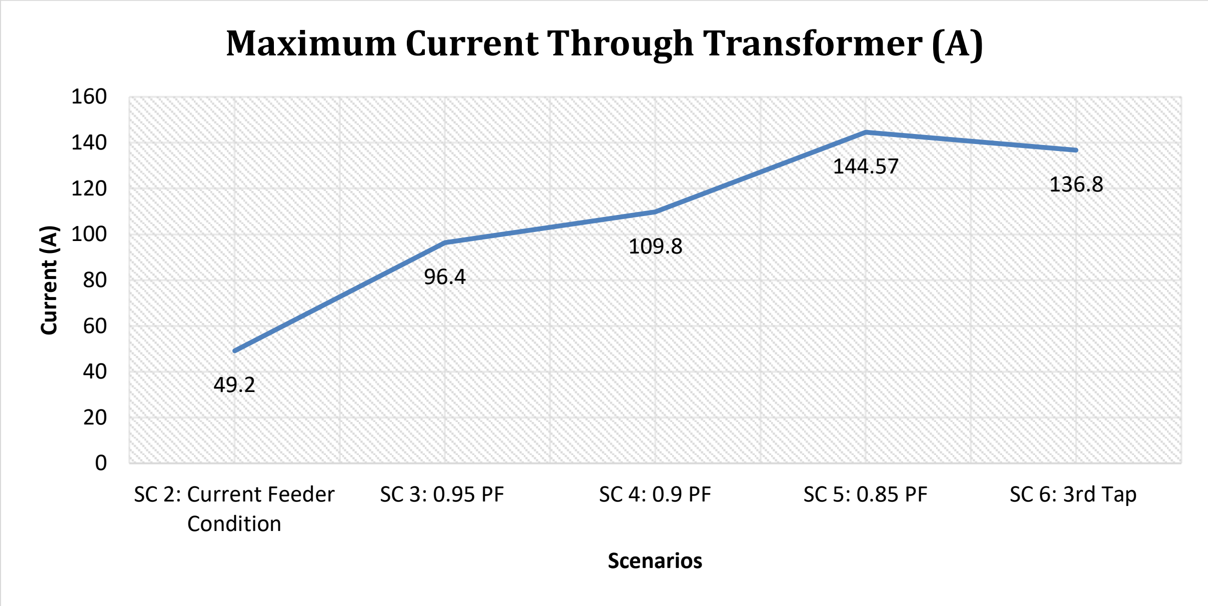


Figure 21: Transformer Current under each Scenario

This graph displays the transformer current observed under each simulation. The base case operates at 128.4 A, while the rated capacity of the transformer is 139.3 A. In Scenario 2, the current drops significantly to 49.2 A, reflecting the reduction in solar integration. However, in Scenario 5, where inverters operate at a 0.85 power factor, the current reaches 144.57 A, exceeding the transformer's rated output. In contrast, Scenario 6, which utilizes the Tap 3 position, maintains the current at 136.8 A, safely within the limit. These findings highlight the risk of transformer overloading if reactive power support is excessively relied upon without hardware upgrades.

5.3.3 Summary of the Result Analysis

Results analysis revealed that addressing the voltage issue of the selected transformer would require applying a power factor of 0.85, as corrections to 0.95 and 0.9 were insufficient in mitigating the overvoltage problem. A comparison between implementing a 0.85 power factor and adjusting the transformer tap setting to the 3rd tap position showed that both approaches deliver similar hosting capacities. However, operating at a 0.85 lagging power factor is not a viable long-term solution, as it causes transformer current to exceed the rated current of

139.3 A, risking thermal overload and increased system losses. Moreover, deviating from the standard grid-maintained power factor of 0.95 is not advisable. Implementing a 0.85 of lagging power factor would also necessitate policy changes and reduces the utility’s control over the adjustment mechanism.

In contrast, due to the fluctuating nature of solar generation, fixed tap positions are inadequate for managing overvoltage issues. During periods of high solar output, voltage levels may rise excessively, while sudden reductions such as those caused by cloud cover or nighttime conditions can result in undervoltage. Because the tap position is static, these fluctuations cannot be effectively controlled without dispatching a technical team to the site. Continuously adjusting the tap manually throughout the day is both impractical and inefficient, potentially leading to service disruptions and reduced reliability for customers.

Therefore, compared to all discussed methods, the implementation of automatic On-Load Tap Changers (OLTC) is recommended to provide responsive, real-time voltage regulation and ensure consistent service quality.

CHAPTER 6

6 Conclusions and Recommendations

The integration of high levels of solar PV into low-voltage networks has introduced notable voltage regulation challenges. In the case study examined, overvoltage across all three transformer feeders was identified as the most critical issue. Various mitigation methods were assessed, including power factor correction, parallel feeder installation, and fixed tap settings.

Among these, power factor correction was partially effective but introduced higher losses and operational limitations. Parallel feeders improved hosting capacity but lacked cost-efficiency. Fixed tap changers failed to respond to real-time voltage fluctuations, making manual adjustments impractical.

The implementation of automatic On-Load Tap Changers (OLTC) emerged as the most effective immediate solution. OLTCs provide continuous, real-time voltage control without requiring major infrastructure changes or regulatory adjustments. Compared to other methods, they offer a reliable, cost-efficient, and scalable approach to managing voltage issues in solar-integrated distribution networks. However, a practical limitation arises when using a single voltage reference point to control tap changes, particularly in networks with multiple feeders exhibiting diverse voltage profiles. Adjustments based on one reference point can lead to voltage imbalances, where correcting overvoltage in one feeder may cause undervoltage in another. To address this, control devices can be positioned at critical points along the feeder, allowing real-time data to be used in setting dynamic reference points for more responsive and accurate regulation.

References

1. Majeed, I.B.; Nwulu, N.I. Impact of Reverse Power Flow on Distributed Transformers in a Solar-Photovoltaic-Integrated Low-Voltage Network. Energies 2022, 15, 9238. https://doi.org/10.3390/ en15239238
2. Majeed, I. B., & Nwulu, N. I. (2023). Reverse power flow due to solar photovoltaic in the low voltage network. *IEEE Access, 11*, 44741–44758. https://doi.org/10.1109/access.2023.3273483
3. Ton, D. T., & Smith, M. A. (2012). The U.S. Department of Energy's Microgrid Initiative. *Electric Power Systems Research, 103,* 13-23.
4. Capasso, A., Villacci, D., & Viggiano, G. (2015). Smart Inverters for Voltage Regulation in Distributed Generation Systems. *International Journal of Electrical Power & Energy Systems, 71*, 227-234.
5. Bollen, M. H. J., Häger, M., & Bertling, L. (2005). Impact of Distributed Generation on Power Quality in Distribution Networks. *IEEE Transactions on Power Delivery, 20(2),* 1800-1807.
6. Hoke, A., Giraldez, J., & Pratt, A. (2013). Voltage Regulation in Distribution Networks with High Penetration of PV Generation. *National Renewable Energy Laboratory (NREL).*
7. Kaundinya, D. P., Balachandra, P., & Ravindranath, N. H. (2009). Grid-connected versus Stand-alone Energy Systems for Decentralized Power—A Review of Literature. *Renewable and Sustainable Energy Reviews, 13(8),* 2041-2050.
8. Murthy, K. S. & Ashok, S. (2016). Effects of High Distributed Generation Penetration on Transformer Performance and Life Expectancy. *Journal of Electrical Engineering, 16(3),* 207-213.
9. Aydin, M., Alnaser, S. and Althaher, S. (2022) 'Using OLTC-Fitted Distribution Transformer to increase residential PV hosting capacity: Decentralized Voltage Management approach,' Energies, 15(13), p. 4836. https://doi.org/10.3390/en15134836.
10. Yoon, K.-H.; Shin, J.-W.;Nam, T.-Y.; Kim, J.-C.; Moon, W.-S. 'Operation Method of On-Load Tap Changer on Main Transformer Considering Reverse Power Flow in

Distribution System Connected with High Penetration on Photovoltaic System. Energies 2022, 15, 6473. https://doi.org/10.3390/en15176473

11. K. A. Tutvedt, P. O. Dypvik, J. Skivdal, R. Tjeldhorn, H. Svanberg, and F. Pizzutto, "Operation of on-load tap changer (OLTC) in MV/LV transformer by using smart meter data for voltage optimization and increasing hosting capacity in low voltage distribution grids with distributed photovoltaics (DPV)," IET Conference Proceedings., vol. 2024, no. 5, pp. 532–535, Jan. 2025, doi: 10.1049/icp.2024.2093.
12. G.R. Chandra Mouli, V. Prasanth, P. Bauer, and EM Bärthlein, "Comparative analysis of on-load tap changing (OLTC) transformer topologies," Sep. 2014, doi: https://doi.org/10.1109/epepemc.2014.6980624.

APPENDIX A: Simulation Results

	Base Case		Current Hosting Capacity 0.55		PF 0.95 x 0.75 solar		PF 0.9 x 0.8 solar		2nd Tap*0.8 solar		3tap x 0.8 solar		3tap		PF 0.85	
	V	I	V	I	V	I	V	I	V	I	V	I	V	I	V	I
Feeder 1- Beginning	238	44.9	233.9	20.7	228.8	34.6	225	38.2	230.7	57.6	225	59.44	221	48.9	220.5	50.2
Feeder 1- Mid	242	47.3	236	23.8	231.8	36.8	228	40.2	235.1	59.2	229.7	61.07	225	51.1	221.2	52.1
Feeder 1- End	246	0.6	238	0.59	234.7	0.58	231	0.57	239.1	0.59	233.9	0.58	229.7	0.57	227.3	0.56
Feeder 2- Beginning	239.2	58.2	234.5	26.4	229.7	44.9	226.2	49.9	231.6	47.3	225.8	48.96	222.5	63.5	221.5	65.9
Feeder 2- Mid	239	1.2	234.3	1.2	229.5	1.14	226	1.13	231.4	1.1	225.6	1.12	222.3	1.1	221.3	1.1
Feeder 2- End	238.9	0	234.2	0	229.4	0	225.9	0	231.2	0	225.6	0	222.2	0	221.2	0
Feeder 2- Spur 1- Beginning	239.2	58.2	234.5	26.4	229.7	44.9	226.2	49.9	231.6	47.3	225.8	48.96	222.5	63.5	221.5	65.9
Feeder 2- Spur 1- Mid	250	35.9	240.2	17.9	238.1	28.2	234.7	30.8	241.1	29.65	235.4	30.5	234.6	38.6	231.3	39.7
Feeder 2- Spur 1- End	259	38.4	244.7	20.3	238.1	30.5	241.3	33	248.2	32.1	242.6	32.9	243.6	41	238.9	41.8
Feeder 2- Spur 2- Beginning	239	1.2	234.3	1.2	229.6	1.4	226	1.13	231.4	1.1	225.7	1.12	222.3	1.1	221.3	1.1
Feeder 2- Spur 2- End	238.9	0.59	234.2	0.58	229.5	0.57	225.9	0.56	231.3	0.57	225.6	0.56	222.2	0.5	221.2	0.55
Feeder 3- Beginning	237.7	24.8	233.5	2.2	228.5	17.3	225.1	22.59	230	17.4	224.7	18.9	221.2	29.9	220.3	34.9
Feeder 3- End	239	0.59	233.6	0.58	229.1	0.57	225.8	0.56	231.2	0.57	225.7	0.56	222.8	0.55	221.3	0.55
Feeder 3- Spur 1-Beginning	237.7	24.8	233.5	2.2	228.5	17.3	225.1	22.59	230	17.4	224.7	18.9	221.2	29.9	220.3	34.9
Feeder 3- Spur 1-End	237.8	0.59	233.4	0.58	228.5	0.57	225	0.56	230.2	0.57	224.6	0.56	221	0.55	220.2	0.55
Feeder 3- Spur 2-Beginning	238.9	11.5	233.6	1.2	228.9	7.9	225.6	11.1	231	7.5	225.4	8.4	222.3	14.4	221.1	17.99
Feeder 3- Spur 2-Mid	242.2	18.7	235	7.7	231.3	13.7	227.8	15.4	233.6	14.5	228.1	15.06	225.9	19.8	223.7	20.6
Feeder 3- Spur 2- End	245.4	10.2	236.5	5	233.5	7.9	230.1	8.7	236.1	8.4	230.8	8.6	229.3	11	226.4	11.2
Feeder 3- Spur 3-Beginning	239.3	0.59	233.6	0.58	229.1	0.57	225.8	0.56	231.3	0.57	225.7	0.56	222.8	0.55	221.4	0.55
Feeder 3- Spur 3-Mid	242.3	0	234	0	230.9	0	227.4	0	233.3	0	227.9	0	226.2	0	223.6	0
Feeder 3- Spur 3- End	242.7	0.6	234	0.58	231	0.57	227.5	0.56	233.5	0.58	228.2	0.57	226.7	0.56	223.8	0.55
Feeder 3- Spur 3- Spur 1- End	240.5	0	233.3	0	229.7	0	226.2	0	232.2	0	226.5	0	224.3	0	222.2	0
Feeder 3- Spur 3- Spur 2- End	245.5	12.9	235.5	6.49	233.1	10.1	229.7	11.06	236.2	10.7	230.6	10.97	229.9	13.9	226.2	14.22
Feeder 3- Spur 3- Spur 3- End	242.2	0.6	233.7	0.58	230.8	0.57	227.3	0.56	233.6	0.58	228	0.57	226.5	0.56	223.6	0.55