MAXIMIZING SOLAR PV INTEGRATION BY ENHANCING HOSTING CAPACITY OF LV NETWORKS USING SMART INVERTERS AND BATTERY ENERGY STORAGE SYSTEMS: A CASE STUDY

Dissanayake Mudiyanselage Krishan Chathuranga Dissanayake

(208671X)

Degree of Master of Science in Electrical Installations

Department of Electrical Engineering

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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

Abstract

The integration of rooftop solar photovoltaic (PV) systems in Sri Lanka, particularly within buildings governed by provincial councils, has been increasing in response to national renewable energy goals. However, the rapid increase of solar PV integration in low-voltage (LV) distribution networks presents considerable technical challenges, notably voltage rise exceeding maximum allowable limits, feeder capacity limitations and transformer capacity limitations. These issues are further compounded by high grid augmentation costs, rendering conventional methods such as feeder upgrades and transformer upgrades economically unfeasible, especially for small to medium-scale PV systems under 42 kVA. As a result, utility providers have imposed restrictions on new PV connections, hindering the full realization of solar energy potential in the region.

This study investigates a cost-effective and technically viable alternative to enhance PV hosting capacity by integrating smart inverters and battery energy storage systems (BESS). A detailed case study was conducted on a 160 kVA transformer located in a solar-rich area in Kotte, where data from actual consumer loads and solar installations were used to model real-world conditions. A series of simulations were developed using MATLAB, exploring different configurations of solar PV system placement, power factor control strategies (Volt-Var and Watt control), and BESS deployment at various feeder locations.

The results indicate that while smart inverters alone can provide limited improvements in voltage regulation, the combined use of smart inverters with BESS—particularly when strategically located at points of maximum voltage—significantly reduces voltage rise and current surges. This facilitates the integration of an additional solar PV without breaching operational voltage limits. Moreover, cost-benefit analysis reveals that the proposed solution offers substantial economic advantages over conventional grid augmentation, with net savings and an acceptable return on investment.

The study concludes that integrating BESS with smart inverter control is a scalable, technically robust, and economically feasible strategy to increase solar PV penetration in

LV distribution networks, thereby supporting the broader transition toward sustainable energy systems in Sri Lanka.

Keywords: Solar PV penetration, Voltage regulation, Grid augmentation, Power factor correction, Battery Energy Storage Systems (BESS), Feeder hosting capacity, Transformer hosting capacity, Smart inverter controls

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D.M.K.C Dissanayake

(208671X)

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	**Description**
PUCSL	Public Utilities Commission of Sri Lanka
LECO	Lanka Electricity Company Private Limited
CEB	Ceylon Electricity Board
LV	Low Voltage
MV	Medium Voltage
BESS	Battery Energy Storage System
PV	Photovoltaic
DoD	Depth of Discharge
ROI	Return on Investment

CHAPTER 1

1 INTRODUCTION

1.1 Background

The global energy sector is undergoing a significant transformation, driven by the urgent need to mitigate climate change, reduce dependence on fossil fuels, and ensure long-term energy security. Central to this transformation is the large-scale adoption of renewable energy technologies, among which solar photovoltaic (PV) systems have gained widespread prominence. Their modular design, decreasing cost trajectory, and adaptability to various scales ranging from small rooftop installations to utility-scale solar farms make solar PV a key pillar of modern energy systems.

In developing countries such as Sri Lanka, the deployment of solar PV technologies has gained policy momentum under the broader objective of transitioning to a low-carbon economy. The Sri Lankan government, through the Ministry of Power and Energy and the Sustainable Energy Authority (SEA), has launched several national programs including the "Soorya Bala Sangramaya" (Battle for Solar Energy) with the aim of increasing rooftop solar penetration and reducing reliance on imported fossil fuels. Rooftop solar PV installations are especially encouraged in government buildings, commercial establishments, and residential homes, with the dual goal of reducing energy costs and supporting national energy targets.

However, as PV adoption accelerates, particularly in low-voltage (LV) networks, technical challenges have emerged that threaten to limit further integration. LV networks, originally designed for unidirectional power flow from substation to end-users, are now facing bi-directional flows due to surplus generation from distributed PV systems. These reversed power flows can cause over-voltage issues, voltage imbalance, and transformer overloading, particularly during mid-day hours when PV generation peaks and local consumption is low.

A critical barrier to higher PV integration is the limited hosting capacity of LV feeders. Hosting capacity refers to the maximum amount of PV that can be connected to a distribution feeder without violating operational constraints such as voltage limits and thermal loading. In Sri Lanka, most distribution feeders especially in urban areas have already reached or exceeded their hosting capacity, leading utilities to impose restrictions or outright rejections on new rooftop PV applications. These challenges are particularly acute in government buildings managed by Provincial Councils, where solar PV projects have been either delayed or halted due to anticipated grid impacts and the high cost of infrastructure upgrades.

Conventional solutions, such as upgrading transformers or installing additional feeder lines, are technically effective but economically burdensome. In many instances, the cost of grid reinforcement can far exceed the capital cost of the rooftop PV system itself. For example, field evidence suggests that the cost of grid augmentation for a rooftop solar system (<42kVA) can exceed 1.5 times the cost of the system. Such financial burdens are unsustainable, particularly in public sector installations with limited capital budgets.

Emerging smart technologies like Battery Energy Storage Systems (BESS) and smart inverters are becoming more popular as a means of overcoming these obstacles. At the point of common coupling, smart inverters that include features like Volt-VAR control, Volt-Watt control, and frequency ride-through capabilities can support reactive power and regulate voltage. These inverters can lessen the negative consequences of high PV penetration when properly programmed, reducing the need for significant modifications to the grid infrastructure.

By collecting excess PV power at times of low demand and releasing stored energy during times of peak demand or voltage drops, BESS provides an additional layer of flexibility. BESS may greatly improve voltage stability, lessen peak load on transformers, and boost the LV network's total hosting capacity when positioned strategically along the feeder. BESS can provide a coordinated, scalable, and financially feasible solution to enable greater PV penetration when paired with smart inverter controls.

In light of this, the current study is to investigate the usage of BESS and smart inverters in conjunction as a less expensive option to expensive grid augmentation for increasing PV hosting capacity. This research aims to offer practical insights for utilities, policymakers, and engineers working toward a more adaptable and robust distribution network by concentrating on a real-world case study with a transformer situated in the Kotte area.

1.2 Problem Statement

Critical flaws in the current infrastructure have been made apparent by the growing installation of rooftop solar PV systems in Sri Lanka's LV distribution networks. The reverse power flows and voltage rise issue that emerge from rooftop systems producing more electricity than is locally used pose serious operational challenges for utilities. The amount of solar PV that LV feeders, especially those in urban areas, can handle is getting close to its technical limit. Because of this, utilities are compelled to postpone or deny new requests for PV connections, even in areas with plenty of rooftop space and strong solar potential.

These limitations are particularly evident in the Rooftop Solar PV Installations Project in Buildings Governed by Provincial Councils in Sri Lanka. Despite policy decisions and financial allocation for solar deployment in public buildings, technical constraints in the LV network have emerged as the primary bottleneck. Grid operators have cited frequent violations of voltage thresholds and transformer overloading, especially during sunny mid-day periods, as reasons for curtailing further PV connections. This situation is counterproductive to Sri Lanka's national goal of achieving a high share of renewable energy in its generation mix.

The high cost of conventional grid upgrades further exacerbates the issue. Field data indicate that reinforcing the grid either through transformer replacement, line reconductoring, or feeder extensions can be prohibitively expensive. In many documented cases, these upgrade costs surpass the investment required for the solar PV system itself, making projects financially infeasible.

Although international studies and industry guidelines increasingly recommend the use of smart inverter functionalities and energy storage systems as viable alternatives, there remains a lack of empirical, locally relevant research to validate these solutions under Sri Lankan conditions. There is limited data on how much additional PV capacity can be integrated through advanced inverter settings or how BESS should be sized and placed for optimal impact on voltage regulation and feeder loading.

Therefore, the core research problem addressed in this study is the limited hosting capacity of LV networks, and how this limitation can be mitigated through a combination of smart inverter controls and Battery Energy Storage Systems, rather than traditional grid augmentation. The study seeks to provide both a technical evaluation and an economic justification for these advanced solutions, using actual feeder data and simulation-based analysis.

1.3 Project Objectives and Scope

1.3.1 Objectives

The main objective of this research is to enhance the hosting capacity of LV networks by evaluating the effectiveness of smart inverter functionalities and Battery Energy Storage Systems (BESS) in increasing solar PV integration.

The specific objectives are as follows:

- To model an existing LV feeder with high solar PV penetration and identify technical constraints affecting further integration.

- To simulate the effects of advanced smart inverter functionalities (e.g., Volt-VAR, Volt-Watt) on voltage profiles and hosting capacity.
- To design and simulate different configurations of BESS (varying in size and location) to assess their impact on feeder performance.
- To compare multiple scenarios ranging from no control, to smart inverter only, to BESS integration in terms of voltage regulation, feeder current, and PV hosting capacity.
- To conduct a 20-year cost-benefit analysis comparing suggested solutions with traditional grid upgrades.
- To propose a set of technical recommendations for facilitating higher rooftop solar adoption in Sri Lanka's LV networks.

1.3.2 Scope

This research is conducted as a case study focusing on a 160 kVA distribution transformer located in Kotte, serving a group of consumers that includes buildings with rooftop PV installations. The scope includes:

- Collection of real-world data, including load profiles, PV capacities, feeder topology, and transformer specifications.
- Development of a feeder model in MATLAB/Simulink to simulate voltage and current behavior under different scenarios.
- Integration of smart inverter controls into the model, including power factor adjustment, Volt-VAR control, and Volt-Watt control.
- Simulation of BESS systems with varied capacities and locations to analyze their effect on voltage rise and current profiles.
- Evaluation of hosting capacity improvement (in kW of additional PV) under each scenario.
- Financial analysis covering battery capital costs, operational benefits, and comparison with conventional grid augmentation costs.

This study does not include high-voltage transmission-level impacts, customer-side inverter behavior beyond utility interface, or the effects of harmonic distortion. Social and environmental aspects are also considered beyond the immediate scope.

1.4 Thesis Outline

The thesis is structured as follows:

- **Chapter 01 – Introduction**
  Provides the background, defines the research problem, outlines objectives and scope, and summarizes the organization of the thesis.

- **Chapter 02 – Literature Review**
  Reviews existing studies on hosting capacity, PV integration in LV networks, smart inverter technologies, BESS applications, and relevant international standards. Highlights research gaps this study aims to address.

- **Chapter 03 – Methodology**
  Describes the modeling approach, simulation environment, data sources, control strategies, and performance metrics used in the analysis.

- **Chapter 04 – Case Study and Simulation Results**
  Presents the case study details, simulation setup, and results for each scenario. Discusses technical improvements achieved through different control strategies and system configurations.

- **Chapter 05 – Financial Evaluation**
  Conducts a detailed cost-benefit analysis comparing BESS/smart inverter integration with traditional grid upgrades. Evaluates payback period, breakeven points, and long-term financial feasibility.

- **Chapter 06 – Conclusions and Recommendations**
  Summarizes the findings, identifies limitations, and provides recommendations for network planners, policy-makers, and future research.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction to PV Hosting Capacity and Grid Integration Challenges

The global drive toward decarbonizing electricity generation has significantly accelerated the adoption of solar photovoltaic (PV) systems, especially at the distribution level. As a flexible, modular, and rapidly deployable renewable energy technology, rooftop solar PV has become a central strategy in both developed and developing nations to reduce dependence on fossil fuels and enhance energy security. However, the integration of PV into existing low-voltage (LV) distribution networks presents a series of technical, economic, and regulatory challenges, particularly in regions where grid infrastructure has not been designed to accommodate distributed generation.

The hosting capacity of LV feeders, which is the maximum solar PV that can be integrated to a network without violating operational restrictions like protection coordination, thermal loading, or voltage rise, is a crucial problem. As PV penetration rises, this constraint becomes more noticeable. Initiatives by Provincial Councils to install rooftop PV on public buildings in Sri Lanka draw attention to the problem. Many of these projects face implementation delays because of technological limitations in the distribution network, even in the face of positive legislative support and high levels of solar insolation. Small-scale installations are not financially feasible since necessary grid modifications frequently cost more than the PV system's capital cost.

Alternative approaches to boosting hosting capacity without expensive traditional grid augmentation are therefore gaining popularity. By providing localized voltage and power control, technologies like smart inverters and Battery Energy Storage Systems (BESS) have demonstrated significant potential in increasing hosting capacity. Furthermore, new solutions including vertical PV systems, combined hybrid controls, Volt-Var, and Volt-Watt have been tried and proposed in a variety of international contexts. These findings are summarized in this review of the literature, which also looks at how applicable and relevant they are to the LV distribution network in Sri Lanka.

2.2 Smart Inverters for Voltage and Power Control

Beyond the conventional unidirectional DC-to-AC conversion, smart inverters are sophisticated power electrical equipment that can support the grid. They provide features including reactive power compensation, voltage regulation, frequency ride-through, and power curtailment and are outfitted with adaptive control algorithms. Many of the voltage-related problems that restrict PV hosting capacity can be resolved by smart inverters using those capabilities.

2.3 Volt–Var Control

Volt–Var control involves adjusting the reactive power output of the inverter based on real-time voltage measurements at the Point of Common Coupling (PCC). The control strategy typically follows a piecewise linear curve defined by voltage thresholds (e.g., V1 to V4). When the PCC voltage exceeds the upper limit (e.g., V3), the inverter absorbs reactive power (acts inductively), thereby reducing local voltage. When the voltage drops below a lower limit (e.g., V2), the inverter injects reactive power (acts capacitively) to increase voltage.

Simulation studies using standard test feeders, such as the IEEE European LV Test Feeder, have demonstrated the effectiveness of Volt–Var control in managing voltage rise due to excess PV generation. Sousa, J.F.B., Borges, C.L.T. and Mitra, showed that Volt–Var control improved voltage profiles across the feeder and allowed for a greater number of PV connections without violating regulatory voltage limits. The simplicity and relatively low implementation cost of Volt–Var control makes it an attractive solution for utility operators in cost-sensitive environments.

2.4 Volt–Watt Control

Volt–Watt control operates by dynamically reducing the active power output of an inverter when the voltage at the PCC exceeds a specified threshold. Unlike Volt–Var control, which adjusts reactive power, Volt–Watt control targets the root cause of voltage rise—excess active power injection from PV systems during periods of low demand.

This control method is particularly useful in LV networks with minimal load diversity and peak solar output during midday hours. While Volt–Watt control is highly effective at mitigating voltage rise, it results in energy curtailment, thereby reducing the utilization of renewable energy. Nevertheless, studies indicate that strategic application of Volt–Watt control can significantly enhance hosting capacity without the need for feeder upgrades.

2.5 Integration of Battery Energy Storage Systems (BESS)

Because BESS offers active power regulation, it offers a more flexible way to address hosting capacity limitations. BESS helps stabilize voltage and lowers the possibility of reverse power flow by storing excess energy during times of high generation and releasing it during times of peak demand.

2.6 BESS with Volt–Var Control

BESS provides two ways to manage feeder voltage when combined with Volt-Var control. When there is a voltage rise, the battery starts charging and absorbs surplus real power, while the inverter absorbs reactive power. Higher PV penetration is supported by this combined reaction, which also improves the inverter's efficiency in regulating voltage.

According to simulation data, this hybrid control greatly enhances voltage stability when compared to any technique applied alone. Particularly in feeders with high PV output and low load profiles, the combination of reactive and actual power absorption offers a reliable solution.

2.7 BESS with Volt–Watt Control

In this configuration, the inverter curtails active power output when voltage limits are breached, while the BESS simultaneously absorbs the excess energy. This results in minimal loss of renewable energy and better energy utilization compared to Volt–Watt control alone. Hashemi and Ostergaard showed that such systems could reduce PV curtailment by up to 50% and improve hosting capacity by more than 70% in certain configurations.

While BESS requires significant capital investment, the long-term operational benefits including peak shaving, load leveling, and deferment of infrastructure upgrades, make it a valuable asset in grid modernization strategies.

2.8 Combined Volt–Var and Volt–Watt Control

Hybrid control strategies that integrate both Volt–Var and Volt–Watt functionalities offer a comprehensive approach to voltage management. These systems can simultaneously absorb reactive power and curtail real power based on voltage conditions, thereby addressing a wider range of grid stability issues.

Fatima, S., Püvi, V. and Lehtonen, M. demonstrated through simulation studies that combined control strategies enhance feeder flexibility and provide more uniform voltage profiles across distributed PV-rich feeders. The added flexibility is especially useful in feeders with highly unbalanced loads or widely varying impedance characteristics. In Sri Lankan networks, where load and PV deployment patterns can be irregular, such hybrid strategies are particularly relevant.

2.9 Impact of Control Strategies on Hosting Capacity: Deterministic vs. Stochastic Analysis

Assessing the effectiveness of voltage control strategies requires robust analytical methods. Two primary approaches are used in the literature: deterministic and stochastic simulations.

2.9.1 Deterministic Analysis

In deterministic analysis, system parameters such as load, PV capacity, and inverter settings are assumed to be fixed. While this approach simplifies modeling, it often overestimates system performance by neglecting real world uncertainties. Studies on the IEEE European LV Test Feeder (Brazil) using deterministic analysis showed that Volt–Var, Volt–Watt, and BESS configurations significantly enhanced hosting capacity and prevented over-voltage events.

2.9.2 Stochastic Analysis

Stochastic methods incorporate random variations in load profiles, PV placement, and weather conditions. This approach offers a more realistic representation of network behavior. Under stochastic analysis, hosting capacity was found to vary widely depending on system randomness. Nevertheless, hybrid control strategies (Volt–Var + BESS, Volt–Watt + BESS) consistently outperformed other methods in terms of voltage stability and system resilience.

2.10 Vertical PV Systems

Vertical PV systems have emerged as a viable alternative to traditional horizontal installations, especially in regions with land constraints or specific load profiles. These systems, often designed with bifacial panels, generate electricity during morning and evening hours, aligning better with residential load demand.

2.11 Bifacial Vertical Systems

Bifacial vertical panels capture sunlight on both sides, increasing overall energy yield. East-west orientations are particularly effective in mitigating the midday peak generation associated with traditional systems. Lee, S. et al. found that vertical PV installations reduced voltage rise and shifted energy production closer to demand peaks, thereby improving hosting capacity by up to 40% without any control intervention.

2.12 Hybrid Configurations

Hybrid PV configurations that blend horizontal and vertical panels offer complementary generation profiles. An optimal mix (e.g., 60% vertical and 40% horizontal) was shown to reduce midday voltage spikes and improve overall feeder performance. These systems are especially useful in densely populated or mountainous regions.

2.13 Transformer and Cable Hosting Capacity Considerations

While much focus has been placed on feeder-level voltage constraints, transformer and cable capacity also play critical roles in determining hosting capacity. Transformers are typically designed for unidirectional flow, and reverse power flow from PV systems can lead to thermal stress and accelerated aging.

Studies have shown that under controlled conditions, transformers can handle PV penetration levels exceeding 100% of their rated capacity. However, without proper voltage regulation, long-term overloading can degrade insulation and reduce transformer lifespan. Cable ampacity, thermal limits, and impedance characteristics must also be considered in hosting capacity evaluations. Coordinated control strategies that manage both voltage and current levels are essential for ensuring long-term network reliability.

2.14 Economic Considerations and Cost-Benefit Analysis

Beyond technical performance, economic feasibility is a major determinant in selecting PV hosting capacity enhancement strategies. While BESS offers superior performance, its high capital cost is a barrier to widespread adoption. Smart inverter functionalities, by contrast, require minimal additional investment if integrated during the initial PV system installation.

N. Withana, V. Gamage, C. Silva and R. Samarasinghe compared the long-term cost of BESS and traditional grid reinforcement and found that, although BESS had higher initial costs, it offered superior life-cycle benefits, including deferred grid upgrades, improved voltage quality, and ancillary services like frequency regulation. Shared ownership models, such as community batteries or utility-managed storage, were proposed to mitigate cost burdens and increase deployment viability.

A comprehensive cost-benefit framework should consider capital expenditures (CAPEX), operational costs (OPEX), avoided upgrade costs, improved energy access, and environmental benefits. In the Sri Lankan context, such analysis is crucial for private and public sector PV investments.

2.15 Gaps in the Literature and Research Direction

Despite significant progress in modeling and evaluating hosting capacity enhancement strategies, several gaps remain:

- Limited application of control strategies tailored to the climatic, operational, and economic conditions of Sri Lanka.
- Minimal research on institutional and policy frameworks to support smart grid and BESS deployment in the Sri Lankan power sector.
- A notable lack of localized studies that combine Volt–Var and Volt–Watt control with Battery Energy Storage Systems (BESS) in a coordinated manner to enhance hosting capacity.

2.16 Summary

Several approaches to increasing PV hosting capacity in LV networks have been examined in this literature review, with an emphasis on developing technologies such vertical PV systems, smart inverter features, BESS integration, and hybrid control strategies. Each approach has unique benefits and drawbacks with regard to technical efficacy, cost effectiveness, and implementation simplicity.

BESS offers a comprehensive solution with higher capital requirements, whilst smart inverters offer inexpensive alternatives for instantaneous voltage adjustment. Innovative possibilities are offered by vertical PV systems and hybrid panel layouts, especially in areas with limited space or difficult terrain.

By assessing the combined use of Volt-Var and Volt-Watt control techniques with BESS in the context of Sri Lanka's LV distribution networks, this study seeks to close this crucial gap. The research offers simulation-based analysis and economic evaluation through a case study centered on Provincial Council buildings in order to suggest workable, scalable, and affordable options.

CHAPTER 3

3 METHODOLOGY

3.1 Introduction

This chapter outlines the thorough study approach used to examine and enhance a low-voltage (LV) distribution network's solar photovoltaic (PV) hosting capability through the use of battery energy storage systems (BESS) and smart inverter features. The method incorporates a comparative cost-benefit analysis, evaluation of control measures, thorough simulation modeling, and collection of real-world data. The study's foundation is a real-world distribution feeder in the Kotte area that is connected to a transformer.

The approach was created to replicate actual implementation circumstances, take into account regional grid constraints, and offer useful information to engineers, utilities, and legislators. It looks for workable ways to increase the solar PV penetration in electrical networks using both technical simulations and cost analysis.

3.2 Overview

The research methodology comprises five interconnected phases, as outlined below:

1. **Data Acquisition**: Collecting real-time load, PV, and feeder data from the selected area of study.
2. **System Modeling**: Developing a detailed MATLAB Simulink model of the feeder using actual electrical and operational data.
3. **Scenario-Based Simulation**: Implementing and testing distinct scenarios combining PV penetration, smart inverter control, and BESS.
4. **Technical Evaluation**: Analyzing voltage profiles, current loading, losses, and PV hosting capacity in each scenario.
5. **Economic Analysis**: Performing a cost-benefit assessment of the identified optimal solution compared to traditional grid upgrades.

This step-by-step approach makes the study realistic, repeatable, and useful for cost-related decisions.

3.3 Data Collection and Transformer Selection

Identifying a representative distribution feeder with significant rooftop solar PV penetration was essential for this study. A survey of the Lanka Electricity Company (LECO) network was conducted to locate areas with high levels of distributed solar PV integration. The area selected for detailed study was located within the Kotte Branch, managed by the Pitakotte Customer Service Center. This location was chosen due to its relatively high number of customers with rooftop solar systems and its relevance as a typical example of emerging PV saturation in low-voltage networks.

This selected distribution area includes 65 low-voltage distribution transformers spread across approximately 3.4 square kilometers. Technical data including transformer ratings, customer counts, and installed solar PV capacities were obtained from LECO's database.

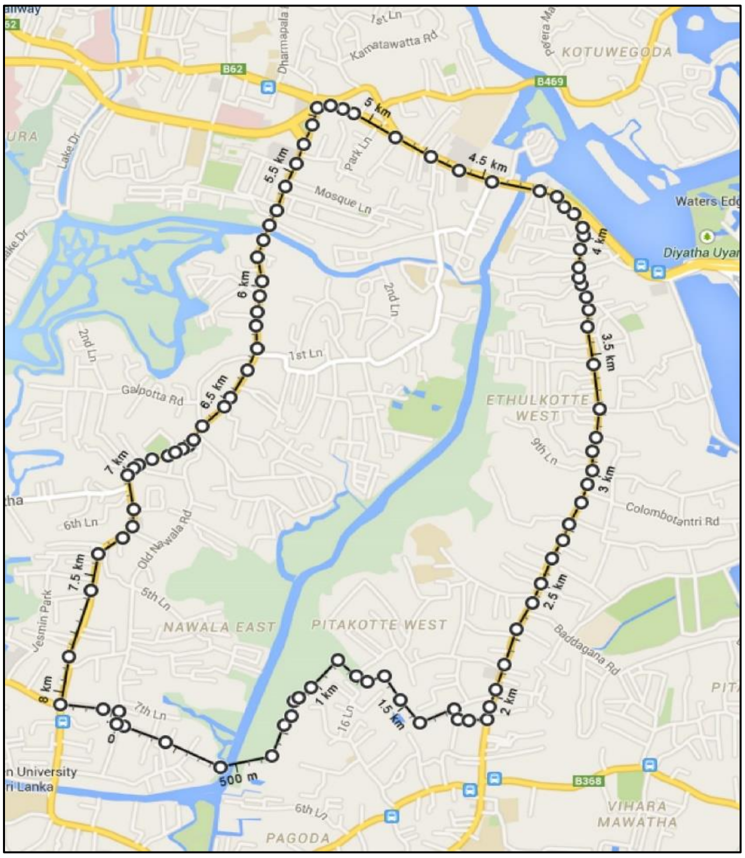


Figure 1 : Selected Distribution Area

To identify the most suitable transformer for detailed analysis, transformers within the area were filtered based on the ratio of installed PV capacity to transformer rated capacity. Transformers where PV installations exceeded 50% of the rated capacity were shortlisted for further study. During times of high solar generation, these units were thought to be particularly vulnerable to voltage rise and other power quality problems related to reverse power flow.

Table 1 : Transformer Data

Code	**Capacity (kVA)**	**No. of Solar Installed Customers**	**Total Solar Installed Capacity (kW)**	**Percentage of Solar Penetration**
AZ-0204	160	22	104	65%
AZ-8251	100	3	63	63%
AZ-0518	100	11	59	59%
AZ-0512	160	17	88	55%
AZ-0531	100	10	57	57%
AZ-0184	250	27	136	54.4%
AZ-0228	250	29	127	50.8%

From the filtered list, a 160 kVA transformer (ID: AZ-0204) was selected for in-depth analysis. It meets several important criteria for a comprehensive hosting capacity evaluation:

- Rated Capacity: 160 kVA
- Total Installed PV Capacity: 104 kW (equivalent to ~65.6% of transformer rating)

- Customer Base: 293 service connections, including 22 rooftop PV systems
- Location: School Lane, Kotte
- Data Availability: Smart meter data of loads are available

The selected transformer feeds three distinct low-voltage feeders (Feeder 1, Feeder 2, and Feeder 3). Feeder 1, in particular, hosts the highest installed PV capacity at 78 kW, distributed across 12 customers. This feeder is approximately 790 meters in length and has exhibited significant voltage rise during peak PV generation hours, making it an ideal subject for simulation and analysis.

Table 2 displays information about the customer base linked to AZ-0204.

Table 2 : Consumer details of AZ-0204

Consumer Category	Number of Consumers
Single Phase - Domestic	161
Three Phase - Domestic	73
Domestic Net Accounting (3ph)	4
Domestic Net Metering (1ph)	1
Domestic Net Metering (3ph)	17
Single Phase – GP1	18
Three Phase – GP1	5
Three Phase – GP2	14
Total	293

The low-voltage (LV) network feeder distribution, obtained from the Geographic Information System (GIS), is illustrated in Figure 2.

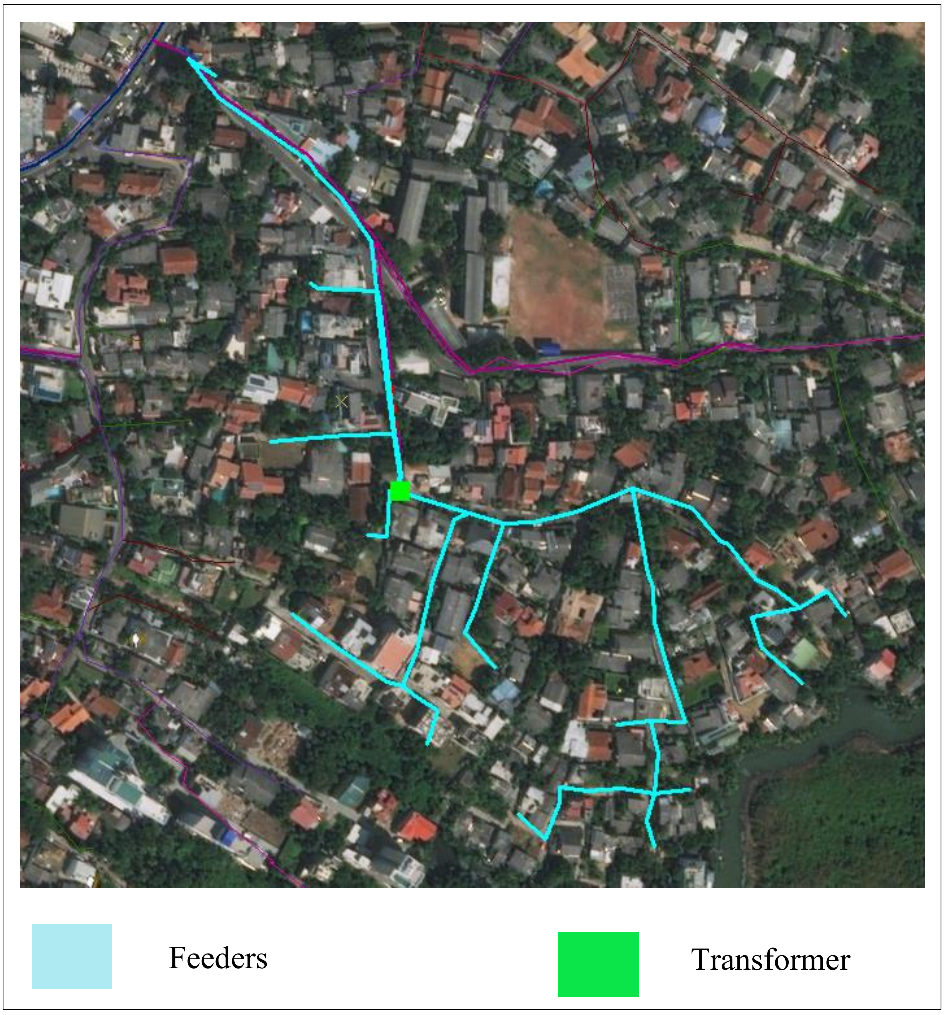


Figure 2 : GIS Map of Transformer AZ0204

In addition, following datasets were collected for the purpose of simulation modeling and validation:

- Customer Load Profiles: Obtained from smart meter data covering weekdays and weekends.
- Solar PV Output Profiles: Generated using irradiance data specific to the Colombo region.

- Feeder Topology: Electrical configuration, conductor types, segment lengths, and impedance values.
- Voltage Profiles: Real-time voltage data from smart meters at multiple locations across the feeder.
- Transformer Electrical Characteristics: Including impedance, voltage regulation behavior, and historical loading patterns.

These inputs were used to develop a simulation model of the feeder in MATLAB/Simulink, forming the basis for evaluating multiple hosting capacity enhancement strategies across different scenarios.

3.4 System Modelling

3.4.1 Modelling of transmission line

The simulation and modeling of the selected low-voltage distribution feeder were carried out using MATLAB/Simulink (version R2023a), specifically utilizing the SimPowerSystems toolbox. This software platform was chosen for its accuracy in power system simulation, fast computational response, availability of standard functional blocks, and its ability to replicate real-world electrical network behavior without convergence issues commonly found in traditional power flow tools.

Given the need to analyze a network with distributed PV systems, both the transmission line and grid-connected inverter systems were modeled individually and then integrated to reflect the actual configuration of the physical system under study. The model was designed to allow flexible simulation of multiple load conditions, PV penetration levels, and control strategies.

The modeling process began with the construction of the physical feeder using the Distributed Parameter Line block, which implements an N-phase transmission line model with distributed parameters and lumped losses. This allowed for accurate replication of line impedance and voltage drop behavior over distance.

A three-phase Dyn11 transformer block with two windings was used to model the transformation from 33 kV to 400 V, reflecting the real system’s configuration. The transformer rating was set to 160 kVA, and the model included a three-phase voltage source at 33 kV and a fundamental frequency of 50 Hz, as per local utility standards.

The Aerial Bundled Cables (ABC) used by LECO's low-voltage feeders are made up of four aluminum conductors, including a neutral wire that also acts as the messenger support. Cross-linked thermosetting polyethylene (XLPE) is used to individually insulate each conductor, and the cores are twisted together in a right-hand lay arrangement. Table 3 provides a summary of the physical and electrical characteristics of the ABC conductors utilized in the simulations.

	Conductor		3x70 +1x50 mm²	3x50 +1x35 mm²	3x50 +1x35 +16 mm²
1	Size of phase conductor	mm²	70	50	50
2	Size of Neutral / messenger conductor	mm²	50	35	35
3	Resistance (20^{0}C) of the conductor				
	a. Phase conductor	Ohm/km	0.443	0.641	0.641
	b. neutral / messenger conductor	Ohm/km	0.086	0.086	0.086
4	Conductor Reactance for 50Hz (20^{0}C)				
	a. Phase conductor	Ohm/km	0.63	0.084	0.084
	b. neutral / messenger conductor	Ohm/km	0.086	0.087	0.087
5	Voltage rating	V	600/1000		600/1000
7	Thickness of the insulation				
	a. Phase conductor	mm	1.8	1.6	1.6
	b. neutral / messenger conductor	mm	1.6	1.6	1.6
	c. street lighting conductor	mm	-	-	1.2
8	Material of Insulation		XLPE	XLPE	XLPE
9	Conductor material				
	a. Phase conductor and street lighting		AAC	AAC	AAC
	b. Neutral / messenger		AAAC	AAAC	AAAC
10	Maximum permissible temperature of cores	Deg C	90	90	90
11	Maximum current rating phase and neutral	Amps	213	168	168

Figure 3: Details of Aerial Bundled Cables

The load contributions from consumers were grouped and represented as aggregated loads within the model. However, households equipped with solar PV systems were modeled individually to accurately assess their specific impact on the overall feeder performance. The power demand of each domestic connection was estimated based on recorded monthly electricity consumption data.

Phase loading for the Red, Yellow, and Blue (RYB) conductors was balanced using historical transformer loading records to reflect realistic operating conditions. Initial simulations without any solar PV integration confirmed that the feeder operated within acceptable voltage limits, validating the baseline model configuration. The configuration of the residential connections within the simulated feeder is illustrated in Figure 3.

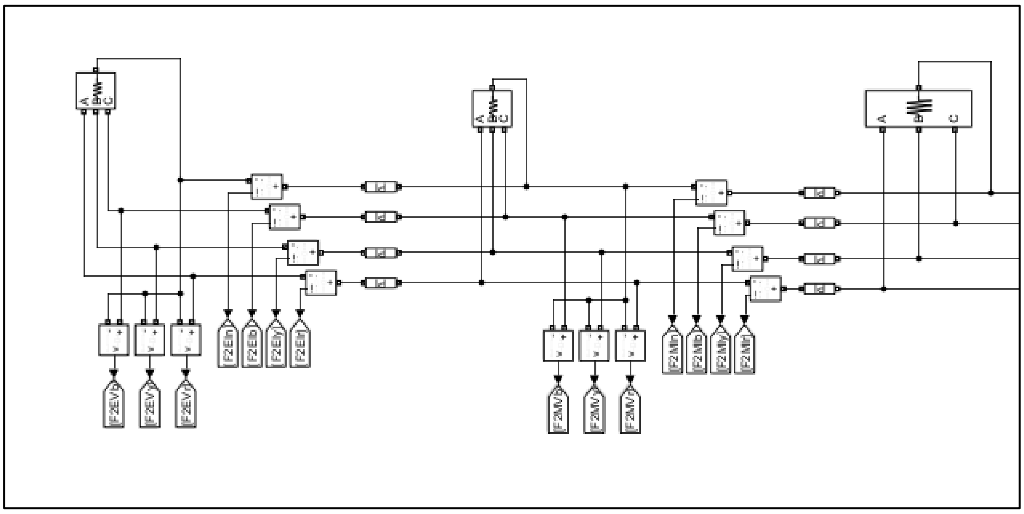


Figure 4 : Residential Loads and Pi-Sections of the Feeder

3.4.2 Modelling of Inverters

A grid-connected inverter converts the DC power from a PV array into synchronized AC power suitable for injection into the utility grid. The simulation setup followed a standard structure: PV array → MPPT → inverter → grid. In the Sri Lankan context, inverters are typically operated at unity power factor, although modeling with adjustable power factor allowed for investigation of voltage support through reactive power absorption.

The simulated inverters utilize Sinusoidal Pulse Width Modulation (SPWM), a widely adopted switching method for achieving smooth, grid-synchronized AC output. The inverter voltage (V_{inv}) is designed to be slightly higher than the grid voltage (V_{grid}) to enable net power flow into the grid. The inverter current (I_{inv}) is kept in phase with Vgrid to maintain unity power factor operation.

SPWM gating signals were generated using a comparator that compared a sinusoidal modulating signal (V_m) with a triangular carrier signal (V_{cr}). The modulation index M is defined as:

$$M = \frac{Am}{Acr}$$

Where A_m is the amplitude of the sinusoidal modulating signal and A_{cr} is the amplitude of the carrier wave.

To enhance current tracking precision, a hysteresis current control loop was implemented. The inverter current is forced to follow a reference current waveform (I_{ref}), with a predefined tolerance band ΔH. The controller ensures that inverter switching occurs whenever I_{inv} crosses the upper or lower hysteresis band limits.

$$\Delta H = 2I_h$$

Where I_h is the hysteresis half-bandwidth. This method offers fast dynamic response and excellent tracking, though it introduces variable switching frequency.

The reference current I_{ref} was generated by dividing the PV power output by the RMS grid voltage, then multiplying by $\sqrt{2}$ to obtain the peak value. A Phase Locked Loop (PLL) was used to detect the grid voltage phase angle ωt, which, combined with the amplitude, generated a reference sine wave using a custom MATLAB function.

```
function a=fcn(x,t,r)

%*codgen
a=x*(sin(t+r));
```

This reference signal was fed into the hysteresis control block to generate accurate switching pulses for the Insulated Gate Bipolar Transistors (IGBTs) within the inverter bridge. Switching logic was managed using an RS flip-flop, ensuring correct operation depending on whether the inverter current was above or below the hysteresis band.

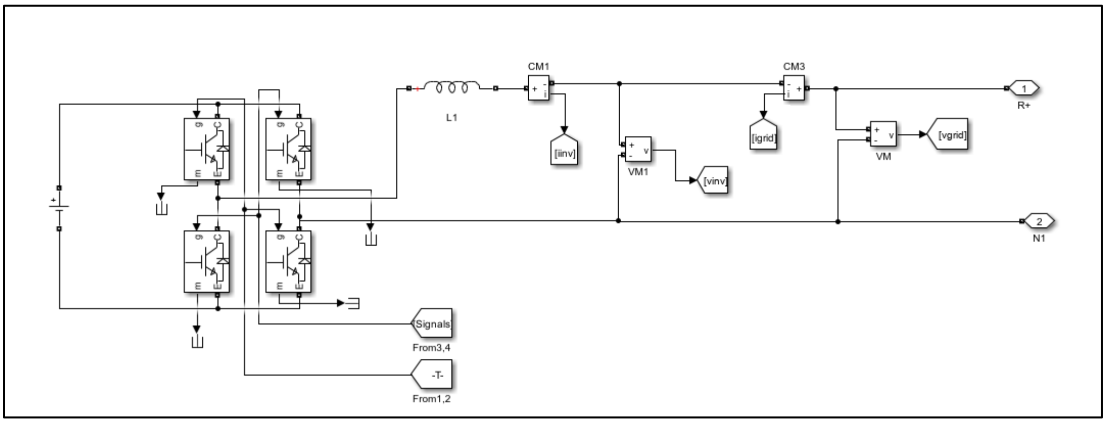


Figure 5 : Power Control Circuit of the Inverter Model

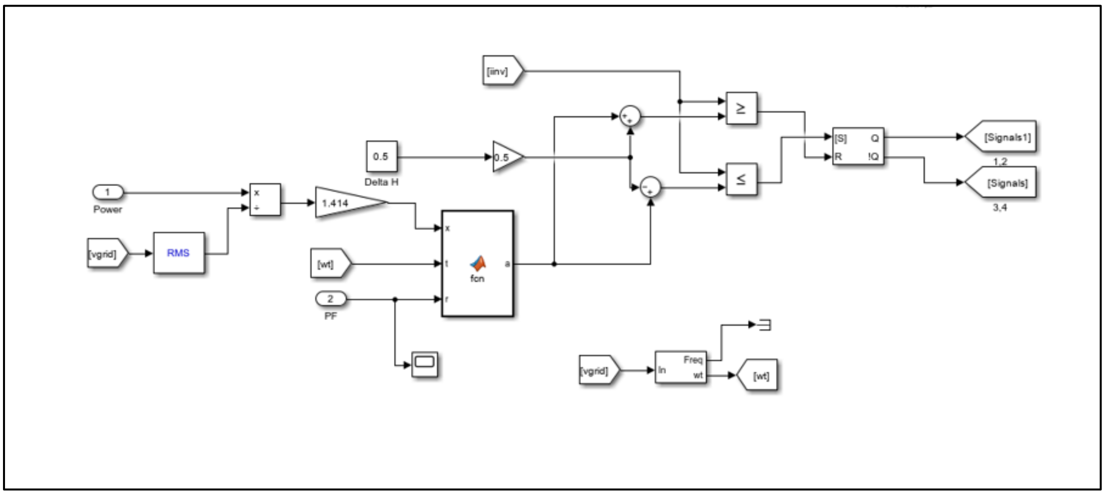


Figure 6 : Control Circuit of the Inverter

The inverter model was developed based on several practical assumptions to reflect typical operating conditions during peak solar generation:

- The DC voltage source in the model represents the collective PV array output, assumed constant during peak irradiance.
- Present-day solar inverters include MPPT algorithms, which were assumed to operate continuously.
- For consumers under net metering, the inverter was modeled to supply residential loads first, with excess energy injected into the grid.

Noise filtering to meet EMC compliance was simulated using suitable LC filters on the DC side of the inverter to suppress harmonics.

To simulate a three-phase inverter, three single-phase inverter modules were connected in parallel, each corresponding to one phase. These were then integrated to form a complete three-phase inverter block within the simulation environment.

3.5 Simulation Scenarios

To assess the impact of various control strategies and integration techniques on voltage regulation and hosting capacity, a series of six simulation scenarios were developed. Each scenario builds progressively on the previous one, enabling a comprehensive evaluation of the system's performance under different PV penetration levels, inverter control settings, and BESS placements.

- Scenario 1 – Baseline Analysis

The initial scenario involved modeling the feeder using real-world load and PV installation data without any additional PV systems or control mechanisms. This served as the reference condition to observe the network's natural voltage behavior and to identify feeders approaching critical voltage limits.

- Scenario 2 – PV Expansion Impact

A 40-kW solar PV system was introduced at three distinct locations—start, middle, and end of Feeder 1, which had previously demonstrated the highest voltage levels in the network. This scenario was designed to evaluate voltage behavior under elevated PV penetration without the application of any control mechanisms. The objective was to identify potential worst-case voltage rise conditions resulting from new solar injection. The 40-kW capacity was selected based on the maximum allowable installation under the 42 kVA consumer category, in accordance with prevailing regulatory guidelines.

- Scenario 3 – Power Factor Control (PF 0.95) Control Mechanism

With inverters running at a lagging power factor of 0.95, this simulation expanded on Scenario 2 by implementing a power factor control approach. Evaluating the effects of moderate reactive power compensation on voltage control in situations with high PV penetration was the aim.

- Scenario 4 – Power Factor Control (PF 0.9) Control Mechanism

With a lagged power factor of 0.90, this scenario was comparable to Scenario 3 but used a more aggressive control. The purpose of the extra reactive power absorption was to lessen overvoltage situations while evaluating how it affected feeder current and losses.

- Scenario 5 – Integration of 16 kW BESS

A power factor control approach (PF = 0.95) was combined with a 16 kW AC charging battery energy storage system (BESS). Using a trial-and-error method and iterative simulation, the BESS capacity was determined with the goal of bringing the maximum recorded feeder voltage below the allowable upper limit. The BESS was integrated at the start, middle, and finish of Feeder 1 to determine the best place for voltage regulation and mitigation in order to evaluate the effect of integration location.

- Scenario 6 – Improved upon Scenario 5 - PV and BESS Expansion

By adding a 15-kW solar PV system and an additional 15 kW BESS, this scenario improved upon Scenario 5. This made it possible to assess the feeder's capacity to handle more PV expansion without going above voltage limitations when using a variety of voltage support mechanisms.

These scenarios offered a strong foundation for assessing the technical viability and financial effects of BESS deployment and smart inverter control. The results served as the foundation for determining the best course of action that strikes a compromise between system cost, voltage regulation, and PV integration.

3.6 Technical Evaluation Metrics

Each scenario was simulated under peak generation (midday), low load, and worst-case PV export conditions. Evaluation was based on:

- Maximum voltage (V_{max}) and minimum voltage (V_{min}) across the feeders
- Feeder current (A) and transformer loading (%)
- I^2R losses, representing distribution losses in the feeder
- Hosting capacity (kW): maximum PV before exceeding 243.8 V

Hosting capacity was calculated by gradually increasing PV in 5 kW increments and simulating voltage response under each control scenario. The optimal configuration was identified through comparative analysis of all simulation results, focusing on compliance with voltage standards, system efficiency, and integration potential.

3.7 Economic Analysis of Optimal Configuration

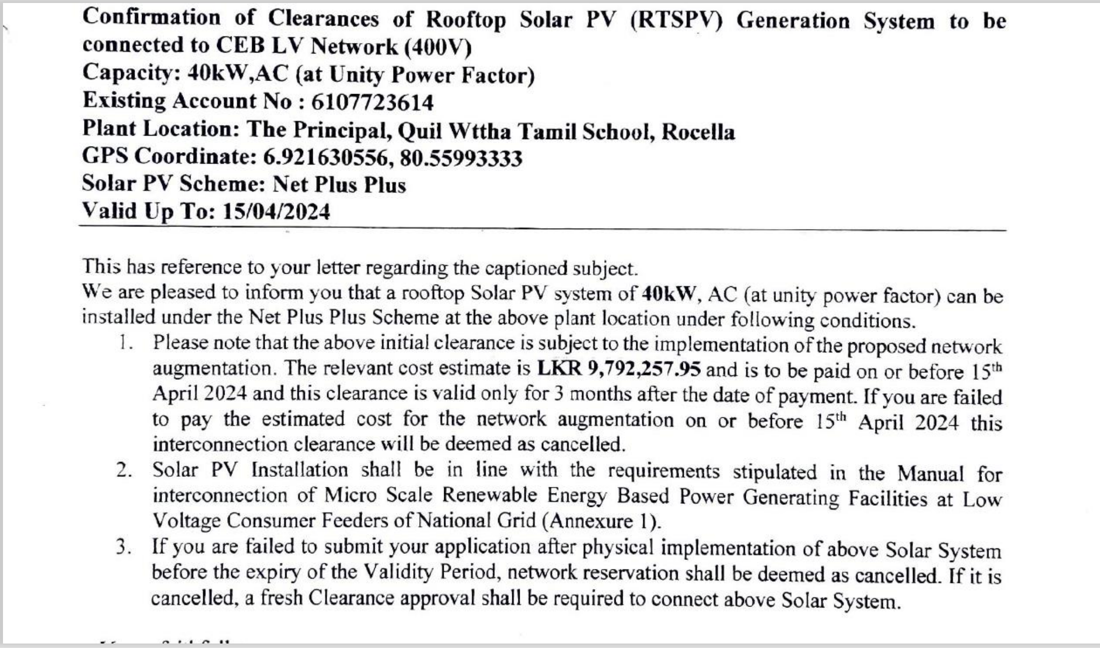
3.7.1 Purpose and Scope

The objective was to determine if the proposed solution (smart inverters + BESS) was economically superior to traditional reinforcement (transformer upgrade and feeder reconductoring).

3.7.2 Considered Parameters

- 1 USD = 300 LKR
- Battery cost: 236 USD/kWh ($LiFePO_4$)
- Battery Charger Cost = 1,200,000.00 LKR
- BESS lifespan: 10 years; DoD = 80%; capacity after 10 years = 80%
- Discount rate: 10%
- Electricity value: Solar – 27 LKR, Thermal furnace oil – 51.37 LKR (where price of furnace fuel is 191 LKR per kg)

The following figures represent two grid augmentation cost estimates that have been provided as references for future calculations and analysis.

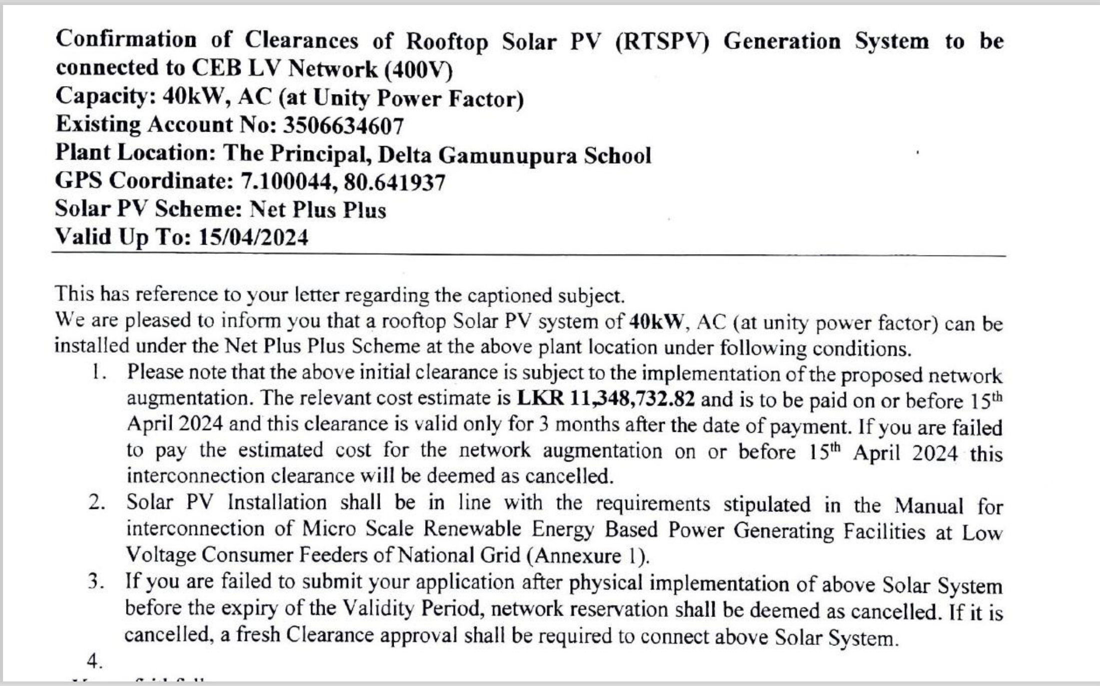


Confirmation of Clearances of Rooftop Solar PV (RTSPV) Generation System to be connected to CEB LV Network (400V)
Capacity: 40kW,AC (at Unity Power Factor)
Existing Account No : 6107723614
Plant Location: The Principal, Quil Wttha Tamil School, Rocella
GPS Coordinate: 6.921630556, 80.55993333
Solar PV Scheme: Net Plus Plus
Valid Up To: 15/04/2024

This has reference to your letter regarding the captioned subject.
We are pleased to inform you that a rooftop Solar PV system of **40kW**, AC (at unity power factor) can be installed under the Net Plus Plus Scheme at the above plant location under following conditions.

1. Please note that the above initial clearance is subject to the implementation of the proposed network augmentation. The relevant cost estimate is **LKR 9,792,257.95** and is to be paid on or before 15th April 2024 and this clearance is valid only for 3 months after the date of payment. If you are failed to pay the estimated cost for the network augmentation on or before 15th April 2024 this interconnection clearance will be deemed as cancelled.
2. Solar PV Installation shall be in line with the requirements stipulated in the Manual for interconnection of Micro Scale Renewable Energy Based Power Generating Facilities at Low Voltage Consumer Feeders of National Grid (Annexure 1).
3. If you are failed to submit your application after physical implementation of above Solar System before the expiry of the Validity Period, network reservation shall be deemed as cancelled. If it is cancelled, a fresh Clearance approval shall be required to connect above Solar System.

Figure 7: Grid Augmentation Cost received for Quilwattha Tamil School



Confirmation of Clearances of Rooftop Solar PV (RTSPV) Generation System to be connected to CEB LV Network (400V)
Capacity: 40kW, AC (at Unity Power Factor)
Existing Account No: 3506634607
Plant Location: The Principal, Delta Gamunupura School
GPS Coordinate: 7.100044, 80.641937
Solar PV Scheme: Net Plus Plus
Valid Up To: 15/04/2024

This has reference to your letter regarding the captioned subject.
We are pleased to inform you that a rooftop Solar PV system of **40kW**, AC (at unity power factor) can be installed under the Net Plus Plus Scheme at the above plant location under following conditions.

1. Please note that the above initial clearance is subject to the implementation of the proposed network augmentation. The relevant cost estimate is **LKR 11,348,732.82** and is to be paid on or before 15th April 2024 and this clearance is valid only for 3 months after the date of payment. If you are failed to pay the estimated cost for the network augmentation on or before 15th April 2024 this interconnection clearance will be deemed as cancelled.
2. Solar PV Installation shall be in line with the requirements stipulated in the Manual for interconnection of Micro Scale Renewable Energy Based Power Generating Facilities at Low Voltage Consumer Feeders of National Grid (Annexure 1).
3. If you are failed to submit your application after physical implementation of above Solar System before the expiry of the Validity Period, network reservation shall be deemed as cancelled. If it is cancelled, a fresh Clearance approval shall be required to connect above Solar System.
4.

Figure 8: Grid Augmentation Cost received for Deltagamunupura School

Estimated Generation Cost : **10th Oct 2024**

Plant Type	Energy Cost (Mn LKR)	Non Fuel Energy Cost (Mn LKR)	Capacity Cost (Mn LKR)	Total Cost of Generation (Mn LKR)	Energy Cost per Unit (LKR/kWh)	Non fuel Energy Cost per Unit (LKR/kWh)	Capacity Charge per Unit (LKR/kWh)	Cost of Electricity per Unit (LKR/kWh)
Major Hydro	0.0	0.0	37.6	37.6	0.00	0.00	2.87	2.87
Thermal - Coal	238.5	27.5	44.5	310.5	18.15	2.09	3.39	23.62
Thermal - Furnace Oil	437.2	9.4	50.3	496.9	45.20	0.97	5.20	51.37
Thermal - Diesel	0.0	1.5	19.8	21.2	0.00	0.00	0.00	0.00
Thermal - Naphtha	178.3	1.9	3.2	183.4	51.52	0.55	0.92	53.00
Wind - CEB	0.0	0.0	20.9	20.9	0.00	0.00	34.76	34.76
Wind - IPP	9.9	0.0	0.0	9.9	16.12	0.00	0.00	16.12
Solar - IPP - Ground Mounted	12.5	0.0	0.0	12.5	19.50	0.00	0.00	19.50
Solar - Roof Top	60.3	0.0	0.0	60.3	24.92	0.00	0.00	24.92
Mini Hydro	39.2	0.0	0.0	39.2	14.61	0.00	0.00	14.61
Municipal Solid Waste	6.6	0.0	0.0	6.6	39.30	0.00	0.00	39.30
Total	**982.4**	**40.2**	**176.2**	**1198.8**	**21.14**	**0.86**	**3.79**	**25.79**

Note -

Start/Stop costs has been excluded in the calculation

Capacity cost is based on the approved BST submission.

Unit Cost of Generation for the day : **25.79 LKR/kWh**

Total Generation Cost for the day: **1198.82 Mn LKR**

Fuel Prices

(as at 1st Oct 2024)

	Price (LKR/Liter or LKR/kg)
Furnace	191.00
Coal	44.20
Naphtha	191.16
Auto Diesel	283.00

Figure 9 : Estimated Generation Cost (10th Oct 2024) Published by PUCSL

Further, Studies indicate that battery prices are expected to decrease significantly in the coming years. Specifically, it is projected that battery prices will decline by approximately 35.5%, from 169 USD per kWh to 109 USD per kWh. The following chart is sourced from an analysis conducted by Bloomberg.

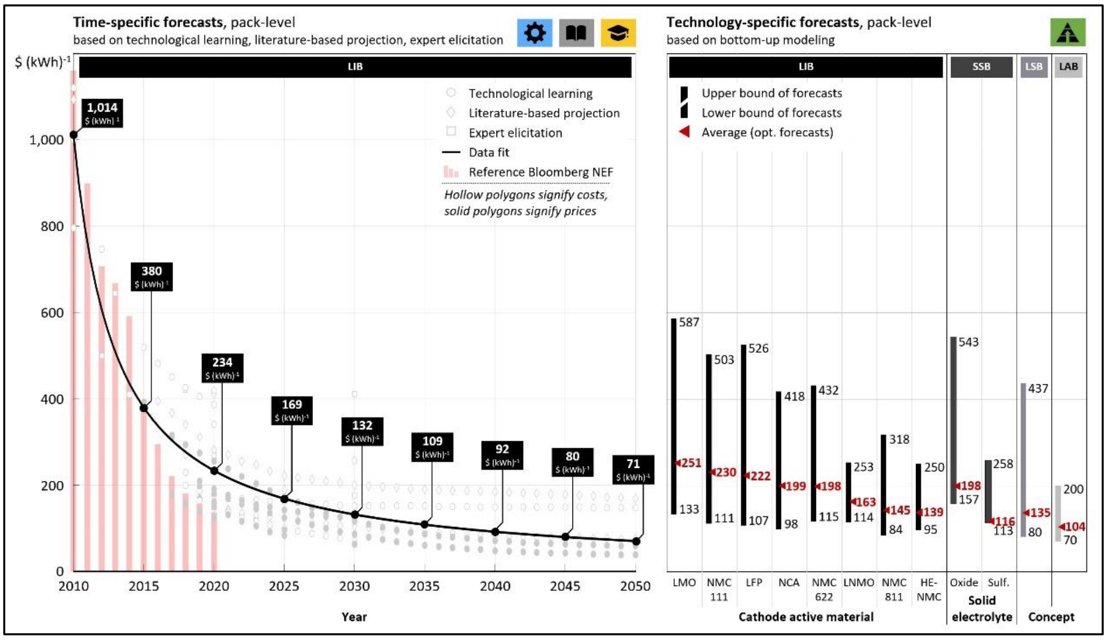


Figure 10 : Time Specific Forecast of Battery Prices

3.7.3 Evaluation Metrics

- Net Present Value (NPV)
- Payback Period

3.8 Summary

A thorough and methodological approach for evaluating solutions for increasing the capacity of solar photovoltaic (PV) hosting in low-voltage (LV) distribution networks was offered in this chapter. The methodology included scenario-based simulations incorporating different smart inverter control strategies and battery energy storage system (BESS) configurations, as well as real-world data collection and extensive feeder modeling using MATLAB/Simulink.

To assess technical effects on voltage profiles, feeder current, distribution losses, and PV hosting restrictions, a total of six simulation scenarios were created. The worst-case operating conditions for reverse power flow and voltage rise were represented by these simulations, which were carried out at periods of peak generation and low load.

To ascertain the suggested solutions' economic viability, a cost-benefit analysis was conducted concurrently with the technical examination. The economic assessment considered parameters such as:

- Capital expenditure (CAPEX) for smart inverters and BESS
- Operational and maintenance (O&M) costs
- Avoided grid reinforcement costs
- Revenue from energy exports (based on feed-in tariffs and avoided cost of thermal generation)
- Battery lifespan and degradation
- Payback period, Net Present Value (NPV)
- Discount rate and project life span assumptions

By combining rigorous technical simulations with practical economic considerations, the methodology offers a viable blueprint for utilities, policymakers, and energy planners seeking to enhance solar PV integration into LV networks—particularly in the context of Sri Lanka and other developing nations with similar grid characteristics.

CHAPTER 4

4 RESULTS AND ANALYSIS

4.1 Introduction

The simulation results from the seven scenarios created to evaluate how various solar PV penetration levels, smart inverter control schemes, and battery energy storage systems (BESS) affect a low-voltage (LV) feeder's hosting capacity and operational performance are presented in this chapter. The results are examined in terms of losses, feeder current, voltage regulation, and the feasibility of integrating more solar PV capacity without going beyond voltage threshold levels. When appropriate, visual outputs like voltage profiles, bar charts, and comparative tables are used to interpret the findings.

4.2 Scenario 1: Baseline (Existing System Without Control)

In the base case, the existing feeders were simulated with 104 kW of connected rooftop PV operating at unity power factor and without any voltage control. The simulation results indicated that the maximum voltage at the end of the feeder 1 reached 243.6 V, which is just below the statutory limit of 243.8 V. The system operated within safe voltage margins under this configuration.

While the system was technically compliant, it was operating close to the voltage limit, indicating limited capacity for further PV expansion without additional control measures.

Table 3 : Measured Voltage Profiles at Various Points Along the Three Feeders (Scenario 1)

	Voltage (V)			Solar Penetration (kW)
	Feeder Beginning	Feeder Mid	Feeder End	
Feeder 1	231.6	237.9	243.6	78
Feeder 2	231.6	230.7	228.3	21
Feeder 3	231.5	231.7	231.8	5

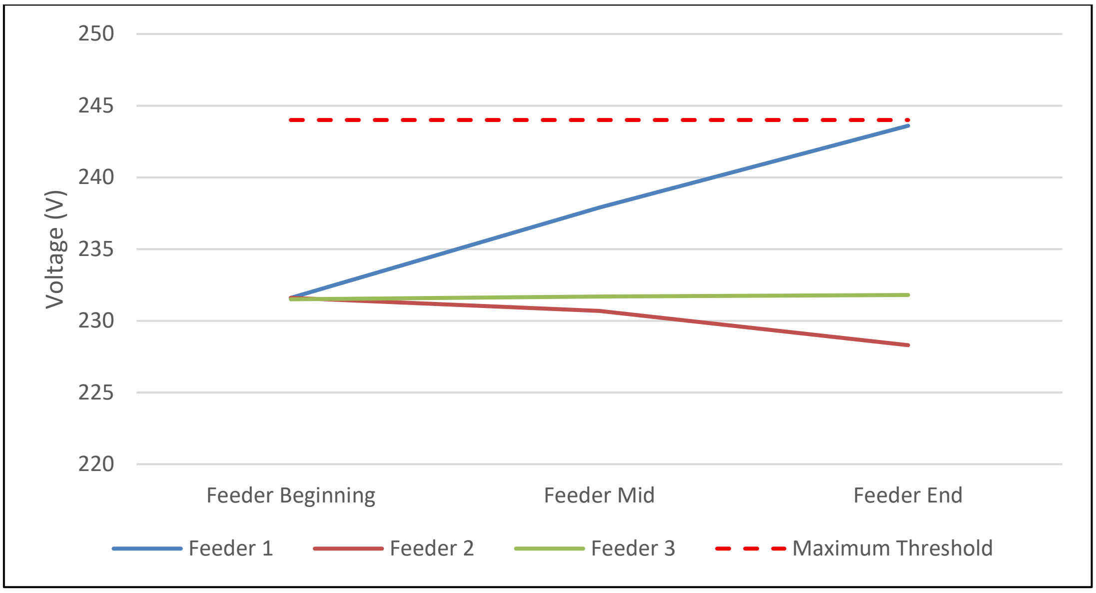


Figure 11 : Voltage Variation at Key Locations Along Each Feeder (Scenario 1)

Based on the results obtained from Scenario 1, Feeder 1 was identified as exhibiting the most critical voltage conditions among the three feeders. Consequently, Feeder 1 was selected for all subsequent simulations and detailed analysis.

4.3 Scenario 2: Additional 40 kW solar PV system (without any Control) integrated to the Feeder 1

In Scenario 2, an additional 40 kW solar PV system was integrated at various points along Feeder 1, and the corresponding voltage levels at multiple locations along the feeder were recorded for each configuration.

Table 4 : Measured Voltage Profiles at Key Locations of Feeder 1 with 40 kW PV System Integrated at Different Feeder Points (Scenario 2)

	40kW at Feeder Beginning	**40kW at Feeder Mid**	**40kW at Feeder End**
Feeder Beginning Voltage (V)	228.4	228.5	228.5
Feeder Mid Voltage (V)	235.4	242.4	241.6
Feeder End Voltage (V)	232.3	246.2	260.0

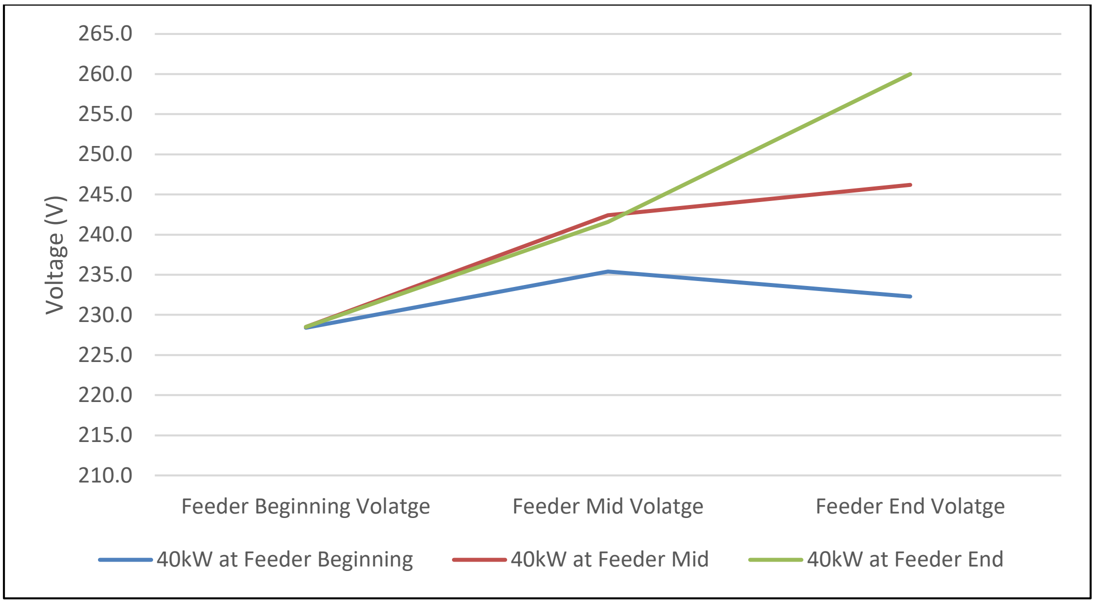


Figure 12 : Voltage Variation at Key Locations of Feeder 1 with 40 kW PV Integrated at Different Points (Scenario 2)

Analysis of Scenario 2 revealed that the worst-case voltage condition occurs when the 40-kW solar PV system is integrated at the end of Feeder 1. As a result, all subsequent simulations were conducted based on this worst-case configuration to ensure a conservative and robust assessment of system performance.

4.4 Scenario 3: Applying Power Factor Control (PF = 0.95) to Scenario 2

To mitigate the voltage rise observed in Scenario 2, smart inverters were configured to operate at a lagging power factor of 0.95, enabling moderate reactive power absorption.

Table 5 : Measured Voltage Profiles at Key Locations of Feeder 1 for Scenario 3

Scenario	Feeder Mid Voltage (V)	Feeder Beginning Voltage (V)	Feeder End Voltage (V)
Scenario 3: Applying 0.95 lagging pf to Scenario 2	228.3	241.6	254.4

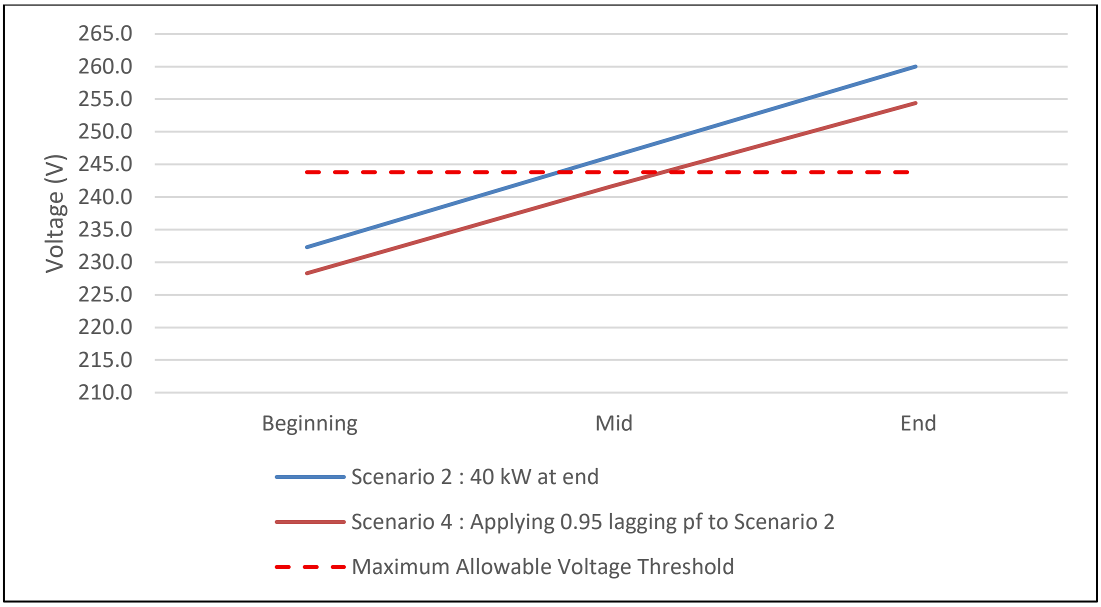


Figure 13 : Comparison of Voltage Profiles Between Scenario 2 and Scenario 3

Applying 0.95 lagging power factor to all solar PV inverters did not bring the maximum recorded voltage below the maximum allowable voltage threshold of 243.8V. It was also determined that the maximum hosting capacity of the feeder 1, when operating at a 0.95 lagging power factor, is 102 kW (comprising 78 kW of existing capacity and an additional 24 kW).

4.5 Scenario 4: Applying Power Factor Control (PF = 0.9) to Scenario 2

In this scenario, a more aggressive lagging power factor of 0.90 was applied to the smart inverters used in Scenario 2, enabling increased reactive power absorption to enhance voltage regulation.

Table 6 : Measured Voltage Profiles at Key Locations of Feeder 1 for Scenario 4

Scenario	Feeder Mid Voltage (V)	Feeder Beginning Voltage (V)	Feeder End Voltage (V)
Scenario 4: Applying 0.9 lagging pf to Scenario 2	225.0	238.2	250.9

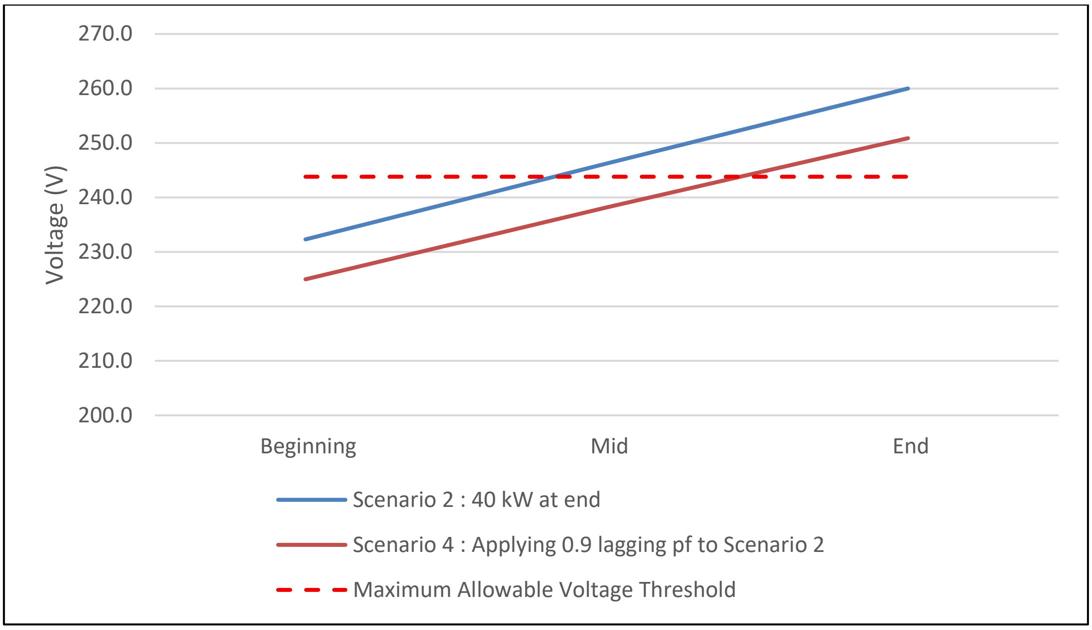


Figure 14 : Comparison of Voltage Profiles Between Scenario 2 and Scenario 4

Even with the power factor reduced to 0.9 lagging, the maximum recorded voltage remained above the allowable threshold. Moreover, while power factor correction aids in voltage regulation, it also results in increased current flow within the feeder, which may have implications for thermal loading and system losses. This trade-off is discussed in a subsequent section and highlights the need for supportive policy adjustments to accommodate reactive power control strategies in distribution networks.

4.6 Scenario 5: Integration of BESS with Power Factor Control (PF = 0.95)

In this scenario, Battery Energy Storage System (BESS) with 16 kW charging capacity was integrated into the configuration defined in Scenario 3, which featured inverters operating at a lagging power factor of 0.95. The objective was to assess whether the combined application of moderate reactive power compensation and energy storage could bring feeder voltage levels within statutory limits.

The BESS capacity was selected through iterative trial-and-error simulations, aiming to reduce the maximum recorded voltage below the allowable threshold. To evaluate the impact of spatial placement, the BESS was simulated at three locations along Feeder 1: the beginning, middle, and end. Voltage profiles and system performance were analyzed for each case to identify the most effective position for mitigating overvoltage conditions.

Table 7 : Measured Voltage Profiles at Key Locations of Feeder 1 for Scenario 5

	BESS at Feeder Beginning	BESS at Feeder Mid	BESS at Feeder End
Feeder Beginning Voltage (V)	225	225.1	225.1
Feeder Mid Voltage (V)	237	234.3	234.5
Feeder End Voltage (V)	248.5	246	243.1

The results indicate that the BESS is most effective when positioned at the end of the feeder, where the highest voltage levels are typically observed. In this configuration, the maximum recorded voltage dropped below the allowable threshold, demonstrating the critical importance of optimal BESS placement for effective voltage regulation.

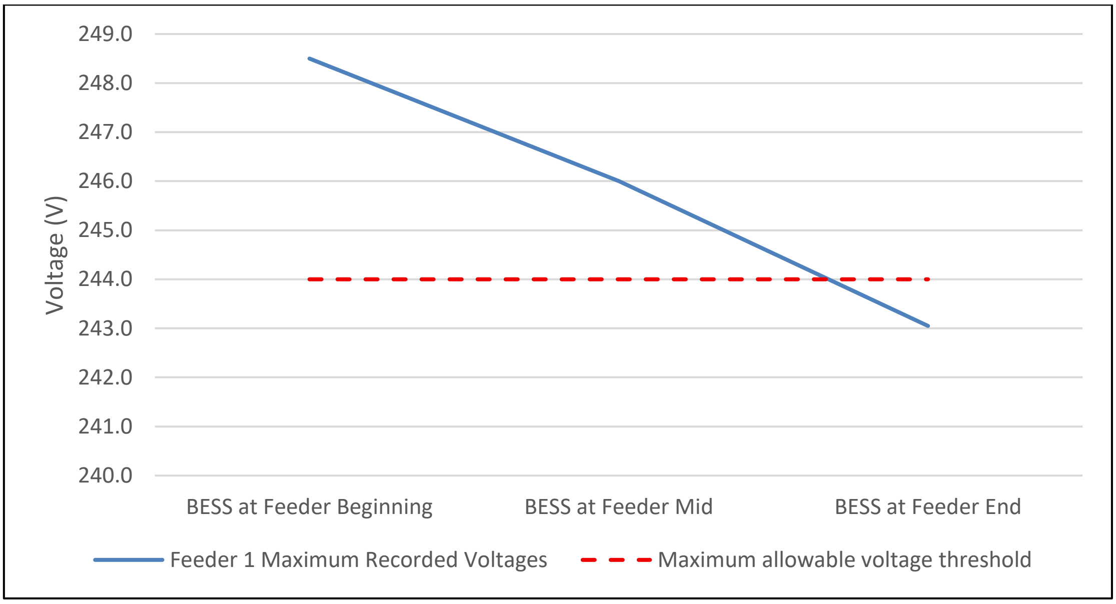


Figure 15 : Maximum Recorded Voltages with BESS Installed at Different Locations Along Feeder 1

Therefore, in the subsequent simulation, the BESS was positioned at the end of Feeder 1, and the analysis was continued based on this optimal placement.

4.7 Scenario 6: Improved upon Scenario 5 - Solar PV and BESS Expansion

An additional 15 kW PV system and an extra BESS with a charging capacity of 15 kW were added to Scenario 5 configuration to test the feeder's capability under expanded solar and storage deployment.

Table 8: Measured Voltage Profiles at Key Locations of Feeder 1 for Scenario 6

Scenario	Feeder Mid Voltage (V)	Feeder Beginning Voltage (V)	Feeder End Voltage (V)
Additional 15kW Solar PV system and BESS added to Scenario 5	224.8	231.7	243.6

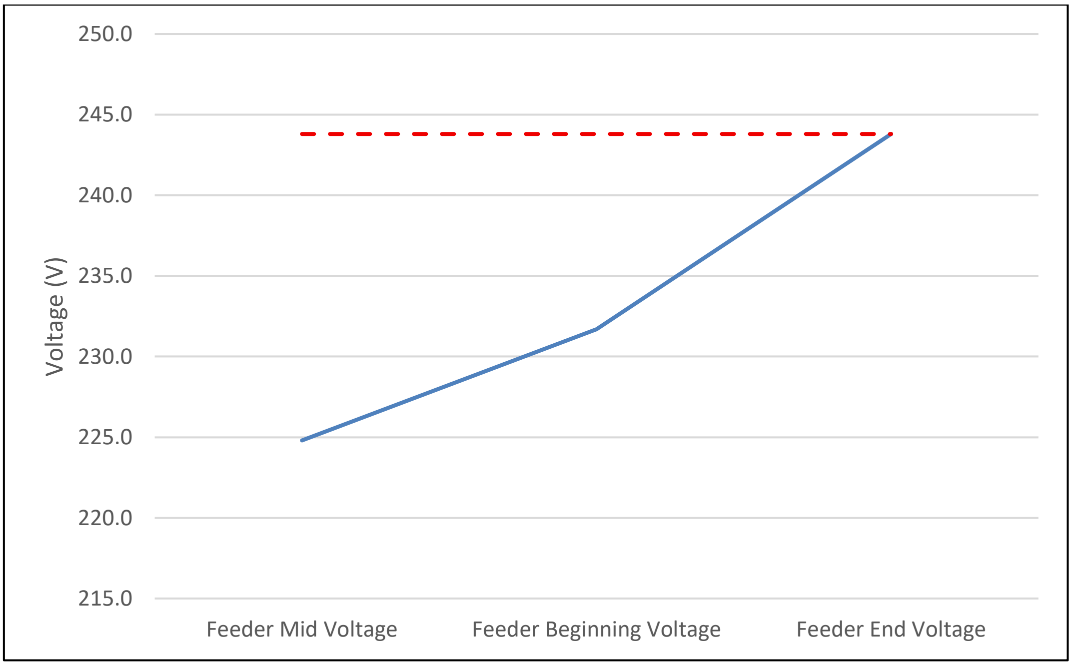


Figure 16: Voltage Profile at Key Locations Along Feeder 1 for Scenario 6

The findings of this study demonstrate that, through the integration of smart inverter control and appropriately sized Battery Energy Storage Systems (BESS), the PV hosting capacity of the feeder 1 was enhanced from 78 kW to 133 kW, enabling the accommodation of an additional 55 kW of solar PV without breaching voltage limits.

While the results suggest that even higher levels of PV penetration may be achievable with further BESS integration, the extent of such expansion is ultimately limited by the grid's capacity to absorb energy discharged from the BESS while maintaining system stability. Addressing this constraint falls beyond the scope of the present study and requires further research.

4.8 Current and I^2R Loss Analysis

In addition to voltage regulation and hosting capacity, feeder current levels and I^2R (resistive) losses were analyzed across the simulation scenarios to assess the impact of control strategies and BESS integration on overall system efficiency.

As PV penetration increased, the magnitude and direction of current flow within the feeder were significantly affected. In Scenarios 2 through 4, where additional PV capacity was integrated without storage, peak feeder currents increased, especially in sections of the network closest to the load center. This increase is attributed to the bidirectional power flow caused by net energy export during midday when generation exceeds local consumption.

The implementation of power factor control in Scenarios 3 and 4 resulted in elevated current levels, due to the reactive power component introduced by the lagging power factor. Although this helped mitigate voltage rise, it also led to increased current magnitudes, particularly in upstream sections of the feeder.

Table 9 : Measured Feeder Currents at Three Key Locations Along Feeder 1 Across Simulation Scenarios

Scenario	Feeder 1 Beginning Current (A)	Feeder 1 Mid Current (A)	Feeder 1 End Current (A)
Scenario 1	3.9	35.8	31.7
Scenario 2	40.6	77.4	76.1
Scenario 3	45.7	86.8	84.2
Scenario 4	43.5	82.6	80.0
Scenario 5	36.7	63.7	60.1
Current Carrying Capacity of Feeder 1	213.0	213.0	213.0

In all simulated scenarios, the measured feeder currents remained within the permissible current-carrying capacity of Feeder 1, confirming the technical feasibility of each control strategy under the current system configuration. Furthermore, scenarios involving BESS integration demonstrated a notable reduction in current levels compared to other control measures, highlighting the effectiveness of energy storage in alleviating current stress on the network.

The I^2R losses were calculated using the following expression:

$$\text{Loss } I^2R = \sum (I^2 \cdot R)_{\text{segment}}$$

Where:

- I = current magnitude through each feeder segment (A)
- R = resistance of the respective segment (Ω)

Table 10 : Calculated I^2R Losses at Three Key Locations Along Feeder 1 for Each Simulation Scenario

Scenario	Feeder 1 Beginning Cumulative Power Loss (W)	Feeder 1 Mid Cumulative Power Loss (W)	Feeder 1 End Cumulative Power Loss (W)
Scenario 1	0.07	220.00	392.51
Scenario 2	7.27	1036.35	2037.65
Scenario 3	9.20	1302.83	2527.70
Scenario 4	8.33	1180.33	2287.89
Scenario 5	5.93	703.10	1328.02

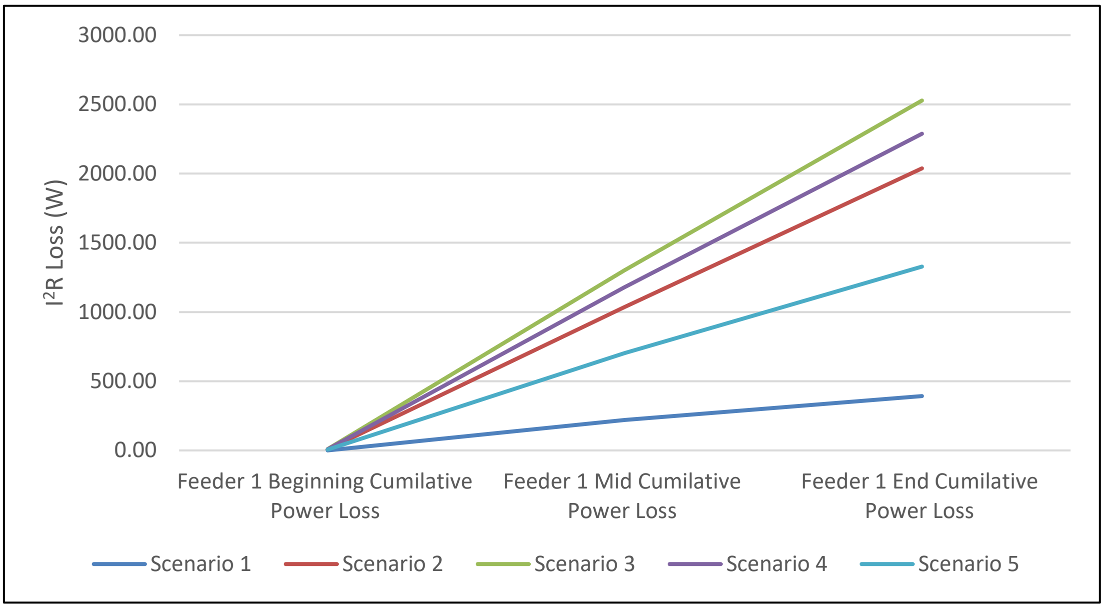


Figure 17 : Comparison of I²R Losses Across All Simulation Scenarios

It Scenario 5 recorded the lowest I²R losses when compared to Scenario 2, primarily due to the effective absorption of excess energy by the BESS, which helped minimize and localize current flow. In contrast, Scenarios 3 and 4 exhibited higher power losses relative to the Scenario 2, as reactive power compensation led to increased current magnitudes throughout the feeder. The results confirm that lower inverter power factors result in greater current flow, thereby contributing to higher system losses.

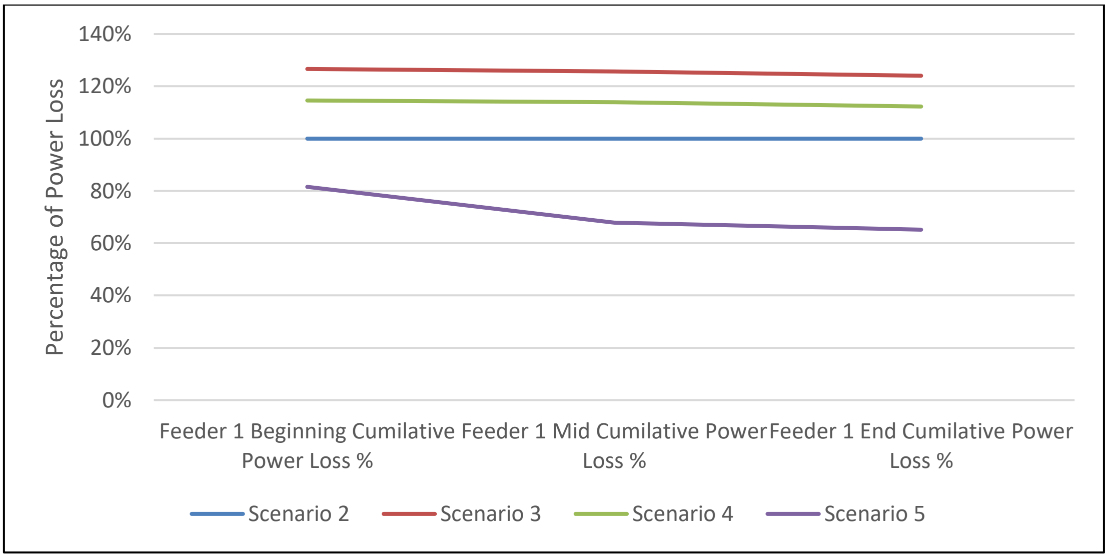


Figure 18 : Comparison of I²R Losses in All Scenarios Relative to Scenario 2

The analysis confirms that while power factor correction aids in voltage regulation, it can increase current flow and associated losses. In contrast, BESS integration offers a dual benefit—supporting voltage and reducing both current magnitude and feeder losses. This reinforces the value of storage not just for hosting capacity, but also for improving overall network efficiency.

CHAPTER 5

5 FINANCIAL EVALUATION

5.1 Introduction

The optimal solution found in Chapter 4 is evaluated financially in this chapter. The optimal technical performance was found in Scenario 5, which included integration of the Battery Energy Storage System (BESS) and smart inverter controls (Volt–Var and Volt–Watt). By weighing the costs and advantages over a normal investment lifecycle, the financial analysis seeks to determine whether implementing this design is economically feasible.

Capital and operating expenses, possible savings from postponed grid upgrades, revenue from surplus energy exports, and important financial metrics like Net Present Value (NPV) and Payback Period are all included in the study.

5.2 Calculations

5.2.1 Battery Sizing and Capital Cost Calculation for First 10 Years

When running at a 0.95 lagging power factor, Feeder 1 can handle up to 102 kW of solar energy without going over voltage limitations. In order to prevent voltage rise and support the load during periods of peak demand, any generation that exceeds this threshold should be sent to a Battery Energy Storage System (BESS).

The generalized generation profile of a 118-kW solar PV system, which consists of an additional 40 kW installation and 78 kW of existing capacity, is shown in the chart below. In order to provide a realistic estimate of system output under typical operating conditions, the profile is developed using typical daily solar irradiance patterns representative of the feeder end location. The curve analysis shows that between 11:00 a.m. and 2:00 p.m., solar production surpasses the 102-kW generation capacity.

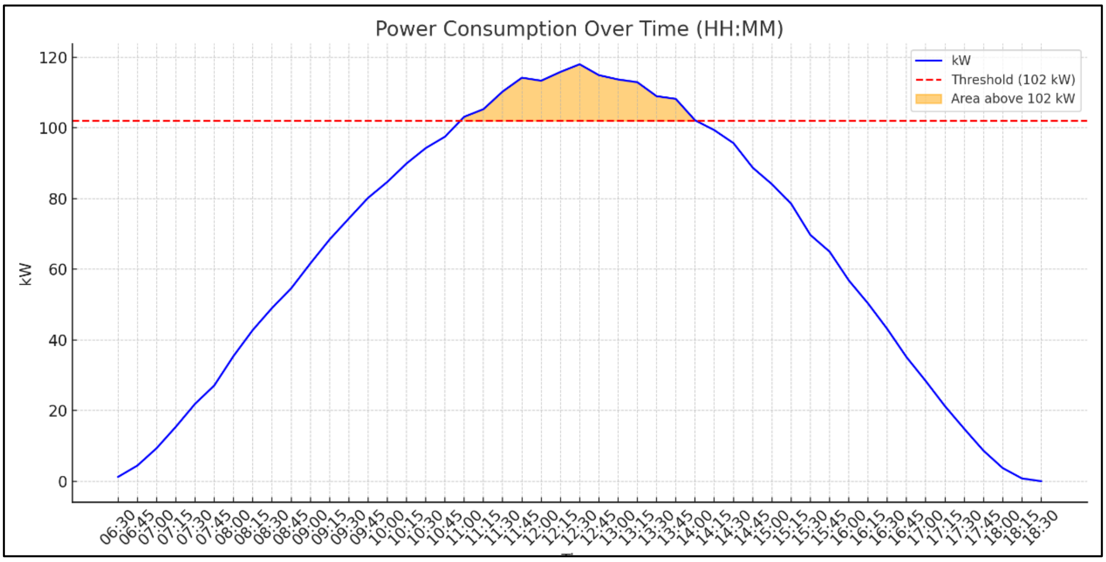


Figure 19: Power Curve of the 118 kW Solar PV System

Using MATLAB, the power curve was plotted, and the area above the 102-kW threshold was computed. The results show that the excess energy generated during this period is approximately 28.74 kWh.

The following equation 5.1 was used to determine the required capacity of the Battery Energy Storage System (BESS) for the first 10 years:

Equation 5-1 :

$$\text{TRBC} = \frac{\text{Area Under the Curve}}{\text{Max DoD} \times (\text{CAY} - \text{ODA})}$$

Where:

TRBC – Total Required Battery Capacity (kW)

CAY - BESS Capacity After 10 Years (%)

Max DoD = Maximum Depth of Discharge

ODA - PV Output Degradation After 10 Years (%)

The following table summarizes the key parameters and cost estimates for the Battery Energy Storage System (BESS) over the first 10 years of operation:

Equation 5-2:

$$\text{Total Cost of Batteries (LKR)} = \text{ER} \times \text{UBK} \times (1 + \text{VAT\%}) \times TRBC$$

Where:

ER – Exchange Rate

UBK – USD Rate of Battery per kWh

TRBC – Total Required Battery Capacity

Table 11: Capacity and Cost Calculation of BESS for the First 10 Years

Parameter	Value
Exchange Rate (USD to LKR)	300
Power Rating (kW)	16
Required Battery Capacity (kWh)	28.74
Maximum Depth of Discharge (DoD) (%)	80
Battery Capacity Retention after 10 Years (%)	80
PV Capacity Reduction after 10 Years (%)	8
Total Required Battery Capacity (kWh)	50
VAT on Batteries (%)	18
Cost per kWh of Battery (Including VAT) (LKR)	83,544.00
Total Cost for Batteries (LKR)	4,177,200.00
Cost of 24 kW AC Charger (Victron) (LKR)	1,200,000.00
Total Cost of Storage System (LKR)	5,377,200.00

5.2.2 Battery Sizing and Capital Cost Estimation for the Second 10-Year Period

When calculating the required BESS capacity for the second 10-year period, the degradation of the solar PV system over the first decade is taken into account. As a result, only 92% of the initially required 28.74 kWh—reflecting an 8% reduction in PV output—is considered in the calculations.

In addition, based on current market projections, battery prices are expected to decrease by approximately 35% over the next 10 years. Therefore, 65% of the current battery price has been used in the cost estimation for the second period. A discount rate of 10% has also been applied to account for the time value of money when projecting the future cost of batteries.

Equation 5-3 :

$$\text{Total Cost of Batteries (LKR)} = \text{ER} \times \text{UBK} \times \text{EBPF} \times (1 + \text{VAT\%}) \times TRBC \times PVF$$

Where:

ER – Exchange Rate

UBK – USD Rate of Battery per kWh

TRBC – Total Required Battery Capacity

EBPF - Effective Battery Price Factor

PVF - Present Value Factor

Table 12: Capacity and Cost Calculation of BESS for the Second 10 Years

Parameter	Value
Exchange Rate (USD to LKR)	300
Power Rating (kW)	16
Required Battery Capacity (kWh)	26.44
Maximum Depth of Discharge (DoD) (%)	80
Battery Capacity Retention after 10 Years (%)	80
PV Capacity Reduction after 10 Years (%)	8
Total Battery Capacity (kWh)	46
Battery Price Reduction Over 10 Years (%)	35
Effective Battery Price Factor (%)	65
Present Value Factor (2% discount rate, 10 years)	1.22
VAT on Batteries (%)	18
Cost per kWh of Battery (Including VAT) (LKR)	66,195.79
Total Cost of Batteries (LKR)	3,045,006.13
Cost of 24 kW AC Charger (Victron) After Present Value Adjustment (LKR)	1,464,000.00
Total Cost of Storage System (LKR)	4,509,006.13

The battery cost was based on the minimum order quantity of 3 MWh, while the AC charger cost was derived assuming a minimum procurement quantity of 100 units.

5.2.3 Operational and Maintenance Cost Calculation

Equation 5-4:

$$\text{Annual O\&M Cost (LKR)} = \text{O\&M Rate} \times \text{CAPEX}$$

Assuming an annual O&M rate of 1% of CAPEX:

Annual O&M for first 10 years = 0.01×5,377,200.00 = LKR 53,772.00

Annual O&M for second 10 years = 0.01×4,509,006.13 = LKR 45,090.06

5.2.4 Energy Export Revenue

Equation 5-5:

$$\text{Annual Export Revenue (LKR)} = \text{RBC} \times (\text{Ethermal} - \text{Esolar}) \times 365$$

Where:

RBC – Required Battery Capacity (kWh)

Ethermal – Electricity cost of furnace oil (LKR per kWh)

Esolar – Electricity cost of solar (LKR per kWh)

Annual Export Revenue per year for 1st 10 years = 28.74 × (51.37 – 27) × 365

= LKR 255,643.74

Annual Export Revenue per year for 2nd 10 years = 26.44 × (51.37 – 27) × 365

= LKR 235,192.24

The following table presents the year-by-year breakdown of calculated expenditures and cost savings, with each value discounted to its present value. This enables a comprehensive comparison between the Net Present Value (NPV) of costs and the NPV of benefits over the project lifespan.

For the financial evaluation, the avoided grid augmentation cost is estimated at LKR 1,000,000.00, based on actual augmentation cost data provided by the supply authority. Additionally, the annual transformer maintenance cost is assumed to be 1% of the transformer's capital cost, reflecting standard utility maintenance practices.

Table 13: Cost Benefit Analysis

Year	0	1	2	3	4
Total cost for storage system	5,377,200.00	-	-	-	-
Yearly Maintenance Cost	53,772.00	53,772.00	53,772.00	53,772.00	53,772.00
Discount Rate	10%	10%	10%	10%	10%
Appreciated Maintenance Cost	53,772.00	59,149.20	65,064.12	71,570.53	78,727.59
Net Present Value - Expenditure	12,965,997.40	-	-	-	-
Cost Saving per kWh	255,643.74	255,643.74	255,643.74	255,643.74	255,643.74
Discount Rate	10%	10%	10%	10%	10%
Discounted Saving per kW	255,643.74	232,403.40	211,275.82	192,068.92	174,608.11
CEB Augmentation Cost Saving	10,000,000.00	-	-	-	-
TF Maintenance Cost Saving	100,000.00	100,000.00	100,000.00	100,000.00	100,000.00
Appreciated Maintenance Cost	100,000.00	110,000.00	121,000.00	133,100.00	146,410.00
Net Present Value - Saving	18,076,173.57	-	-	-	-

Year	5	6	7	8	9
Total cost for storage system	-	-	-	-	-
Yearly Maintenance Cost	53,772.00	53,772.00	53,772.00	53,772.00	53,772.00
Discount Rate	10%	10%	10%	10%	10%
Appreciated Maintenance Cost	86,600.34	95,260.38	104,786.42	115,265.06	126,791.56
Net Present Value - Expenditure	-	-	-	-	-
Cost Saving per kWh	255,643.74	255,643.74	255,643.74	255,643.74	255,643.74
Discount Rate	10%	10%	10%	10%	10%
Discounted Saving per kW	158,734.65	144,304.22	131,185.66	119,259.69	108,417.90
CEB Augmentation Cost Saving	-	-	-	-	-
TF Maintenance Cost Saving	100,000.00	100,000.00	100,000.00	100,000.00	100,000.00
Appreciated Maintenance Cost	161,051.00	177,156.10	194,871.71	214,358.88	235,794.77
Net Present Value - Saving	-	-	-	-	-

Year	10	11	12	13	14
Total cost for storage system	-	4,509,006.13	-	-	-
Yearly Maintenance Cost	53,772.00	45,090.06	45,090.06	45,090.06	45,090.06
Discount Rate	10%	10%	10%	10%	10%
Appreciated Maintenance Cost	139,470.72	153,417.79	168,759.57	185,635.53	204,199.08
Net Present Value - Expenditure	-	-	-	-	-
Cost Saving per kWh	255,643.74	235,192.24	235,192.24	235,192.24	235,192.24
Discount Rate	10%	10%	10%	10%	10%
Discounted Saving per kW	98,561.73	82,433.44	74,939.50	68,126.81	61,933.47
CEB Augmentation Cost Saving	-	-	-	-	-
TF Maintenance Cost Saving	100,000.00	100,000.00	100,000.00	100,000.00	100,000.00
Appreciated Maintenance Cost	259,374.25	285,311.67	313,842.84	345,227.12	379,749.83
Net Present Value - Saving	-	-	-	-	-

Year	15	16	17	18	19
Total cost for storage system	-	-	-	-	-
Yearly Maintenance Cost	45,090.06	45,090.06	45,090.06	45,090.06	45,090.06
Discount Rate	10%	10%	10%	10%	10%
Appreciated Maintenance Cost	224,618.99	247,080.89	271,788.98	298,967.87	328,864.66
Net Present Value - Expenditure	-	-	-	-	-
Cost Saving per kWh	235,192.24	235,192.24	235,192.24	235,192.24	235,192.24
Discount Rate	10%	10%	10%	10%	10%
Discounted Saving per kW	56,303.15	51,184.68	46,531.53	42,301.39	38,455.81
CEB Augmentation Cost Saving	-	-	-	-	-
TF Maintenance Cost Saving	100,000.00	100,000.00	100,000.00	100,000.00	100,000.00
Appreciated Maintenance Cost	417,724.82	459,497.30	505,447.03	555,991.73	611,590.90
Net Present Value - Saving	-	-	-	-	-

Total Benefit = Net Present Saving – Net Present Expenditure

= 18,076,173.57 – 12,965,997.40

= LKR 5,110,176.17

Equation 5-6:

$$ROI = \frac{Total\ Benefit}{Net\ Present\ Expenditure} \times 100$$

Based on the financial calculations, the project yields a Return on Investment (ROI) of approximately 39.4%, indicating that the proposed optimal solution is financially viable and economically justifiable.

CHAPTER 6

1. CONCLUSIONS AND RECOMMENDATIONS

a. Conclusions

This study has demonstrated that while smart inverter controls such as Volt-VAR and Watt control through power factor management can offer some improvement in hosting capacity, their effectiveness is limited when solar PV penetration increases significantly. Specifically, at higher levels of PV integration—such as the addition of a 40-kW system at the feeder end—a lagging power factor of 0.9 was insufficient. Instead of alleviating voltage issues, it led to an increase in the feeder's maximum current and associated I^2R losses, undermining grid efficiency.

The analysis further revealed that, given the low penetration rate of rooftop solar PV systems (7.6% of customers), voltage regulation solely through power factor-based smart inverter control is not a feasible long-term solution. While customer load profiles are naturally diversified, solar PV generation is typically synchronous across the network, limiting the voltage regulation benefits of this method.

In contrast, the integration of a Battery Energy Storage System (BESS) along with 0.95 lagging power factor correction proved to be a more effective strategy. A BESS with a 16 kW AC charging capacity and a 0.95 lagging power factor successfully mitigated voltage rise issues and reduced maximum current in the feeder, enabling the integration of the additional 40 kW solar PV system without violating voltage or current limits. The results indicate that voltage regulation is highly dependent on the strategic placement of BESS units at voltage-critical points on the feeder. Proper sizing of the BESS ensures that voltage remains below the maximum threshold while maintaining feeder current within safe operational limits.

From an economic perspective, the capital cost of BESS integration is significantly lower than the cost of grid augmentation. Although BESS units have a lifespan of 10 years and require periodic replacement, their ability to store energy generated at low daytime tariffs (LKR 27/kWh) and dispatch it during high-tariff nighttime periods improves their economic viability. Moreover, the reduced reliance on thermal power generation, particularly from costly furnace oil, strengthens the financial case for BESS deployment. With the continued decline in battery costs and the rise in fossil fuel prices, the long-term financial sustainability of BESS is expected to improve further.

Overall, this study concludes that integrating BESS into solar-rich distribution feeders is a practical and cost-effective approach to enhancing hosting capacity. By supporting the integration of an additional 40 kW of solar PV—an increase of 51.2% of hosting capacity of the feeder, the BESS-based solution effectively addresses both technical and economic challenges. Furthermore, it offers a scalable pathway to achieve solar PV capacities equivalent to transformer ratings, thereby promoting wider adoption of distributed solar energy systems without necessitating costly grid reinforcements.

It is important to note, however, that these findings are specific to the area of study, where the distribution feeder has already reached its maximum daytime voltage threshold and where solar PV installations are primarily concentrated between the mid-point and end of the feeder. To generalize these results, further studies are necessary for feeders with different load profiles and spatial distributions of solar generation.

b. Recommendation for further studies

This study identified BESS integration with a 0.95 lagging power factor as the most effective and economical solution to enhance solar PV hosting capacity. While this approach demonstrated a significant improvement over existing solutions, the study did not evaluate the maximum possible hosting capacity that can be achieved using this method. Future research should quantify this limit and assess the impact on grid stability, frequency, and inertia to ensure reliable operation under higher PV penetration levels.

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4. Hashemi, S. and Ostergaard, J. (2016) 'Efficient control of energy storage for increasing the PV hosting capacity of LV grids,' IEEE Transactions on Smart Grid, p. 1. https://doi.org/10.1109/tsg.2016.2609892.
5. N. Withana, V. Gamage, C. Silva and R. Samarasinghe, "Financial Feasibility of Battery Storage based Approach for Renewable Rich Distribution Feeders," 2020 IEEE International Conference on Power Systems Technology (POWERCON), Bangalore, India, 2020, pp. 1-6, doi: 10.1109/POWERCON48463.2020.9230576
6. Electricity Act No.20 of 2009, Sri Lanka, April 2009
7. LECO GIS data and LECO billing database

APPENDIX A: Grid Augmentation Cost Estimates (Received Documents)

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இலங்கை மின்சார சபை
CEYLON ELECTRICITY BOARD

Your Ref: My Ref: Solar Clearance/Nawa Date: 19th March 2024

Project Manager
GAIA Green Energy CEN (Pvt) Ltd
14/12A, Park Street
Colombo 02

Dear Sir/Madam,

Confirmation of Clearances of Rooftop Solar PV (RTSPV) Generation System to be connected to CEB LV Network (400V)
Capacity: 40kW,AC (at Unity Power Factor)
Existing Account No : 6107723614
Plant Location: The Principal, Quil Wttha Tamil School, Rocella
GPS Coordinate: 6.921630556, 80.55993333
Solar PV Scheme: Net Plus Plus
Valid Up To: 15/04/2024

This has reference to your letter regarding the captioned subject.
We are pleased to inform you that a rooftop Solar PV system of **40kW**, AC (at unity power factor) can be installed under the Net Plus Plus Scheme at the above plant location under following conditions.

1. Please note that the above initial clearance is subject to the implementation of the proposed network augmentation. The relevant cost estimate is **LKR 9,792,257.95** and is to be paid on or before 15th April 2024 and this clearance is valid only for 3 months after the date of payment. If you are failed to pay the estimated cost for the network augmentation on or before 15th April 2024 this interconnection clearance will be deemed as cancelled.
2. Solar PV Installation shall be in line with the requirements stipulated in the Manual for interconnection of Micro Scale Renewable Energy Based Power Generating Facilities at Low Voltage Consumer Feeders of National Grid (Annexure 1).
3. If you are failed to submit your application after physical implementation of above Solar System before the expiry of the Validity Period, network reservation shall be deemed as cancelled. If it is cancelled, a fresh Clearance approval shall be required to connect above Solar System.

Yours faithfully
CEYLON ELECTRICITY BOARD

O/C Eng. W.M.S.W. Weerasinghe
Deputy General Manager
(Central Province 02)

Deputy General Manager
Central Province 02
Ceylon Electricity Board

Annexure 1: Manual for interconnection of Micro Scale Renewable Energy Based Power Generating Facilities at Low Voltage Consumer Feeders of National Grid.

OFFICE OF THE CHIEF ENGINEER (COMMERCIAL)–CENTRAL PROVINCE 2
431, Colombo Road, Pilimatalawa, Sri Lanka.

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இலங்கை மின்சார சபை
CEYLON ELECTRICITY BOARD

Your Ref: My Ref: Solar Clearance/Nuwara Date: 19th March 2024

Project Manager
GAIA Green Energy CEN (Pvt) Ltd
14/12A, Park Street
Colombo 02

Dear Sir/Madam,

Confirmation of Clearances of Rooftop Solar PV (RTSPV) Generation System to be connected to CEB LV Network (400V)
Capacity: 40kW, AC (at Unity Power Factor)
Existing Account No: 3506634607
Plant Location: The Principal, Delta Gamunupura School
GPS Coordinate: 7.100044, 80.641937
Solar PV Scheme: Net Plus Plus
Valid Up To: 15/04/2024

This has reference to your letter regarding the captioned subject.
We are pleased to inform you that a rooftop Solar PV system of **40kW**, AC (at unity power factor) can be installed under the Net Plus Plus Scheme at the above plant location under following conditions.

1. Please note that the above initial clearance is subject to the implementation of the proposed network augmentation. The relevant cost estimate is **LKR 11,348,732.82** and is to be paid on or before 15th April 2024 and this clearance is valid only for 3 months after the date of payment. If you are failed to pay the estimated cost for the network augmentation on or before 15th April 2024 this interconnection clearance will be deemed as cancelled.
2. Solar PV Installation shall be in line with the requirements stipulated in the Manual for interconnection of Micro Scale Renewable Energy Based Power Generating Facilities at Low Voltage Consumer Feeders of National Grid (Annexure 1).
3. If you are failed to submit your application after physical implementation of above Solar System before the expiry of the Validity Period, network reservation shall be deemed as cancelled. If it is cancelled, a fresh Clearance approval shall be required to connect above Solar System.
4.

Yours faithfully
CEYLON ELECTRICITY BOARD

Eng. W.M.S.W. Weerasinghe
Deputy General Manager
(Central Province 02)

Deputy General Manager
Central Province - 02
Ceylon Electricity Board

Annexure 1: Manual for interconnection of Micro Scale Renewable Energy Based Power Generating Facilities at Low Voltage Consumer Feeders of National Grid.

OFFICE OF THE CHIEF ENGINEER (COMMERCIAL)–CENTRAL PROVINCE 2
431, Colombo Road, Pilimatalawa, Sri Lanka.
Tel: – (+9481) 24949160 - Fax: + (+94 81)2388283 - e-mail:- cecomcp2@gmail.com

APPENDIX B: Simulation Model