IDENTIFICATION OF THE KEY FACTORS AND DEVELOPMENT OF STRATEGIES FOR PROMOTING RESIDENTIAL CUSTOMER PARTICIPATION IN DEMAND RESPONSE PROGRAMS

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Degree of Master of Science in Electrical Installations

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DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgment any material previously submitted for a degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgment is made in the text. Also, I hereby grant to the University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books)

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Date: 03/07/2024

(M.A.I.N. Chathurangi)

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

Signature of the supervisor:

Date: 03/07/2024

(Prof . K.T.M.U. Hemapala)

ABSTRACT

Effective Demand Response (DR) design plays a crucial role in mitigating peak demand increases and price volatility. Understanding diverse customer behavior, particularly in the residential sector, is pivotal for successful DR implementation. Recently, there has been a growing focus on price-based demand response programs, offering increased flexibility and potential for enhanced demand responsiveness. The success of these programs hinges on encouraging greater residential customer participation, necessitating the formulation of more effective incentive schemes. DR programs, including direct load control, empower utilities to manage peak loads by temporarily reducing electricity demand. While the efficacy of direct load control on individual appliances is well-established, utility demand-side management strategies often integrate multiple DR programs to optimally reduce demand during peak events.

Power distribution transformers are one of the key assets to be managed by the utility. The aging of transformers causes operational and financial burdens on the utility. Insulation failure due to overloading is the primary cause of the aging of the transformer. In Sri Lanka high peak demand appears at nighttime due to the residential loads are increasing. Therefore, the transformers are overloading at nighttime. Instead, the concept of demand response can be used to reduce the transformer overloading at the nighttime peak considering the requirements of the load. In this, I have demonstrated how Demand Response can positively affect the lifespan of the transformer.

To characterize the psychological behaviors of the customer by analyzing the conduct of a customer survey among the residential customers of the overloaded feeder. From this, the available capacity of DR can be measured. The consumer willingness to participate in DR is also measured by identifying the key factors the customer expects to participate in such program.

After that, analyze the customer load profiles and transformer load profiles to find the necessary load reduction in the night peak.Finally, based on the available capacity, a DR scheduling model is developed.

Then, according to the scheduling results, an incentive scheme is proposed to evaluate the impact of DR on generation adequacy and analyze the benefits to the utility and the customers who participated in DR.

ACKNOWLEDGEMENT

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

First, I would like to express my sincere gratitude to my internal supervisor, Dr. K.T.M.U. Hemapala for providing me with the concept of study and continuous guidance throughout the period.

Also, I take this opportunity to extend my gratitude to Dr. H.M. Wijekoon Banda for the guidance and encouragement, which helped me to complete this task successfully. Further, I appreciate the guidance, support, and advice given by the evaluation panel on numerous times to make my research more fruitful.
My sincere thanks go to all of my colleagues at Lanka Electricity Company (LECO) and Ceylon Electricity Board (CEB) who helped me in many ways during this journey. Last but not least, I express my heartiest gratitude and love to my husband and my parents,who took a lot of burden and patience, which helped me to complete this task under difficult circumstances while being a mother and a full-time employee.

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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
DR	Demand Response

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Revolution of Demand Response for Power System

The modern electrical grid faces numerous challenges, including the growing energy demand, the integration of renewable resources, and the need for increased efficiency. One promising avenue for addressing these challenges is the implementation of Demand Response (DR) programs. Demand Response involves actively engaging electricity consumers to modify their consumption patterns in response to price signals or other incentives. By encouraging consumers to shift their energy usage during periods of high demand, utilities can better balance the supply and demand on the grid, which will inevitability help to achieve grid stabilization.

1. Growing Importance of Demand Response:

The importance of demand response has escalated with the increasing penetration of intermittent renewable energy sources, such as wind and solar power. These sources introduce variability into the grid, requiring a flexible and responsive system to maintain stability. Demand Response, when effectively harnessed, not only helps in balancing supply and demand but also supports the integration of renewable energy by mitigating the impact of their intermittency.

2. Challenges of Peak Demand:

One critical aspect of demand response is addressing peak demand periods, particularly during nighttime peaks. Nighttime peaks, though less conspicuous than daytime peaks, can put significant stress on the grid infrastructure. Transformers, crucial components of the electrical grid, are particularly affected by extended periods of high demand. The continuous operation at or near their rated capacity during peak times can contribute to increased wear and reduced lifespan of transformers.

3. Significance of Transformer Longevity:

Transformers play a pivotal role in the power distribution system by stepping up or stepping down voltage levels. Their reliability is paramount for maintaining a stable and efficient grid. Premature failure or degradation of transformers not only incurs substantial replacement costs but can also lead to service disruptions and cascading effects on the entire power network.

1.1.2 Impact of Demand Response in Sri Lanka National Grid

Sri Lanka, with its rapidly increasing economy and increasing energy demand, stands at the crossroads of energy transition. The National Grid serves as the backbone of the country's power infrastructure, tasked with meeting the demands of a growing population and expanding industrial base. Against this backdrop, understanding and harnessing the potential of demand response becomes imperative for achieving a resilient and sustainable energy future.

Demand Response (DR) has emerged as a critical tool in the sustainable management of energy resources, playing a pivotal role in enhancing the efficiency and reliability of national grids across the globe. In the context of Sri Lanka, the implementation of Demand Response mechanisms in the National Grid has demonstrated significant positive impacts on energy consumption patterns, grid stability, and overall energy sustainability.

One of the key benefits of Demand Response in Sri Lanka is its contribution to peak load management. By incentivizing consumers to adjust their electricity consumption during periods of high demand, the National Grid can mitigate the need for costly infrastructure upgrades to handle peak loads. This not only reduces operational costs for the grid but also minimizes the environmental footprint associated with increased energy production during peak times.

Moreover, DR fosters a more resilient and adaptable energy grid. Sri Lanka, like many other nations, faces challenges such as variable renewable energy generation and occasional grid instability. DR allows for the integration of renewable energy sources by enabling consumers to align their electricity usage with periods of abundant renewable energy production. This helps balance the grid and enhances its capacity to handle fluctuations in energy supply.

In terms of economic benefits, Demand Response programs empower consumers with the ability to make informed choices about their energy consumption. This not only leads to cost savings for individual consumers but also promotes a culture of energy conservation at the national level. Additionally, the reduced reliance on expensive plants during peak demand periods contributes to overall cost-effectiveness in the energy sector.

As Sri Lanka continues to develop and modernize its energy infrastructure, the incorporation of Demand Response mechanisms proves instrumental in achieving a more sustainable and resilient National Grid. The positive impacts encompass environmental sustainability, economic efficiency, and grid reliability, positioning DR as a crucial element in shaping the future of Sri Lanka's energy landscape.

1.2 Problem Statement and Motivation

Under the guidelines established by the CEB, it's mandated that the voltage level on the feeder must be kept within 6% and the load on a transformer should not exceed 70% of its capacity. Exceeding this threshold leads to transformer overload, a condition that accelerates the aging of its insulation. This premature aging significantly shortens the transformer's operational life. A notable challenge to the power system is the high demand for electricity during nighttime, primarily driven by residential consumers. This demographic represents a substantial portion of the national electricity usage. Given the pronounced impact of residential consumption patterns on the power system, particularly concerning the issue of transformer overload and peak night-time demand, this area has been selected for my research focus.

1.3 Scope and Motivation of the Study

This research is focused on developing a demand response strategy to increase participation of the residential customers which applies to low-voltage distribution networks in Sri Lanka. For the analysis, data is taken from the LECO distribution network, which operates in highly urbanized areas of the country. This initial study was based on existing transformers in the LECO area.

A generalized methodology was formulated by incorporating the specifications of the selected overloaded transformer and integrating feedback gathered from customer surveys.

For the modeling purpose, an OpenDSS simulation tool, integrated with Python software, has been used. The model was designed as three phase four wire network that allows for analysis of the behavior of the customers while increasing their participation. A model has been developed with transformer, feeders, and customer loads and the simulation runs with load reduction of residential customers.

A cost analysis study was done by considering the customer categorization after the customer survey and transformer load profiles were used to make an average load curve for calculations.

Different time slots in a day were taken as simulation results of the model. Final limits were determined by considering the CEB regulations. Conditions were identified for the limits and further studies were carried out to confirm the behavior with different loading levels of the transformer.

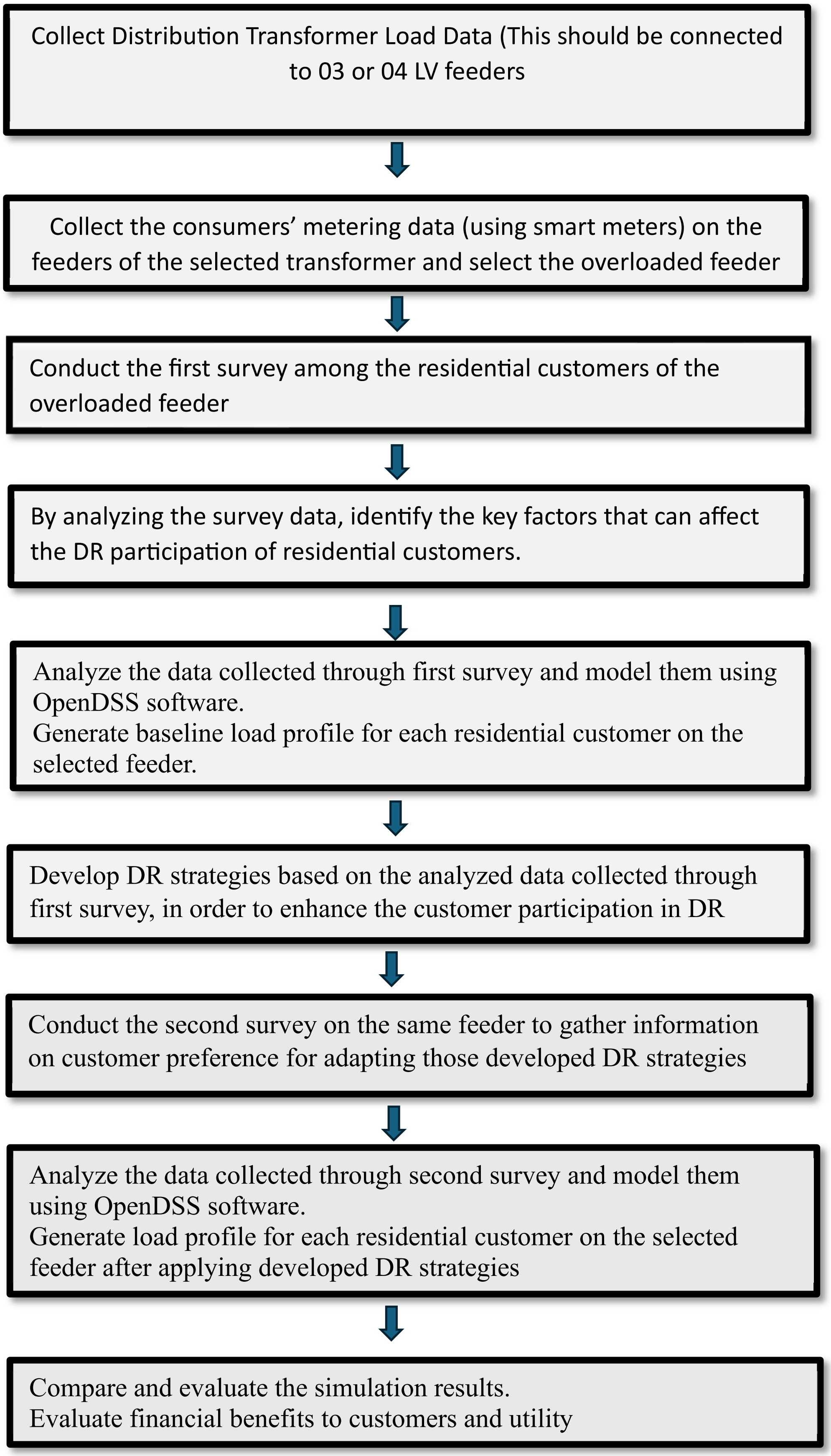
1.4 Objective of the Study

To develop a strategy for encouraging residential consumer participation in Demand Response, designed for peak clipping.

Specific Objectives;

1. To identify the factors that impact residential demand response participation in Sri Lanka through surveys and data analysis.
2. To develop strategies to enhance customer participation in DR programs and simulate the effect of those strategies with and without the developed strategies.
3. To develop recommendations based on proposed strategies for increasing residential demand response participation in Sri Lanka.

1.5 Implementation plan of the project



1.6 Thesis Organization

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

Chapter 1	This chapter describes the revolution of demand response integration in local context. A description of the problem statement & motivation, scope, objective, and methodology of research has been provided in this chapter.
Chapter 2	As the research work is based on the impact of demand response to the Sri Lanka power system, this chapter provides details of hosting capacity and limiting factor concepts.
Chapter 3	This chapter captures the research works done on selected test feeders, with detailed explanation of modeling and features of OpenDSS. The results and observations of the case study have been discussed.
Chapter 4	This chapter explains how the modeling and development were done through OpenDSS for this study using my selected transformer data and customer data.
Chapter 5	In this, the load curtailment program development process and the curtailment criteria are explained.
Chapter 6	The financial evaluation part and the benefit calculations for consumers and the utility are explained in this.
Chapter 7	Generalized Methodology of implementing a DR program according to the findings of this study is explained here.
Chapter 8	Final conclusion of my research is explained in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The research presented in this thesis is a study carried out to develop a Demand Response strategy to increase the participation of residential customers. By focusing on increasing the lifetime of the transformer by reducing the night peak without overloading the transformer.

Transformer load profiles were studied in initiation to select the overloaded transformer. According to the regulations set by the CEB,[07] the voltage level on the feeder should be maintained at 6%. The transformer capacity should not exceed 70% of its rated capacity. Overloading of a transformer can cause the insulation to age, which can greatly impact the lifespan of the transformer. The high night-time peak in electricity demand is largely driven by residential customers, who account for a significant portion of the country's overall electricity consumption. Because of this, the residential customers were chosen residential customers as my research area.

Table 2-1 : Summery of literature review

Item no.	Title of Research	Year of Publication	Work Done	Research Gap
01	"Demand Response Strategies for Residential Customers: A Review"	2020	Analyzed various demand response programs implemented for residential customers. - Evaluated the effectiveness of different strategies in reducing peak demand.	Limited understanding of the key factors influencing residential customer participation in demand response programs. - Lack of comprehensive strategies tailored to address barriers to participation identified in the literature.
02	"Behavioral Economics and Demand Response: A Literature Review"	2019	Explored behavioral economic theories and their application in designing demand response programs for residential customers. - Examined the influence of factors such as social norms,	Limited understanding of the efficacy of behavioral interventions in sustaining demand response participation over time. - Need for empirical research to validate the applicability of behavioral theories in

			peer pressure, and framing effects on consumer response to demand management initiatives.	diverse cultural and socioeconomic contexts.
03	"Technological Innovations in Demand Response for Residential Customers"		Reviewed recent technological advancements and their application in enhancing demand response capabilities for residential users. Assessed the potential of emerging technologies to optimize energy consumption patterns and improve demand response efficiency.	Lack of considering on the real-world performance and cost-effectiveness of emerging demand response technologies in residential settings. - Need for user-centric design approaches to ensure usability and acceptance of advanced demand response solutions among diverse consumer segments.
04	"Behavioral Insights into Residential Demand Response Programs"	2019	Utilized behavioral insights from psychology and economics to design and evaluate residential demand response programs. - Investigated the impact of personalized feedback, social comparisons, and incentives on consumer behavior and participation in demand response initiatives.	Insufficient understanding of the long-term behavior changes mechanisms underlying successful residential demand response interventions informed by behavioral insights. Need for scalable strategies to integrate behavioral nudges into existing demand response infrastructure and program designs.
05	"Smart Meter Data Analytics for Residential Demand Response"	2018	Applied advanced analytics techniques to smart meter data to facilitate demand response in residential settings. Explored methods for identifying consumption patterns, predicting peak demand periods, and targeting interventions to optimize energy usage.	Lack of standardized protocols for sharing and analyzing smart meter data across utility providers and demand response aggregators. Need for transparent data governance frameworks to address privacy concerns and ensure consumer trust in smart meter-based demand response programs.

06	Demand Response in the Residential Sector: A Critical Feature of Sustainable Electricity Supply in New Zealand		Address the issue of peak demand in the residential sector in New Zealand, by implementing a demand response approach. Method developed after selecting the feeder which was needed the demand response.	Need to use most suitable DR technique. Need to consider social norms, personal commitments, and external influences, interact with price signals to affect consumer response.
07. Operating manual- Provincial System Planning Engineer- Ceylon Electricity Board				

2.2 Feeder Selection Criteria

Feeder selection stands as a crucial preliminary step before the implementation of DR programs within the residential sector. This process involves meticulous evaluation of various criteria to identify the most suitable feeders for DR integration [06]. The significance of feeder selection lies in its direct influence on the effectiveness and efficiency of DR initiatives. Moreover, feeder selection enables utilities to tailor their DR strategies to match the specific needs and capabilities of each feeder and its corresponding residential customer base.

This targeted approach enhances the likelihood of successful DR implementation, maximizing energy savings, grid reliability, and customer satisfaction. Thus, feeder selection serves as a cornerstone in the planning and execution of DR programs, facilitating their seamless integration into the residential energy landscape.

By carefully assessing the following factors, utilities can pinpoint the optimal locations for DR deployment.

- Geographic distribution of the feeder

Feeders located in urban or semi-urban areas are often preferred for demand response programs due to their higher population density, more complex energy usage patterns, and typically, a better infrastructure for electricity distribution and communication. Urban areas might also have more commercial and industrial customers whose energy usage can be more flexibly managed compared to rural areas. Additionally, urban settings often provide easier access for maintenance and monitoring activities.

- Residential density

Specifying that each feeder must serve a minimum of 50-100 residences ensures there's a substantial base of residential customers to participate in demand response programs. This density is crucial for achieving significant aggregate energy savings or shifts in energy consumption patterns. A feeder serving a high number of residences can lead to more impactful demand response actions, as small adjustments per home can cumulate into substantial changes at the feeder level.

- Customer diversity

Customer diversity, particularly with a focus on customers who has a high consumption rate of energy, ensures participation from households that have a significant energy footprint. Targeting customers with higher energy usage may allow for more substantial demand response potential, as these customers might have more flexibility in adjusting their consumption patterns or shifting loads.

- Solar potential

This criterion considers the potential for solar energy production within the area served by the feeder. A high solar potential means that residences could generate a significant portion of their electricity demand on-site, reducing the load on the grid. In demand response terms, this could also mean leveraging solar energy during peak times or storing excess solar energy for use during high-demand periods, enhancing grid stability and reducing reliance on traditional power sources.

- Availability of Smart Meters

Smart meters are crucial for real-time or near-real-time monitoring and management of electricity consumption. They enable more sophisticated demand response strategies, such as dynamic pricing signals or direct load control by the utility. By ensuring all consumers on a selected feeder have smart meters, utilities can more effectively implement and manage demand response programs.

- Available space for new renewable sources

The availability of space for installing additional renewable energy sources (like solar panels or small wind turbines) can enhance a feeder's suitability for demand response. It allows for greater flexibility in managing local energy resources, contributing to grid stability and resilience.

- Cost

The cost implications of demand response is crucial. This includes assessing the potential revenue loss due to reduced energy consumption and the upfront and ongoing costs associated with implementing demand response programs. Ensuring these costs are justified by the benefits of the demand response program, such as reduced peak demand, improved grid reliability, and deferred infrastructure investments, is essential for the economic viability of the initiative.

2.3 Factors Influencing Residential Customer's Participation

In highlighting the significance of Demand Response for residential customers, several pivotal factors must be acknowledged. Foremost among these is the imperative to comprehend the distinctive energy consumption patterns and preferences exhibited by residential consumers [2],[3]. This understanding serves as a foundation for tailoring DR initiatives to align with consumer behaviors effectively. Through a comprehensive consideration of the following factors, both utilities can optimize the potency and efficacy of Demand Response programs targeted toward residential customers.

- Incentives and Rewards

Incentives and Rewards are powerful motivators for residential customers to participate in demand response programs. Financial incentives, such as discounts on electricity bills, cash rewards, or rebates on energy-efficient appliances, can significantly encourage participation. Non-financial incentives might include recognition programs or priority service offerings. The key is to align the incentives with the interests and values of the residential customers, making participation financially and emotionally rewarding. The study I carried out focused only on financial incentives because that is the best tool to incentivize consumers.

- Awareness and Outreach

Awareness and Outreach efforts are crucial to educate customers about the existence, benefits, and importance of demand response programs. This can involve marketing campaigns, informational workshops, social media engagement, and personalized communication through emails or letters. Awareness campaigns aim to inform customers how their participation helps ensure grid stability, contributes to environmental sustainability, and can lead to personal benefits, such as cost savings or enhanced service reliability.

- Technological Solutions

Technological Solutions refer to the deployment of smart technologies that facilitate easier and more effective participation in demand response programs. This includes smart meters, smart thermostats, energy management systems, and mobile apps that provide users with real-time data on energy usage, control over their home appliances, and notifications about demand response events. Technology can automate the process of adjusting energy consumption, making participation seamless and less intrusive for the customer.

- Ease of Participation

Ease of Participation is about removing barriers and making it as simple as possible for customers to join and stay in demand response programs. This could mean straightforward signup processes, minimal requirements for initial investment (e.g., in smart home technologies), and providing customers with clear, concise instructions on what is expected from them during demand response events. The easier it is to participate; the more likely customers will join and remain active participants.

- Transparency and Trust

Transparency and Trust are foundational to successful Demand Response programs. Utilities and program operators should be clear about how the program works, how data about customers' energy usage is collected and used, and what benefits and risks are involved. Building trust also involves demonstrating reliability and consistency in program management, honoring incentives and rewards as promised, and maintaining open lines of communication for feedback and support. Trust ensures that customers feel safe and valued in their participation, fostering long-term engagement.

2.4 Survey to Identify Customer Behavior to Participation in DR

- Consumer Appliances and Power Consumption

This section aims to collect data on the types of appliances consumers have in their homes and their respective power consumption. This information is crucial for identifying which appliances contribute most to the household's energy consumption and could be targeted for Demand Response initiatives [1],[4]. Understanding the energy profile of a household's appliances can help in designing DR strategies that are both effective and minimally intrusive to the consumer.

- Consumption Pattern

Analyzing consumption patterns involves looking at when and how energy is used throughout the day or during different seasons. This information can reveal peak usage times and opportunities for shifting or reducing consumption. Understanding consumption patterns helps in tailoring DR programs to fit actual energy usage trends, ensuring that the timing of DR events corresponds with periods of high demand on the grid.

- Essential Loads of Each Consumer

Identifying essential loads involves determining which appliances or systems (e.g., heating, cooling, refrigeration) consumers consider critical and would prefer not to be affected during DR events. This information ensures that DR programs respect consumer needs and safety, by avoiding disruptions to essential services. It helps in designing DR strategies that are acceptable and feasible for consumers to participate in, without compromising their comfort or well-being.

- Consumer Response to DR

This section seeks direct feedback from consumers on their awareness, understanding, and perceptions of demand response programs. It can include questions about their previous experiences with DR, if applicable, and their willingness to adjust energy consumption habits. The feedback gathered here can highlight potential barriers to participation and areas where additional education or support may be needed.

- Consumer Agreement for Load Shedding and the Time

Here, the questionnaire probes the consumer's willingness to have their load reduced (load shedding) during DR events and their preferences or constraints regarding the timing of such events. Understanding consumer flexibility helps in scheduling DR events in a way that maximizes participation and effectiveness while minimizing inconvenience to participants.

2.5 Load curtailment program

A Load Curtailment Program for Demand Response is a strategic approach used by utilities and grid operators to manage the electric grid's reliability and efficiency by reducing or shifting electricity use during peak demand periods. These programs are critical for maintaining grid balance, especially during times of high demand or when the grid is under stress, such as during extreme weather conditions. Load curtailment can be voluntary or mandatory, depending on the program's structure and the agreements between the utility and the customers.

2.5.1 Benefits of load curtailment program

- Reduce Peak Demand: To decrease the highest levels of electricity demand, thereby avoiding the need for additional, often less efficient, and more expensive, peaking power plants.
- Enhance Grid Stability: To maintain the balance between electricity supply and demand, ensuring the reliability of the power system.
- Promote Energy Efficiency: To encourage consumers to adopt more energy-efficient practices and technologies.
- Support Renewable Integration: To facilitate the integration of renewable energy sources by managing demand to match the variable supply from sources like wind and solar.

2.5.2 Key Components for Load curtailment

- Participant Recruitment: Utilities enroll customers who agree to reduce their electricity use upon request. Participants often include large commercial and industrial customers, as well as residential consumers.
- Incentive Structure: Participants receive compensation or incentives for reducing their power usage during DR events. Incentives can be based on the amount of energy curtailed or a flat rate for participation.
- Communication Infrastructure: Effective communication channels are established to notify participants of upcoming DR events, provide instructions, and gather feedback.
- Monitoring and Verification: Technologies such as smart meters and energy management systems are used to monitor participants' energy consumption and verify compliance with the program's requirements.
- Curtailment Strategies: Participants reduce their load by turning off non-essential lights and equipment, adjusting Heating, Ventilation, and Air Conditioning (HVAC) settings, or using on-site generation like solar panels or battery storage.

CHAPTER 3

MODELING AND DEVELOPMENT

This study is used to model the selected transformer with its feeders.

The selected LECO network was modeled by using actual load profiles of customers in the selected transformer. The main objective is to develop a strategy for encouraging residential consumer participation in demand response designed for peak clipping.

Generalized methodology implies a structured, broad approach or framework that can be applied to residential customers. A generalized methodology is developed to be flexible enough to adapt to different households' needs, preferences, and capacities to participate in Demand Response.

This methodology focuses on creating individual households to participate in these programs. It involves a load curtailment strategy since the consumption patterns, incentives, and capabilities can vary widely among different households.

The methodology could include several components, such as:

- ❖ Technological tools: Smart meters, home energy management systems, and smart appliances can help in monitoring and controlling energy use more effectively.
- ❖ Incentive structures: Financial or other incentives to encourage households to adjust their energy use, such as reduced electricity rates during off-peak hours or rewards for reducing total consumption.
- ❖ Communication and education: Informing customers about how and why to participate in demand response, including the benefits not just for themselves but for the community and the environment.
- ❖ Customization and flexibility: Recognizing that one size does not fit all in residential settings, the methodology might include ways to tailor programs to different household needs, preferences, and energy-use patterns.
- ❖ The Open Distribution System Simulator (OpenDSS) is been used for the modeling. It is a comprehensive electrical system simulation tool for electric utility distribution systems. OpenDSS can drive with Python programs and be used in development.

The model of the test feeder was developed using OpenDSScodes according to the actual data of the transformer, lines, and loads. steady-state analysis was executed for a defined loading level of the feeder.

3.1 Modeling of LV Transformer

The selected transformer name of my study is AZ0526 and it was 160kVA transformer. It consists of two windings in a delta-wye connection. The transformer and feeders were modeled using a OpenDSS library in the Transformer object.

Parameters 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. The 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 the actual winding kV rating. Two-phase transformers are assumed to be employed in a 3-phase system. The default is 12.47 kV.
- kVa= Base kVA rating (OA rating) of this winding.
- Tap = Per unit tap on which this winding is set.
- %R = Percent resistance of this winding on the rated kVA base. (Reactance is between two windings and is specified separately)
- %Loadloss = Percent Losses at rated load. Causes the %r values to be set for
- windings 1 and 2.
- %Noloadloss = Percent No load losses at nominal voltage. The default is 0. This causes
- a resistive branch to be added in parallel with the magnetizing inductance.

Sample code

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

To model the LV feeder, a LineCode object from the OpenDSS general library was utilized. The parametes of the LineCode object are as follows.

- Nphases= Number of phases. Default = 3.
- Rmatrix= Series resistance matrix, ohms per unit length.
- Xmatrix= Series reactance matrix, ohms per unit length.
- Cmatrix= Shunt nodal capacitance matrix, nanofarads per unit length.
- BaseFreq= Base Frequency at which the impedance values are specified.
- Default = 60.0 Hz.
- Units= {mi |km | kft | m| ft | ine | cm} Length units. If not specified, it is assumed that the units correspond to the length being used in the Line models.

Sample code

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

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

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

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

Line segments were defined as the distances between two poles. Each end of the line representing a node. Each line segment was named based on the poles it connected.

- These parameters were specified for each line segment
- Bus1/Bus2 = Start and end of the segment.
- Length = Length of the line segment
- Phases = Number of phases
- Line code = pre-defined line code which should be referred

Sample code for line segment in Feeder A

```
!AZ0526 Feeder A Lines
new line.LB_83/5/3-1 bus1=loadbus bus2=83/5/3-1  length=0.010 phases=4 units=km linecode=LVB244
new line.83/5/3-1_83/5/3 bus1=83/5/3-1 bus2=83/5/3  length=0.025 phases=4 units=km linecode=LVB244
new line.83/5/3_83/5/2 bus1=83/5/3 bus2=83/5/2  length=0.033 phases=4 units=km linecode=LVB244
new line.83/5/2_83/5/1 bus1=83/5/2 bus2=83/5/1  length=0.037 phases=4 units=km linecode=LVB244
new line.83/5/1_83/5-1 bus1=83/5/1 bus2=83/5-1  length=0.034 phases=4 units=km linecode=LVB244
new line.83/5-1_83/5 bus1=83/5-1 bus2=83/5  length=0.028 phases=4 units=km linecode=LVB244
new line.83/5_83/4 bus1=83/5 bus2=83/4  length=0.032 phases=4 units=km linecode=LVB244
new line.83/4_83/3-2 bus1=83/4 bus2=83/3-2  length=0.018 phases=4 units=km linecode=LVB244
new line.83/3-2_83/3-1 bus1=83/3-2 bus2=83/3-1  length=0.006 phases=4 units=km linecode=LVB244
new line.83/3-1_83/3 bus1=83/3-1 bus2=83/3  length=0.005 phases=4 units=km linecode=LVB244
new line.83/3_83/2 bus1=83/3 bus2=83/2  length=0.060 phases=4 units=km linecode=LVB244
new line.83/2_83/1 bus1=83/2 bus2=83/1  length=0.028 phases=4 units=km linecode=LVB244
new line.83/1_83/1A bus1=83/1 bus2=83/1A  length=0.018 phases=4 units=km linecode=LVB243
```

Modeling of Loads

In a low voltage (LV) distribution feeder, the loads are the customers connected at each utility pole. Therefore, each pole can be considered a node, leading to a total of 67 nodes in this model. These loads can either be single-phase or three-phase.

The load at an LV feeder node is the cumulative load of all customers connected to that node. A single pole node might have a mix of single-phase and three-phase customers. However, the overall load at a pole node can be represented as a balanced three-phase load by aggregating all the loads.

To model the loads at each node, actual energy consumption data for the customers were taken from the LECO system database.

The load models were created using the Load object from the OpenDSS library, defined by its nominal kW and power factor (PF) or its kW and kilovolt-ampere reactive (kVAr). Loads are assumed to be balanced three-phase. The properties of the Load object are as follows.

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

Sample code for Feeder A loads

```
!AZ0526 Feeder A Loads
new load.83/5/3-1 bus1=83/5/-1 phases=3 kV=0.4 kW=2.05 kvar=0.63 model=1
new load.83/5/3 bus1=83/5/3 phases=3 kV=0.4 kW=3.07 kvar=0.95 model=1
new load.83/5/3/1 bus1=83/5/3/1 phases=3 kV=0.4 kW=2.05 kvar=0.63 model=1
new load.83/5/3/2 bus1=83/5/3/2 phases=3 kV=0.4 kW=7.50 kvar=2.33 model=1
new load.83/5/2 bus1=83/5/2 phases=3 kV=0.4 kW=5.46 kvar=1.69 model=1
new load.83/5/1 bus1=83/5/1 phases=3 kV=0.4 kW=4.09 kvar=1.27 model=1
new load.83/5-1 bus1=83/5-1 phases=3 kV=0.4 kW=2.39 kvar=0.74 model=1
new load.83/5-1/2 bus1=83/5-1/2 phases=3 kV=0.4 kW=5.80 kvar=1.80 model=1
new load.83/5 bus1=83/5 phases=3 kV=0.4 kW=2.05 kvar=0.63 model=1
new load.83/4 bus1=83/4 phases=3 kV=0.4 kW=6.82 kvar=2.11 model=1
new load.83/3-2 bus1=83/3-2 phases=3 kV=0.4 kW=2.05 kvar=0.63 model=1
new load.83/3-1 bus1=83/3-1 phases=3 kV=0.4 kW=0.68 kvar=0.21 model=1
new load.83/3 bus1=83/3 phases=3 kV=0.4 kW=2.39 kvar=0.74 model=1
new load.83/2 bus1=83/2 phases=3 kV=0.4 kW=6.14 kvar=1.90 model=1
new load.83/1 bus1=83/1 phases=3 kV=0.4 kW=1.71 kvar=0.53 model=1
new load.83/1A bus1=83/1A phases=3 kV=0.4 kW=2.73 kvar=0.85 model=1
```

CHAPTER 4

DEMAND RESPONSE PROGRAM DEVELOPMENT

4.1 Case Study

The overloaded transformer was selected by considering the transformer load profile of transformers in the LECO network. After selecting the transformer, the six-month load profiles were considered and the average of the values and the common load profile was generated for further calculations. The load curtailment program and the benefit calculations were done according to the load profile.

4.1.1 Case Study Results

The case study has been carried out on the above modeled AZ0526 transformer by simulating base cases without demand response applying to the system and with applying the demand response to the system. the case studies are listed below.

Scenario 1: Simulation for the system without response applying to feeder: base case.
Scenario 2: Simulation after applying demand response to the selected feeder.

Scenario 1 is the base case where no demand response program applies to the transformer. In that case night peak of the transformer indicates 164.6 kW. The threshold value of the transformer is 70%.

Scenario 2 is after applying demand response to the selected feeders. The load curtailment program was developed to cut off the loads from customers to keep the transformer load on its threshold value. Therefore 127 kWh energy can be saved in peak time.

4.2 Development of Demand Response Strategy

The overloaded transformer was selected by considering the transformer load profile of transformers in the LECO network.

Table 4-2: Test Feeder Details

Transformer Name	AZ0526
Source	Ethulkotte Primary Substation
Branch	Kotte Branch
Customer Service Center	Pitakotte CSC
Transformer Capacity	160kVA
Location	Lat:6°53'41.369, Lon:9°53'35.308 (School Lane, Kotte)
Total Number of Customers	312
Number of feeders	3
Maximum demand recorded in 2019	162kVA

Feeder distribution of the LV network extracted from Geographical Information in the system is shown in Figure 4-2-1.

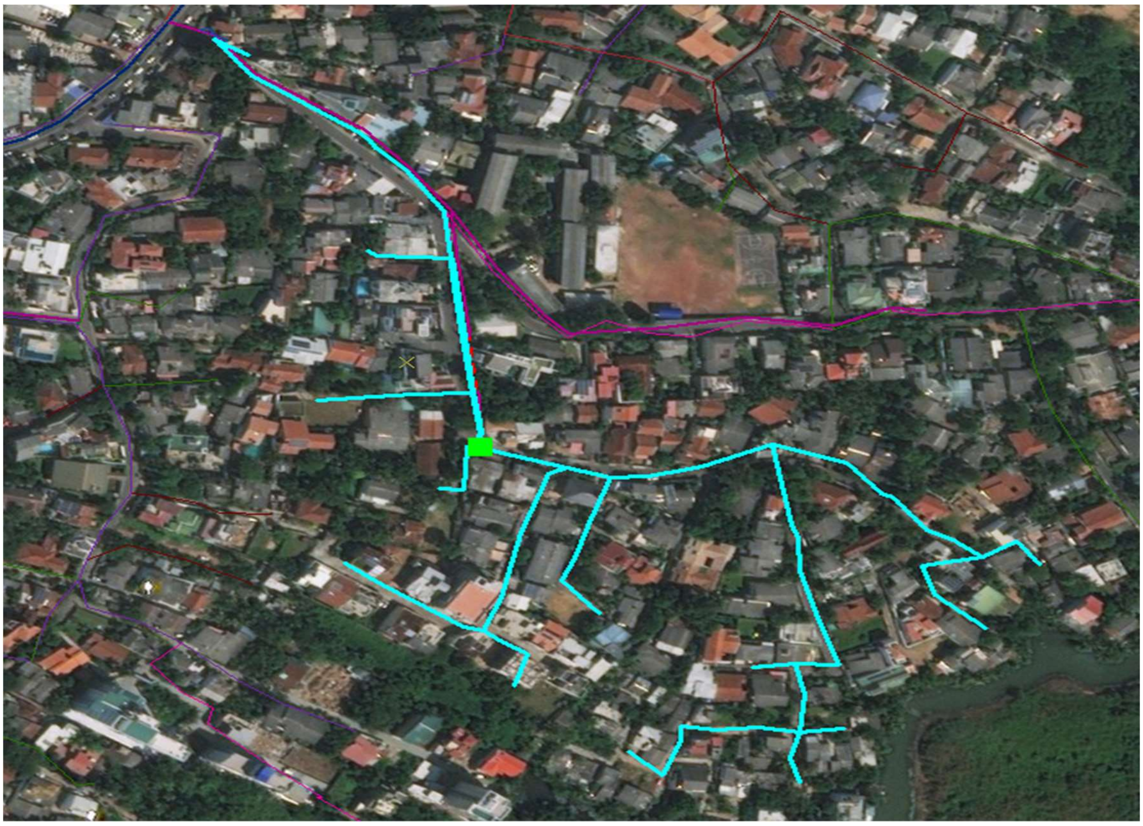


Figure 4-2-1: GIS map of AZ0526

AZ0526 transformer served a total of 312 customers, of which 300 agreed to participate in the Demand Response program, receiving satisfactory benefits. Details of the customer base connected to AZ0526 are provided in Table 4-3.

Table 4-3: Customer details of AZ0526

Customer category	Number of customers
Domestic - SP	175
Domestic - TP	78
Domestic – TP Net Accounting	2
Domestic – SP Net Metering	6
Domestic – TP Net Metering	14
General Purpose 1 - SP	20
General Purpose 1 - TP	4
General Purpose 2 - TP	13
Total	312

After the transformer selection process, six-month load profiles were analyzed, and an average value along with a common load profile was generated for subsequent calculations. The load curtailment program and benefit calculations were conducted following the determined load profile.

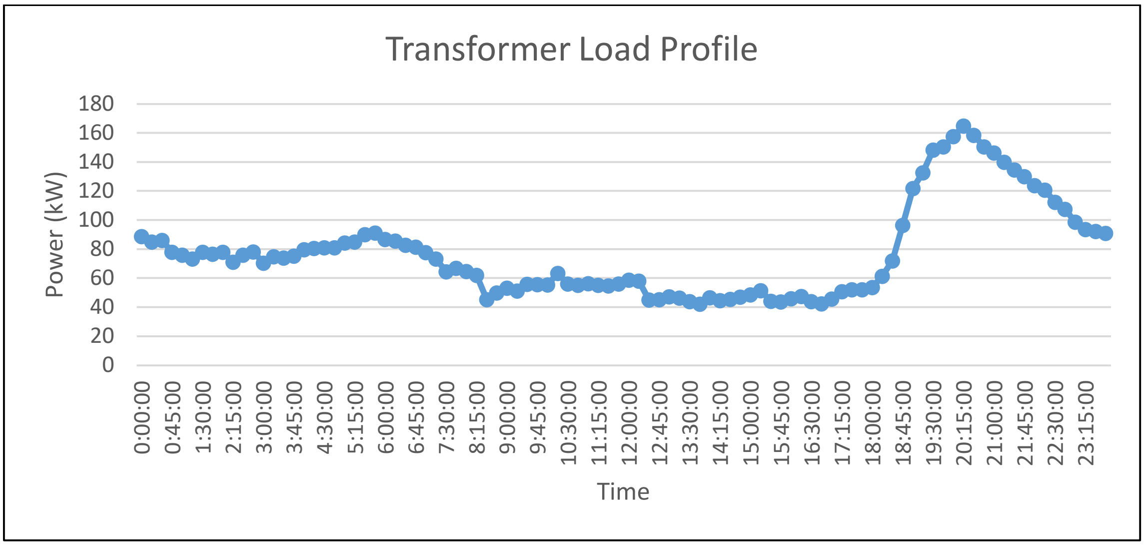


Figure 4-2-2: Transformer Average Load Profile

4.3 Survey Design and Results

4.3.1 Customer Survey Design

A customer survey was conducted as part of the preparatory measures for initiating the demand response program. To facilitate this, a comprehensive questionnaire was formulated with the primary objective of eliciting feedback from potential demand response participants and gauging their perceptions regarding the program. Additionally, the questionnaire sought to ascertain information about their energy consumption habits, utilized appliances, and overall power consumption patterns.

The questionnaire aimed at identifying consumers who are willing to participate in the demand response program, along with their preferences regarding the timing of load-shedding activities. This information serves as crucial groundwork for the effective implementation and customization of the program to align with the preferences and expectations of the participants.

4.3.2 Survey Questionnaire for the Residential Sector

- Consumer appliances and power consumption
- Consumption pattern.
- Essential loads of each consumer.
- Consumer response about DR.
- Consumer agreement for load shedding and the time.
- Consumer expectation to participate in a DR program.

The survey conducted as part of this research aimed to gauge consumer reactions to various aspects of Demand Response improvement. Key factors explored in the survey included incentives, awareness and outreach, technology, ease of participation, and regulatory frameworks governing DR programs.

4.3.3 Consumer Expectation to Participate in a DR Program

This section is designed to understand what consumers expect in return for their participation in a DR program, such as financial incentives, enhanced service reliability, or contributing to environmental sustainability. Understanding consumer expectations can guide the design of incentive structures and communication strategies to boost participation rates and ensure consumer satisfaction.

Analysis of the collected data revealed significant insights into consumer preferences regarding DR participation as over 90% of respondents expressed a strong interest in participating in DR programs. The majority of consumers indicated a preference for hassle-free DR programs offering attractive incentives.

Factors such as awareness and outreach efforts, technological advancements, and regulatory clarity were identified as influential in shaping consumer attitudes toward DR participation.

Table 4-3-3 – Summary of Customer Survey

Item No.	Demand response improving factor	Description	Consumer Agree (%)	Consumer Disagree (%)
1.	Incentives	Payments	98	2
		Rebates	92	8
		Discounts	80	20
2	Awareness and outreach	Make the benefits of demand response clear	89	11
		Explain how demand response works	85	15
		Use a variety of communication channels	71	29
3	Technology	Use smart meters and other devices	88	12
		Develop new technologies	88	12
		Develop open-source software	35	65
4	Ease of Participation	Program Flexibility	92	8
		Equipment maintenance	69	31
		Enhanced Consumer Involvement	99	1
		Monitor and evaluate facilities	88	12
5	Regulations	Create a regulatory framework for demand response	71	29
		Set clear and transparent rules	94	6
		Provide adequate compensation	80	20
		Monitor and evaluate the market	83	17

The findings underscore the importance of designing DR programs that prioritize simplicity and offer appealing incentives to consumers. Effective outreach strategies and educational campaigns are crucial for increasing consumer awareness and participation in DR initiatives. Technological innovation should be leveraged to streamline participation processes and enhance consumer engagement. Regulatory frameworks need to provide clear guidelines and incentives to both consumers and utility providers to foster greater participation in DR programs.

The survey results highlight the strong consumer interest in participating in DR programs that offer attractive incentives and streamlined processes. By addressing consumer preferences and concerns identified in the survey, stakeholders can design more effective DR programs, contributing to energy efficiency and grid reliability goals.

4.4 Implementation of the Program

A load curtailment program aimed at implementing a Demand Response strategy to alleviate strain on a designated overloaded transformer, as well as the associated feeder and consumers. Through a comprehensive assessment of key factors, informed by survey data and literature review findings, I developed the load curtailment program. This process involved the following steps:

- Selection of an Appropriate Simulation Tool:

This step involves choosing a software or tool capable of simulating the behavior of the electrical grid, including the transformer, feeder, and consumer load. The simulation tool helps in predicting how changes in energy consumption and curtailment strategies will impact the system.

- Modeling of Energy Consumption Patterns:

the energy consumption patterns of the consumers connected to the overloaded transformer and feeder are modeled. This includes analyzing historical energy usage data to understand peak demand periods, typical usage patterns, and variations over time.

- Implementation of Various Curtailment Strategies:

different strategies for reducing energy consumption during peak periods or when the transformer is overloaded are developed and implemented. These strategies could include voluntary load reduction programs, time-of-use pricing incentives, or automated load-shedding measures.

- Definition of Participant Responses to Curtailment Initiatives:

This step involves defining how participants, such as consumers or businesses, will respond to the curtailment strategies implemented. It includes communicating the objectives of the program, explaining how participants can reduce their energy usage, and outlining any incentives or rewards for participation.

- Monitoring and Analysis of the Outcomes Obtained:

Finally, the effectiveness of the curtailment program is monitored and analyzed. This includes tracking energy consumption before, during, and after implementing curtailment measures, assessing participant engagement and satisfaction, and evaluating the program's impact on reducing strain on the transformer and feeder. Analysis of outcomes helps refine and improve the curtailment strategies for future implementation.

It is to be noted that this program was formulated after the completion of a thorough customer survey, underscoring its responsiveness to consumer needs and preferences. This delineated approach serves as a framework for the development and implementation of effective load curtailment strategies.

4.5 Flow chart of Algorithm

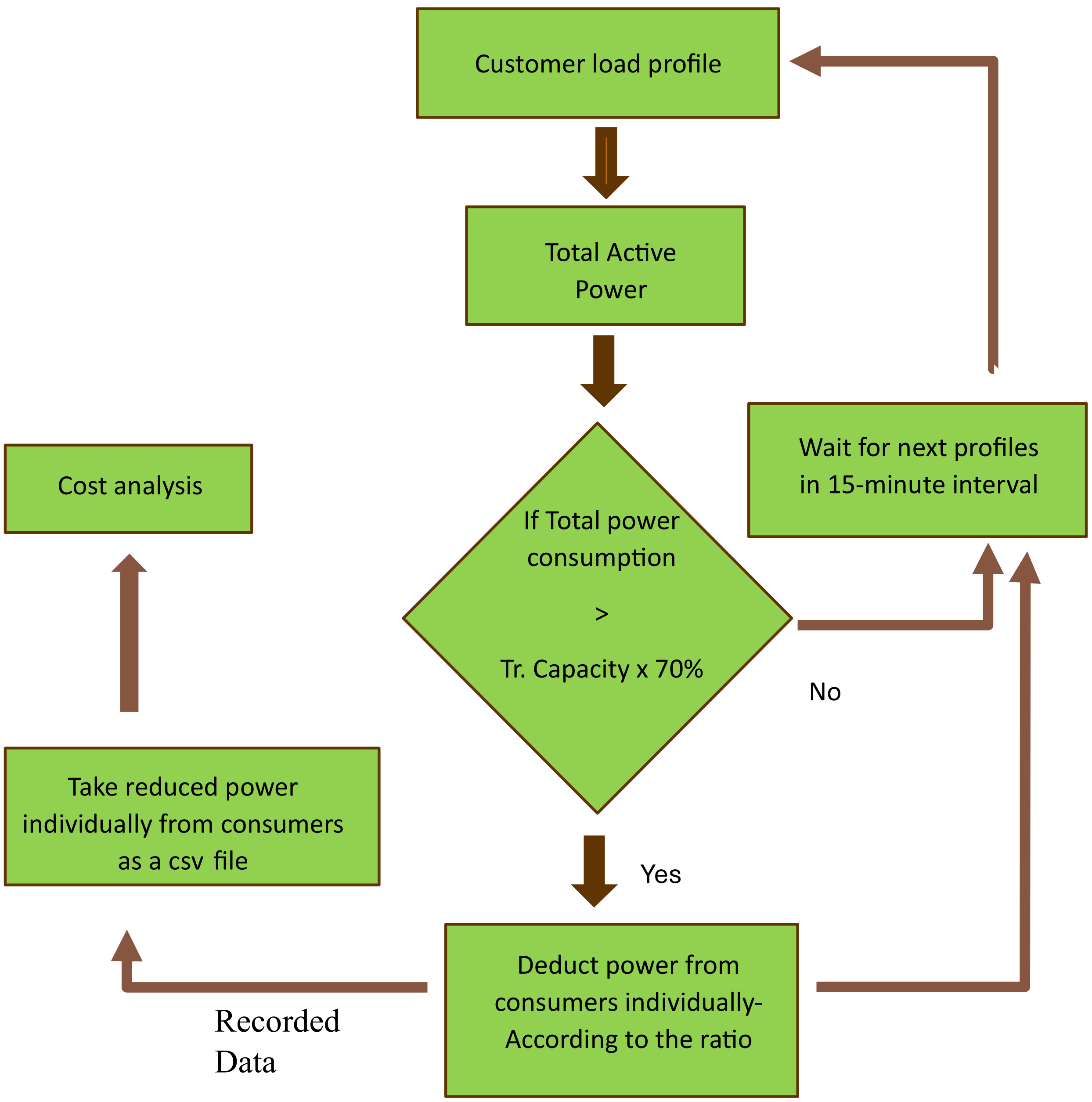


Figure 4-5- Flow chart of Algorithm

The above load curtailment program flow chart, the process begins by capturing the consumer load profile at a specified time interval. Subsequently, the individual total active power of each consumer is calculated. This total active power is then compared against the predefined threshold value for the transformer.

If the calculated total active power surpasses the transformer threshold, indicating an overload condition, a load deduction procedure is initiated. This entails proportionally reducing the load of individual consumers according to predetermined agreements regarding curtailment periods. If the total active power falls below the threshold, the process awaits the next consumer load profile for reassessment.

Following the deduction of power, a Comma-Separated Values (CSV) file is generated to document the reduced load. This CSV file serves as input for the subsequent cost analysis phase. During cost analysis, various factors such as energy savings, demand response effectiveness, and overall program performance are evaluated. This analysis is essential for determining the incentives to be provided to consumers as compensation for their participation in the load curtailment program. By incorporating this feedback loop, the program ensures not only effective load management but also fair and equitable consumer engagement.

CHAPTER 5

EVALUATION OF THE DEVELOPED DR PROGRAM

5.1 Introduction

In this chapter, the development and evaluation of the load curtailment program using Python and OpenDSS are discussed. This program aims to simulate and analyze load curtailment strategies within the context of power distribution systems. The chapter outlines the process of program development, including the methodologies employed, and presents the results obtained from the simulations conducted.

5.2 Program Development

The load curtailment program was developed using Python programming language, leveraging the capabilities of the OpenDSS library for power system simulation. The program follows a structured approach outlined as follows:

5.3 Data Collection and Preprocessing

The initial phase of the research involved the meticulous collection and preprocessing of load profiles and system parameters essential for our simulation endeavors. This process entailed acquiring historical load data and configuring requisite system parameters for the OpenDSS simulation platform.

Integration of transformer average load data and consumer data was imperative to establish a unified dataset, facilitating coherent data analysis and interpretation. To ensure consistency and comparability across disparate datasets, normalization techniques were employed, addressing variations in scale and units inherent in the collected data.

A main consideration during dataset integration was the alignment of temporal information, particularly if sourced independently. Techniques such as interpolation or aggregation were deployed to harmonize time intervals, ensuring seamless integration and analysis.

Subsequently, an exploratory data analysis phase was undertaken to glean insights into data distribution, patterns, and interrelationships.

In addition to elucidating existing patterns, novel features were derived from the dataset to augment the analytical scope. Statistical analysis played a pivotal role in discerning underlying trends and patterns, complemented by the use of visual aids such as plots and charts to effectively communicate findings and insights derived from the data.

Time	18.30-18.45	18.45-19.00	19.00-19.15	19.15-19.30	19.30-19.45	19.45-20.00	20.00-20.15	20.15-20.30	20.30-20.45
Power consumption	57.52	96.49	121.87	132.61	148.31	150.47	157.48	164.95	158.46

Time	20.45-21.00	21.00-21.15	21.15-21.30	21.30-21.45	21.45-22.00	22.00-22.15-	22.15-22.30	22.30-22.45
Power consumption	150.48	146.25	139.86	134.57	129.91	123.90	120.65	112.46

The findings of this research highlight the significant impact of implementing Demand Response programs on reducing night peak energy consumption. Through the strategic deployment of DR initiatives, substantial energy savings were achieved during periods of heightened demand, particularly during nighttime peak hours. This reduction in night peak loads not only contributes to overall energy conservation efforts but also plays a crucial role in enhancing the stability and efficiency of the electrical grid, if implemented in a wider scale. Furthermore, the alleviation of nighttime peak demand has been shown to extend the operational lifespan of transformers and other critical infrastructure components, thereby improving the reliability and resilience of the power system. These results underscore the effectiveness of Demand Response strategies in optimizing energy usage patterns and promoting sustainable energy management practices.

Capacity of the transformer = 160 kVA

Maximum demand of the transformer= 152 kW

Transformer threshold value = 70% of transformer capacity

= 152 X 70/100

= 106.4 kW

Power factor for a domestic distribution transformer = 0.95

5.4 Customer Categorization

To execute the load curtailment program effectively, it was imperative to ascertain the willingness of consumers to participate in load-shedding activities during various time intervals. To accomplish this, a customer survey was conducted to identify those willing to curtail their electricity usage and specify the preferred time durations for such actions. Results indicate that out of the 300 surveyed consumers, 220 expressed willingness to participate in load shedding during nighttime peaks. The primary motivation cited by these participants for their agreement to participate was the incentivization offered by the program.

Table 5-4 : Customer Categorization

Time duration	Energy to be reduced (kWh)	Number of customers
22.30-05.30- Off peak	-	45
05.30-18.30- Day peak	-	35
18.30-22.30- Night peak	127	220

5.5 Program for the load curtailment

To achieve the research objectives, developed a model of the transformer, feeders, and consumer loads by using OpenDss. This model is controlled via a Python program which is used for load shedding when the total customer load is greater than the transformer load profile.

```
import csv
import os
import pathlib
import py_dss_interface

# Function to read data from CSV file
def read_csv(file_path):
    data = []
    with open(file_path, 'r') as csv_file:
        csv_reader = csv.DictReader(csv_file)
        for row in csv_reader:
            data.append(row)
    return data

def update_load_values(opendss_path, data, power_limit=106):
```

```
total_original_power = 0  # Variable to store the total original power
total_deducted_power = 0  # Variable to store the total deducted power

with open(opendss_path, 'r') as opendss_file:
    opendss_lines = opendss_file.readlines()

reduced_power_data = []  # List to store reduced power data

for entry in data:
    load_name = entry.get('LoadName', '')
    active_power = entry.get('ActivePower', '')

    try:
        float_active_power = float(active_power)
    except ValueError:
        print(f"Warning: Invalid active power for load '{load_name}'. Skipping this entry.")
        continue

    bus_name = entry['BusName']
    voltage_magnitude = entry['VoltageMagnitude']
    power_factor = entry['PowerFactor']

    total_original_power += float_active_power  # Accumulate valid original power

# Calculate the reduction ratio
reduction_ratio = min(1.0, power_limit / total_original_power)

for entry in data:
    load_name = entry.get('LoadName', '')
    active_power = entry.get('ActivePower', '')

    try:
        float_active_power = float(active_power)
    except ValueError:
        print(f"Warning: Invalid active power for load '{load_name}'. Skipping this entry.")
        continue

    bus_name = entry['BusName']
    voltage_magnitude = entry['VoltageMagnitude']
    power_factor = entry['PowerFactor']

    # Calculate the deducted power
    deducted_power = max(0, float_active_power - float_active_power * reduction_ratio)
    total_deducted_power += deducted_power  # Accumulate deducted power

    # Append data to the list
    reduced_power_data.append({
        'LoadName': load_name,
        'OriginalPower': str(float_active_power),
        'DeductedPower': str(deducted_power),
        'BusName': bus_name,
```

```
            'VoltageMagnitude': voltage_magnitude,
            'PowerFactor': power_factor
        })

        # Find and update the load line
        for i, line in enumerate(opendss_lines):
            if line.startswith(f'new load.{load_name} '):
                opendss_lines[i] = f'new load.{load_name} bus1={bus_name} phases=3
kv={voltage_magnitude} kw={deducted_power} pf={power_factor}\n'
                break

    reduced_power_csv_path = 'reduced_power.csv'
    with open(reduced_power_csv_path, 'w', newline='') as reduced_power_file:
        fieldnames = reduced_power_data[0].keys()
        writer = csv.DictWriter(reduced_power_file, fieldnames=fieldnames)
        writer.writeheader()
        writer.writerows(reduced_power_data)

    print(f"Total original power before reduction: {total_original_power} kW")
    print(f"Total deducted power after reduction: {total_deducted_power} kW")
    print(f"Reduced power CSV file created: {reduced_power_csv_path}")

    with open(opendss_path, 'w') as opendss_file:
        opendss_file.writelines(opendss_lines)

# Function to run OpenDSS script
def run_opendss_script(script_path):
    dss = py_dss_interface.DSSDLL()
    dss.text(f"compile [{script_path}]")
    dss.text("solve")

    Total_power = -dss.circuit_total_power()[0]
    Total_power = round(Total_power, 3)
    #print(f"Total active power after OpenDSS simulation: {Total_power} kW")
    # Update your Excel sheet with Total_power if needed

# Example usage
csv_file_path = r'C:\Users\Acer\PycharmProjects\py-dss-interface\your_data.csv'
opendss_script_path = r'C:\Users\Acer\PycharmProjects\py-dss-
interface\OpenDSS_Script_1.dss'

data_from_csv = read_csv(csv_file_path)
update_load_values(opendss_script_path, data_from_csv)

# Run OpenDSS script
run_opendss_script(opendss_script_path)
```

The Python program integrates with the OpenDSS library to create and simulate distribution system models. OpenDSS provides functionalities for defining system components, specifying load profiles, and performing power flow analysis. Load curtailment strategies were implemented within the program. These strategies include Demand Response, load shedding, and other control mechanisms aimed at reducing load during peak periods or emergencies. Different scenarios were generated to assess the effectiveness of the load curtailment strategies under various operating conditions. These scenarios vary in parameters such as load levels, generation capacities, and system contingencies. The program executes simulations for each scenario, running OpenDSS models and applying the specified load curtailment strategies. During simulation, the program monitors system performance metrics such as voltage levels, power losses, and curtailed load.

5.6 Results Evaluation

The developed program was evaluated using a test distribution system representative of a real-world scenario. The simulations were conducted under different load conditions, and the effectiveness of the load curtailment strategies was assessed based on various performance metrics.

The simulation results indicate that the implemented load curtailment strategies effectively reduce peak load demand during critical periods. This leads to improved system reliability and stability.

The developed load curtailment program demonstrates the feasibility and effectiveness of employing Demand Side Management (DSM) strategies to enhance the operation of distribution systems. The integration of Python programming with OpenDSS provides a flexible and powerful platform for conducting simulations and analyzing system performance. Future work may involve further refinement of the program, additional scenario analysis, and real-world validation through field trials or case studies.

Table 5-6: Summary of Results

Time	Loading Power Scenario 1 (Without DR)		Loading Power Scenario 2 (With DR)		Load Deduction (kW)	
	kW	Percentage	kW	Percentage	kW	Percentage
18.30-18.45 PM	57.52	37.84%	57.52	37.84%	No reduction is needed.	
18.45-19.00 PM	96.49	63.48%	96.49	63.48%	No reduction is needed.	
19.00-19.15 PM	121.87	80.18%	106.4	70. 00 %	15.47	10.18%
19.15-19.30 PM	132.6	87.24%	106.4	70. 00 %	26.2	17.24%
19:30-19.45 PM	148.31	97.57%	106.4	70. 00 %	41.91	27.57%
19.45-20.00 PM	150.47	98.99%	106.4	70. 00 %	44.07	28.99%
20:00-20.15 PM	157.48	103.61%	106.4	70. 00 %	51.08	33.61%
20.15-20.30 PM	164.95	108.52%	106.4	70. 00 %	58.55	38.52%
20:30-20.45 PM	158.46	104.25%	106.4	70. 00 %	52.06	34.25%
20.45-21.00PM	150.47	98.99%	106.4	70. 00 %	44.07	28.99%
21:00-21.15 PM	146.25	96.22%	106.4	70. 00 %	39.85	26.22%
21:15-21.30 PM	139.86	92.01%	106.4	70. 00 %	33.46	22.01%
21:30-21.45 PM	134.57	88.53%	106.4	70. 00 %	28.17	18.53%
21.45-22.00 PM	129.91	85.47%	106.4	70. 00 %	23.51	15.47%
22:00-22.15 PM	123.9	81.51%	106.4	70. 00 %	17.5	11.51%
22:15-22.30 PM	120.65	79.38%	106.4	70. 00 %	14.25	9.38%
22.30-22.45 PM	112.46	73.99%	106.4	70. 00 %	6.06	3.99%

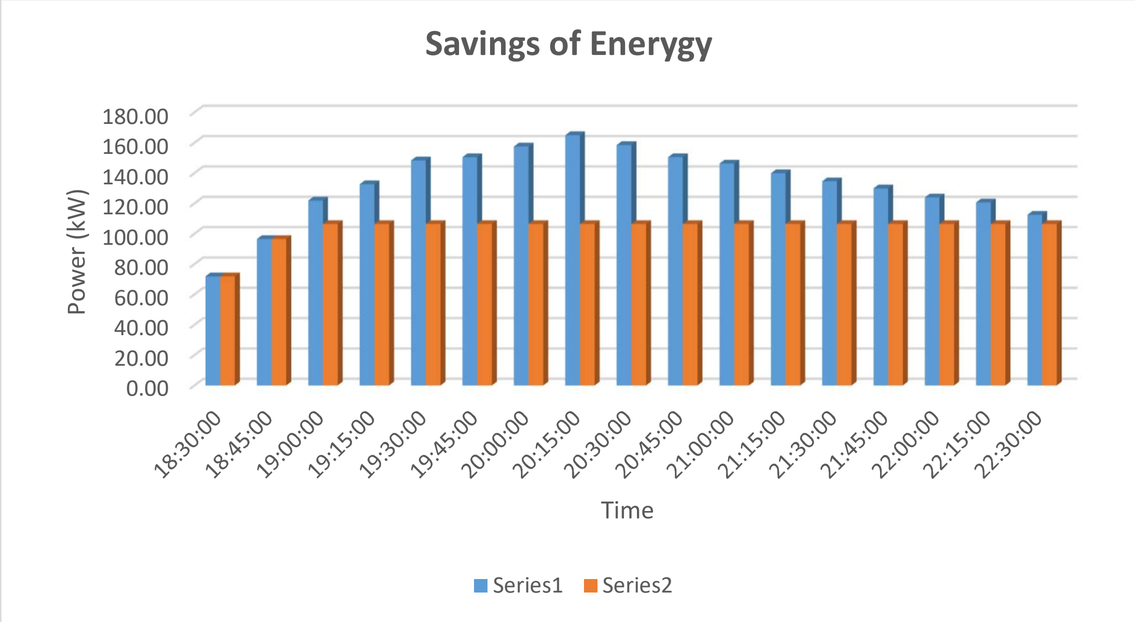


Figure -5-6: Comparison of the Two Scenarios

When a transformer becomes overloaded, it means that the electrical load connected to it is drawing more current than the transformer is designed to handle. This can lead to overheating, insulation breakdown, and ultimately, transformer failure.

To address the issue of overloading, there are a few potential solutions, one of which is replacing the existing transformer with a higher capacity transformer.

Implementing a Demand Response program may be a preferable option to simply replacing an overloaded transformer, as it offers a more dynamic and adaptable solution to managing electricity demand. Demand response programs allow businesses and utilities to actively manage energy consumption during peak periods by incentivizing participants to reduce their electricity usage temporarily. This approach not only helps alleviate strain on the electrical grid during times of high demand but also provides financial benefits through incentive payments from utilities or grid operators. Additionally, Demand Response programs promote energy efficiency and sustainability by encouraging businesses to adopt more efficient practices and technologies. While transformer replacement addresses the immediate issue of overloading, demand response programs offer a broader range of benefits, including cost savings, grid reliability, and environmental sustainability, making them a more comprehensive and cost-effective solution in many cases.

CHAPTER 6

Financial Analysis

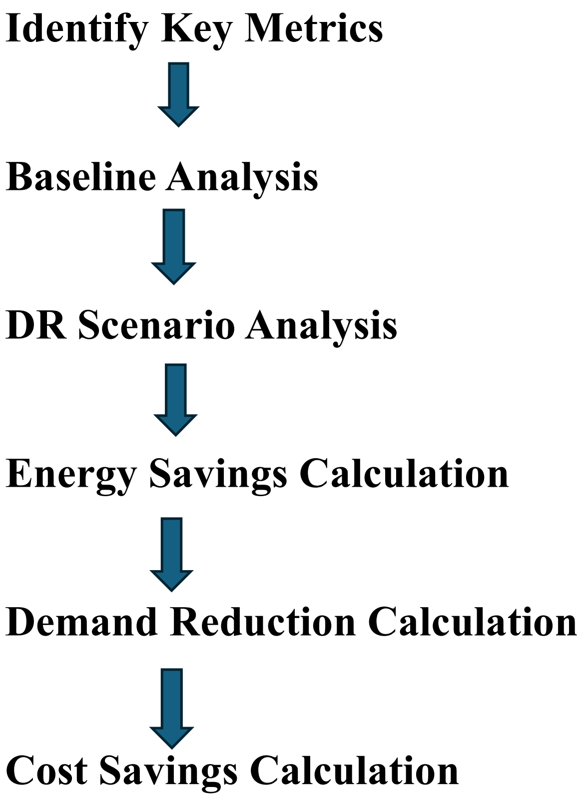
6.1 Cost Analysis of Demand Response Program Implementation

6.1.1 Introduction

Demand Response programs have gained significant attention as a means to manage energy consumption effectively, especially during peak periods. In this chapter, we undertake a comprehensive cost analysis of implementing a demand response program targeted at residential customers. The focus lies on assessing the economic viability of load curtailment strategies compared to the costs associated with upgrading transformers to meet increased demand.

6.1.2 Cost Components

The cost analysis involves the examination of various components associated with implementing a Demand Response program. The following analysis is based on the Bulk Supply Tariff of 2023 and explores the potential benefits of integrating Demand Response mechanisms within feeder systems. Our focus lies on assessing the cost-effectiveness of this approach through detailed calculations and projections.



6.2 Project Implementation Costs

Cost Estimate

This includes the expenses related to designing and deploying the Demand Response infrastructure, such as smart meters, communication systems, and control devices.

Cost of energy meter	= 25,000.00 LKR

(Meters are already existing in the consumer locations)

Cost breakdown

Interface	= 2,000.00 LKR
Network and communication	= 3,000.00 LKR
Total cost for infrastructure	= 5,000 LKR x 300 Houses
	= 1,500,000.00 LKR

The project implementation cost for 300 consumers to apply DR is 1.5 million. This total is calculated excluding the cost of the already existing smart meter in the consumer's premises.

Energy Savings: Calculating the energy savings achieved through load curtailment during peak periods is crucial. This involves determining the reduction in energy consumption resulting from customer participation in the program. The following analysis is based on the Bulk Supply Tariff of 2023 and explores the potential benefits of integrating Demand Response mechanisms within feeder systems. Our focus lies on assessing the cost-effectiveness of this approach through detailed calculations and projections.

Upon examination, it has been determined that the selected transformer exhibits a notable night peak saving of 127 kWh per day. Extrapolating this efficiency over a monthly period yields a significant total saving of LKR 397,235.24 This calculation is predicated on the energy conserved through the implementation of Demand Response strategies.

Maximum Demand Savings: Assessing the reduction in peak demand achieved through load curtailment activities is essential. This helps quantify the capacity relief provided to the grid during critical periods.

6.3 Conventional method of transformer replacement in LECO,

Existing transformer 160 kVA → New transformer 250 kVA

Cost for the transformer upgrading (replacing)	= 2,080,630.00 LKR
Total project implementation cost	= 1,500,000.00 LKR

This analysis has been conducted to compare the expenses associated with the project implementation and upgrading of the current 160 kVA transformer to a 250 kVA capacity. The findings indicate that the implementation of the project entails a more cost-effective approach compared to the alternative of replacing the transformer.

Total project implementation cost < Cost of transformer upgrading.

6.4 Cash Flow Analysis

The cashflow analysis was done for the calculation of loss or profit of the implementation project.

An analysis has been conducted by assuming a loan value of 1,500,000.00 LKR, with a repayment period of 5 years at an interest rate of 15%. The project's internal rate of return (IRR) stands at 25%. Additionally, an incentive of 97.50 LKR/kWh/day has been factored into the evaluation. This analysis aims to provide a comprehensive cash flow assessment to determine the viability and financial implications of the project under consideration.

Loan shedulle

Project cost	1,500,000.00	LKR
Debt :Equity	0	:0
Loan	1500000	LKR
Equity	0	LKR
Loan period	6	years
Interest ratio	12%	

Year	0	1	2	3	4	5	6
Opening balance		1,500,000.00	1,250,000.00	1,000,000.00	750,000.00	500,000.00	250,000.00
Interest		165,000.00	135,000.00	105,000.00	75,000.00	45,000.00	15,000.00
Loan repayment		250,000.00	250,000.00	250,000.00	250,000.00	250,000.00	250,000.00
Closing balance		1,250,000.00	1,000,000.00	750,000.00	500,000.00	250,000.00	-

Profit and Loss Statement

Year					0	1	2	3	4	5	6	7	8	9	10
Energy supplied (kWh)						45,720.00	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00
Maximum damad (Kw)						58.00	58.00	58.00	58.00	58.00	58.00	58.00	58.00	58.00	58.00
Tariff (Rs)															
Tier 1	42.20	LKR /kWh													
Tier 2	48921.36	LKR /kW													
Revenue (Energy Saving * Cost per kWh)						1,929,384.00	##########	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00
Revenue (Max.demand Saving * Cost per kW)						2,837,438.88	##########	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88
Total revenue						4,766,822.88	##########	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88
O&M cost	0.50	LKR/kWh	1%	Annual increment		(22,860.00)	(23,088.60)	(23,319.49)	(23,552.68)	(23,788.21)	(24,026.09)	(24,266.35)	(24,509.01)	(24,754.10)	(25,001.65)
Depreciation						(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)
Finance cost						(165,000.00)	(135,000.00)	(105,000.00)	(75,000.00)	(45,000.00)	(15,000.00)	-	-	-	-
Incentive	97.5	LKR/kWh				##########	##########	(4,519,612.50)	(4,519,612.50)	##########	(4,519,612.50)	(4,519,612.50)	##########	##########	(4,519,612.50)
Profit before tax						29,350.38	59,121.78	88,890.89	118,657.70	148,422.17	178,184.29	192,944.03	192,701.37	192,456.28	192,208.73
Tax (0% and 30%)	0%					-	-	-	-	-	-	-	-	-	-
Profit After Tax						29,350.38	59,121.78	88,890.89	118,657.70	148,422.17	178,184.29	192,944.03	192,701.37	192,456.28	192,208.73
Cash flow															
Profit After Tax						29,350.38	59,121.78	88,890.89	118,657.70	148,422.17	178,184.29	192,944.03	192,701.37	192,456.28	192,208.73
Add															
Dipriciation						200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00
Finance Cost						165,000.00	135,000.00	105,000.00	75,000.00	45,000.00	15,000.00	-	-	-	-
Net flow of project					(1,500,000.00)	394,350.38	394,121.78	393,890.89	393,657.70	393,422.17	393,184.29	392,944.03	392,701.37	392,456.28	392,208.73
Cumulative Net flow						394,350.38	788,472.16	1,182,363.05	1,576,020.75	1,969,442.93	2,362,627.22	2,755,571.25	3,148,272.61	3,540,728.89	3,932,937.62
Project IRR					26%										
Less															
Finance cost						165,000.00	135,000.00	105,000.00	75,000.00	45,000.00	15,000.00	-	-	-	-
Capital repayments						250,000.00	250,000.00	250,000.00	250,000.00	250,000.00	250,000.00	-	-	-	-
Total Debt Service						415,000.00	385,000.00	355,000.00	325,000.00	295,000.00	265,000.00	-	-	-	-
Cash inflow					-	(20,649.62)	9,121.78	38,890.89	68,657.70	98,422.17	128,184.29	392,944.03	392,701.37	392,456.28	392,208.73
Equity IRR					1.51										

Year	11	12	13	14	15	16	17	18	19	20
Energy supplied (kWh)	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00	45,720.00
Maximum damad (Kw)	58.00	58.00	58.00	58.00	58.00	58.00	58.00	58.00	58.00	58.00
Tariff (Rs)										
Tier 1										
Tier 2										
Revenue (Energy Saving * Cost per kWh)	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00	1,929,384.00
Revenue (Max.demand Saving * Cost per kW)	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88	2,837,438.88
Total revenue	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88	4,766,822.88
O&M cost	(25,251.66)	(25,504.18)	(25,759.22)	(26,016.81)	(26,276.98)	(26,539.75)	(26,805.15)	(27,073.20)	(27,343.93)	(27,617.37)
Depreciation	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)	(30,000.00)
Finance cost	-	-	-	-	-	-	-	-	-	-
Incentive	(4,519,612.50)	##########	(4,519,612.50)	(4,519,612.50)	##########	(4,519,612.50)	##########	##########	##########	(4,519,612.50)
Profit before tax	191,958.72	191,706.20	191,451.16	191,193.57	190,933.40	190,670.63	190,405.23	190,137.18	189,866.45	189,593.01
Tax (0% and 30%)	-	-	-	-	-	-	-	-	-	-
Profit After Tax	191,958.72	191,706.20	191,451.16	191,193.57	190,933.40	190,670.63	190,405.23	190,137.18	189,866.45	189,593.01
Cash flow										
Profit After Tax	191,958.72	191,706.20	191,451.16	191,193.57	190,933.40	190,670.63	190,405.23	190,137.18	189,866.45	189,593.01
Add										
Dipriciation	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00
Finance Cost	-	-	-	-	-	-	-	-	-	-
Net flow of project	391,958.72	391,706.20	391,451.16	391,193.57	390,933.40	390,670.63	390,405.23	390,137.18	389,866.45	389,593.01
Cumulative Net flow	4,324,896.34	4,716,602.54	5,108,053.70	5,499,247.27	5,890,180.67	6,280,851.30	6,671,256.53	7,061,393.71	7,451,260.16	7,840,853.17
Project IRR										
Less										
Finance cost	-	-	-	-	-	-	-	-	-	-
Capital repayments	-	-	-	-	-	-	-	-	-	-
Total Debt Service	-	-	-	-	-	-	-	-	-	-
Cash inflow	391,958.72	391,706.20	391,451.16	391,193.57	390,933.40	390,670.63	390,405.23	390,137.18	389,866.45	389,593.01
Equity IRR										

Asumptions :

The cash flow analysis conducted for the determination of incentive payments to residential customers engaged in the load curtailment program reveals a comprehensive assessment of financial viability. Through meticulous examination, energy savings during night peak periods and maximum demand savings are identified as substantial benefits accruing to the utility. These savings represent pivotal metrics in the evaluation of program effectiveness and financial gains. Conversely, operational and maintenance costs, depreciation expenses, and incentive disbursements constitute the expenditures borne by the utility.

The calculated Internal Rate of Return (IRR) of 26% underscores the program's robust financial performance, indicative of its potential for sustained profitability and utility satisfaction. This analysis not only elucidates the financial dynamics underlying the incentive framework but also provides crucial insights for strategic decision-making within the utility sector.

6.5 Benefits calculation

The total incentive of 97.50 per kWh was divided to three time slots, day, off peak and night peak. BST Rate ratio is used to calculate the incentive for three time slots.

Table- 6-5-1: Energy Saving calculation

Saving of kWh- Consider the load profile in the day			
Description	**Area of graph (kWh)**	**BST Rate (LKR/kWh)**	**Savings (LKR)**
Off peak		19.17	
Day peak		32.21	0
Night peak	127	42.2	5359.4
Total cost saving from energy per day			**5359.4**

Incentive for one day = 97.50 LKR / kWh

Total energy saving per day = 127 kWh

Cost saving for one month (from energy saving) = 127 x 30 x 42.2

= 160782.00 LKR/Month

Cost saving from Maximum demand = 4076.78 X (164 -106) LKR/Month

= 236453.24 LKR/Month

Total cost savings/Month = 397235.24 LKR /Month

The incentive scheme was prepared according to the BST rates:

Table 6-5-2 : Proposed Incentive scheme

Time	Offered incentive (LKR/kWh)
Day time (05:30-18:30)	33.56
Nighttime (18:30-22:30)	43.97
Off peak time (22:30-05:30)	19.97

Benefits to Utility Calculation;

Net profit per month = Total cost savings - (Customer Incentive + Depreciation + O&M Cost + Loan installment)

= 2445.36 LKR

Benefits to Customer Calculation;

Income per month = (Units to be reduced/number of consumers) x Offered incentive at relevant time slot X 30 days

= 761.48 LKR /Month

CHAPTER 7

THE GENERALIZED METHODOLOGY

In an era marked by increasing energy consumption and the imperative of sustainability, utilities face the challenge of balancing supply and demand while optimizing system efficiency. Demand Response programs have emerged as a pivotal strategy, enabling utilities to manage peak demand periods effectively while fostering consumer engagement and resource conservation. In this context, the development of a systematic methodology for the implementation of Demand Response initiatives is imperative. This chapter introduces a generalized methodology designed to guide utilities through the essential steps involved in applying Demand Response programs to residential customers. The methodology delineates a structured approach encompassing key phases, from initial assessment to program execution and incentive provision.

The importance of a standardized methodology for Demand Response program implementation cannot be overstated. As utilities endeavor to navigate the complexities of modern energy landscapes, a systematic framework serves as a roadmap, ensuring consistency, efficiency, and efficacy throughout the process. By providing a structured approach, the methodology facilitates streamlined decision-making, enhances stakeholder communication, and promotes transparency in program administration. Moreover, a standardized methodology enables utilities to leverage best practices, learn from past experiences, and adapt strategies to specific contexts, thereby maximizing the impact of demand response initiatives. In essence, the development and adoption of a generalized methodology represent a fundamental step toward achieving the overarching objectives of reliability, affordability, and sustainability in the utility sector.

The generalized methodology outlined in this research comprises a series of sequential steps tailored to guide utilities in the successful implementation of DR programs for residential customers. Each step is meticulously designed to address distinct aspects of program deployment, from initial planning to post-implementation evaluation.The methodology emphasizes proactive engagement with customers, meticulous assessment of infrastructure, and strategic allocation of resources to optimize program outcomes. By delineating clear responsibilities, timelines, and performance metrics, the methodology empowers utilities to navigate the complexities of demand response program implementation with confidence and precision. Moreover, the iterative nature of the methodology facilitates continuous improvement and adaptation to evolving market dynamics and regulatory frameworks.The generalized methodology for applying DR to residential customers can be summarized with the following step by step guide.

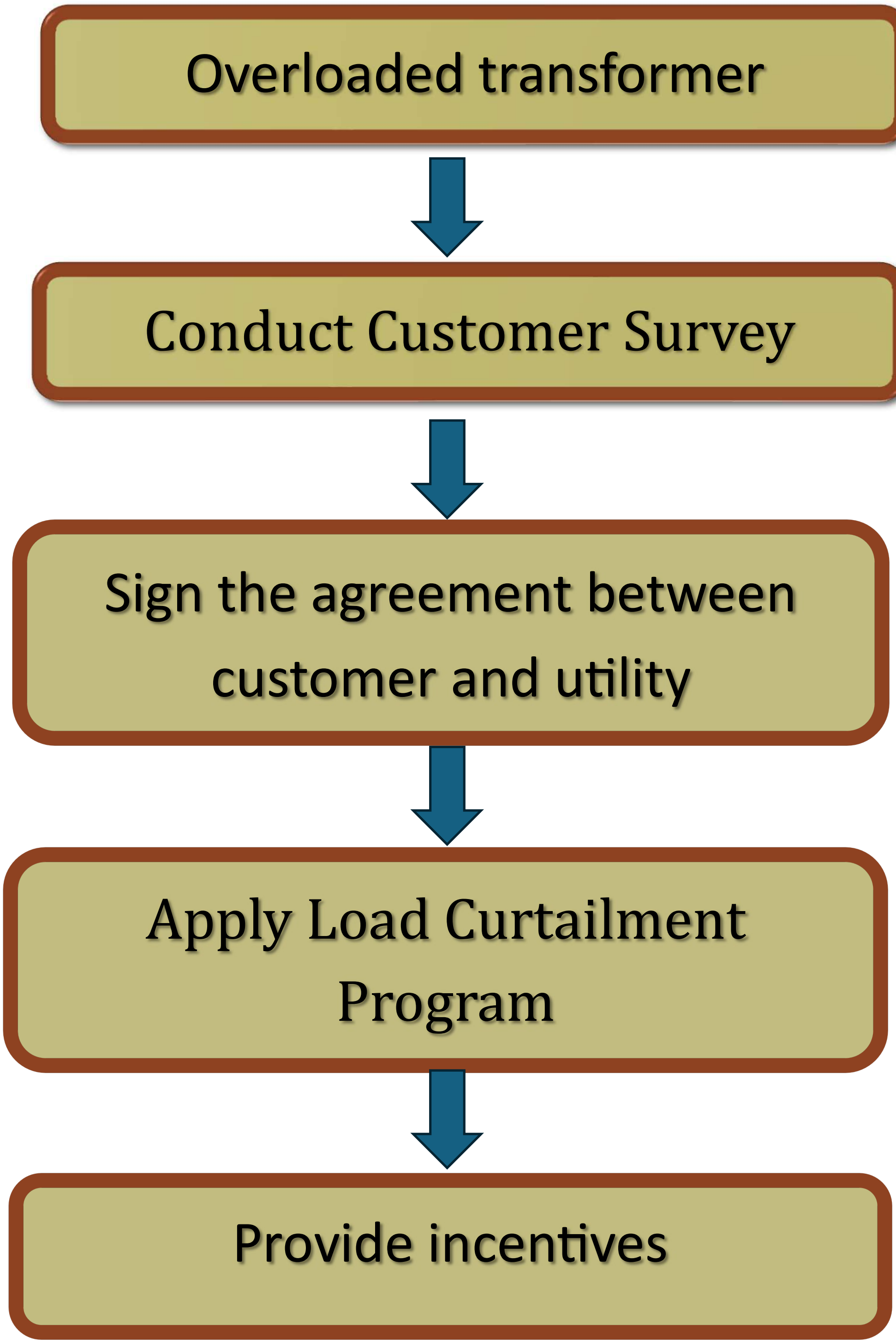


Figure 7-1 : Flow chart of generalized methodology

CHAPTER 8

CONCLUSION

Transformers represent the cornerstone of a distribution system, constituting vital assets crucial for both economic viability and operational reliability. The efficient utilization of transformers is paramount to ensuring optimal system performance and longevity. However, the occurrence of overloading conditions, driven by peak load growth or contingencies, poses a formidable threat to transformer integrity. Such overloading can accelerate insulation aging, thereby compromising the transformer's lifespan. To safeguard the longevity of transformers, meticulous maintenance of insulation levels is imperative. Nevertheless, addressing overloading challenges becomes increasingly complex amidst a backdrop of escalating demand, particularly evident in Sri Lanka's electricity load profile characterized by a pronounced nighttime peak.

This research underscores the significance of Demand Response as a strategic tool for mitigating transformer overloading and managing nighttime peak demand in the residential sector. By incentivizing residential consumers to participate in DR initiatives, substantial reductions in nighttime peak load have been achieved, thereby alleviating the strain on transformers and extending their lifespan. Furthermore, the successful implementation of a generalized DR program not only enhances system reliability but also fosters sustainability by reducing the need for emergency power procurement. Thus, this research elucidates the critical importance of addressing peak demand challenges through proactive measures, underscoring the pivotal role of DR in bolstering transformer efficiency and overall system resilience.

The implementation of Demand Response emerges as a highly effective strategy for managing nighttime peak demand and extending transformer lifespan within the residential sector. This research has been dedicated to fostering nighttime peak reduction and alleviating transformer overloading by incentivizing residential consumers to participate in DR initiatives. Through the development of a tailored load curtailment program, significant reductions in required load have been achieved.

Notably, customer response proved pivotal, with an overwhelming majority of 300 out of 312 residential consumers actively engaging in DR, driven by a carefully structured incentive scheme. The program yielded a substantial reduction of 127 kWh during night peak hours, indicative of its efficacy in promoting energy conservation. Moreover, the implementation of a suitable incentive framework effectively encouraged residential consumer participation, consequently extending the lifespan of transformers through night peak clipping. Undoubtedly, the DR program demonstrates mutual benefits for both consumers and utilities, fostering enhanced system reliability while mitigating the necessity for emergency power procurement. Therefore, the adoption of a generalized demand response program stands as a promising avenue for bolstering system resilience, reducing operational costs, and fostering sustainability within the utility sector.

REFERANCES

1. Yusuf Ozturk, Prakash Jha, Sunil Kumar and Gordon Lee," A Personalized Home Energy Management System for Residential Demand Response"4th International conference in power Engineering

2. Zhao Mengmeng, Wang Xiaoying,"A Survey of Research on Datacenters Using Energy Storage Devices to Participate in Smart Grid Demand Response" 2020 IEEE International Conference on Power, Intelligent Computing and Systems (ICPICS)

3. Sumit Kumar Mandal,Trishala Pal Choudhuri , "Development of domestic load management scheme to participate in demand side integration" 2017 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)

4. Sereen Althaher, Student Member, IEEE, Pierluigi Mancarella, Senior Member, IEEE, and Joseph Mutale, Senior Member, IEEE," Automated Demand Response From Home Energy Management System Under Dynamic Pricing and Power and Comfort Constraints", IEEE TRANSACTIONS ON SMART GRID

5. Samuel. Gyamfi, Susan. Krumdieck, Larry. Brackney, "Demand Response in the Residential Sector: A Critical Feature of Sustainable Electricity Supply in New Zealand

6. B. Capitão, J. Lagarto, R. Pereira , P. Almeida, P.M.Fonte," Demand Response Model for Hardware Implementation"

7. Mohammad Hossein Fouladfar , Amir Baharvandi, Mousa Marzband, Nagham Saeed, Ameena Saad al-sumaiti," Efficient Energy Managemet System Based on Demand Shifts in Domestic Grid Considering Emission and Tax on Carbon", 2020 2nd International Conference on Smart Power & Internet Energy Systems

8. Jiahuan Feng, Student Member, IEEE, Bo Zeng, Member, IEEE, Dongbo Zhao, Senior Member, IEEE, Geng Wu, Student Member, IEEE, Zongqi Liu and Jianhua Zhang, Member, IEEE," Evaluating Demand Response Impacts on Capacity Credit of Renewable Distributed Generation in Smart Distribution Systems "

9. Samuel. Gyamfi, Susan. Krumdieck, Larry. Brackney, Pattern Recognition Residential Demand Response: An Option for Critical Peak Demand Reduction in New Zealand",

10. Yan Nan, Cui Chenggang, Li Xiaotong, Chen Jing, Xi Peifeng," Research on Demand Response Strategy of HVAC Based on Deep Reinforcement Learning ",2020 The 5th International Conference on Power and Renewable Energy