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A Smart Technology Driven Framework for Improved Supply Restoration and Load Management in Urban and Semi Urban Low Voltage Distribution Networks

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Abstract: Consumers in urban and semi urban areas heavily depend on reliable electricity for socio economic activities. Consumers connected to traditional low voltage distribution networks (LVDNs) suffer from prolonged outages due to manual restoration procedures and limited operational control, despite the presence of alternative supply paths within the network. Furthermore, demand management is typically implemented through indiscriminate load shedding, which interrupts supply to all consumers regardless of priority. This paper proposes a smart technology driven framework for improving supply restoration and demand management in urban and semi urban low voltage distribution networks. The proposed framework integrates dual load control smart meters at consumer premises and remotely operated switches within the LV network, coordinated through an advanced Distribution Management System. A novel optimization algorithm is developed to dynamically maximize the number of consumers served during supply restoration and demand management while considering real time load forecasts, consumer priority levels, and network operational constraints such as voltage limits and feeder capacities. The algorithm is formulated as a mixed integer linear programming problem and solved using the PuLP optimization library. The proposed framework is validated using a modified IEEE 33 bus test system incorporating real consumer load data. Simulation results demonstrate significant improvements in restoration time, improved prioritization of essential loads, and compliance with system operating constraints. Additionally, the proposed framework reduces the Energy Not Supplied (ENS), resulting in notable economic benefits. The proposed approach provides a scalable pathway for transitioning from manually operated distribution networks to intelligent and resilient LVDNs capable of accommodating increasing demand and distributed renewable energy integration.

Keywords: Demand management, Energy not served, Essential load, Low voltage distribution network, Non essential load, Optimization algorithm, Smart technology, Supply restoration,

1. Introduction

Electricity is a fundamental requirement of humans in modern society, and serving as a cornerstone for economic development, socio economic stability, comfortable living standards, and technological progress. In Sri Lanka, like in many other countries, the critical role of electricity is evident in national consumption trends. Between 2002 and 2022, electricity demand in Sri Lanka nearly doubled, increasing from 7,255 GWh to 14,520 GWh [1]. At present, there are approximately 7 million electricity consumers, including residential, industrial and commercial categories [1]. This widespread access highlights the importance of ensuring supply reliability and system resilience.

In recent years, electricity consumers have experienced a considerable number of supply interruptions. According to the Ceylon Electricity Board (CEB) Annual Statistical Report 2023, the System Average Interruption Duration Index (SAIDI) for Distribution Divisions 1, 2, 3, and 4 was reported as 2447, 6074, 4606, and 4489 minutes per customer per year, respectively. These values correspond to outage durations ranging approximately from 10 to over 100 hours per consumer annually, highlighting the significant reliability challenges faced by the distribution network [1], [2]. In addition, information published by the Public Utilities Commission of Sri Lanka (PUCSL) indicates that load shedding exceeding two hours per day was intermittently implemented in 2022 due to generation shortages and operational constraints. These interruptions were caused by a combination of factors, including natural events, technical failures, human related factors, construction

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accidents, vandalism, operational errors, and system overload conditions, where electricity demand exceeded the available supply capacity [3].

The economic consequences of such interruptions are reflected through the ENS cost, which represents the economic value of electricity that could not be delivered to consumers during supply interruptions. The report titled "Estimation of the Cost of Energy Not Served in Sri Lanka", published by the Public Utilities Commission of Sri Lanka (PUCSL) in March 2024, demonstrates the substantial economic burden associated with unreliable electricity supply [4],[5].

To assess the time involved in the operational activity process in LVDN, a study was conducted using 250 randomly selected low voltage supply restoration (SR) cases from Western Province. The analysis is summarized in Table I. The results indicate that consumers experienced, on average, an additional two and a half hours of power outage due to delays in field crew mobilization and manual switching operations, primarily caused by the absence of remote operation capabilities and limited automation within the existing LVDN infrastructure.

Table 1 – Time involved in the manual restoration process

Activity	Mean time (Minutes)	Standard Deviation (Minutes)	Minimum time (Minutes)	Maximum time (Minutes)
Mobilization	80	12	50	110
Operation (per tie point)	20	5	15	30
Mobilization between two tie points	25	7	20	30
Identify fault	25	12	25	40
Total	150	-	110	210

At the consumer level, existing network configurations do not provide separate circuits for Essential Load (EL) and Non Essential Load (NEL). ELs, which are critical for daily activities, may include refrigerators, lighting, and personal computers, while non essential loads include appliances such as air conditioners, washing machines, and entertainment devices. Because both EL and NEL share the same circuit, consumers experience complete power loss during interruptions or load shedding. Furthermore, current utility arrangements do not support selective load control.

Despite ongoing developments in distribution automation worldwide, most research efforts have primarily focused on Medium Voltage (MV) distribution networks, where monitoring and control infrastructures are relatively well established. In contrast, LVDNs still rely heavily on manual operations and lack automated restoration capabilities, real time monitoring, and selective load management mechanisms at the consumer level.

To address these challenges and improve supply reliability for urban and semi urban consumers in Sri Lanka, this study proposes a smart technology driven framework for upgrading the existing LVDN infrastructure. The proposed approach integrates communication enabled smart devices, including dual load control smart meters at consumer premises and remotely operated switching devices within the LV network, coordinated through an Advanced Distribution Management System (ADMS). In addition, an optimization based algorithm is developed to support automated SR and coordinated demand management (DM) while considering consumer priority levels and network operational constraints.

2. Literature Survey

2.1 Literature Studies on Automated Systems

Automation and intelligent systems, powered by information and communication technology advancement, have significantly improved operational efficiency across various sectors. In the power sector, these technologies have enhanced monitoring, control, and performance in generation, transmission and sub transmission networks [6]-[8]. Globally, the focus is now shifting toward enabling smart distribution networks [9]. However, Sri Lanka has lagged in this transition due to the inherent complexity of LVDNs and the large number of dispersed consumers.

In recent years, numerous studies have focused on developing self healing power distribution networks capable of automatically detecting, isolating, and restoring outage areas to enhance grid reliability, resilience, and supply security [10]-[16]. Most of these studies have targeted the MV level, where network topology, data availability, and control mechanisms are relatively manageable. In contrast, LVDNs have received significantly less attention, primarily due to their higher complexity, scalability challenges, and large volume of connected nodes and devices [9], [10].

Many MV level SR strategies involve the deployment of Distributed Generation (DG)

[11],[15], often in combination with tie-switches to reconfigure the network and restore supply. While these approaches have demonstrated strong effectiveness in MV systems, their application to LVDNs is considerably more challenging due to the significantly higher number of connections, increased network complexity and associated scalability challenges.

Distributed Energy Resources (DERs) are increasingly present at the LV level, offering benefits such as peak load reduction and improved reliability. However, their integration introduces additional challenges, including voltage regulation issues, reverse power flow, and generation variability [8]. To address these issues, modern techniques such as Volt/VAR control, smart inverter functions, and Dynamic Optimal Energy management are used to enhance coordination, maintain voltage profiles, and optimize DER dispatch. However, implementing such methods in existing traditional LVDNs remains questionable due to limited infrastructure and control capabilities.

In addition to SR, load curtailment strategies play an important role in maintaining grid stability during system disturbances or generation shortages [11], [12], [14]. Common approaches include Under Frequency Load Shedding (UFLS) and Under Voltage Load Shedding (UVLS) [11], which are typically implemented at the MV level through automated feeder level control schemes. In some countries, legacy systems such as Audio Frequency Load Control (AFLC) are also used to switch groups of loads by transmitting control signals through the power network. Although these systems allow utilities to manage demand during peak conditions, they generally operate at feeder or group level and do not provide selective control of individual consumer loads. Consequently, implementing such conventional technologies in Sri Lanka's LVDNs presents technical limitations and does not support consumer specific load management.

In addition to improving reliability, optimization of operational (losses, voltage, restoration, etc.) and planning functions (DG placement, reconfiguration, curtailment, etc.) play a critical role in enhancing the performance of distribution systems. Numerous studies have examined optimization approaches for network reconfiguration, DG placement, and load curtailment to minimize power losses, improve voltage profiles, reduce interruption duration during SR, and maximize the number of consumers served, during DM operations. Common optimization techniques include deterministic, heuristic, metaheuristic, and genetic algorithms [15], [16], [17]. In Sri Lanka, the adoption of customized optimization methods is feasible, particularly given the presence of an established Distribution Control Centre (DCC). However, successful deployment requires effective integration with existing systems and real-time control infrastructure.

Despite significant research efforts on SR, load curtailment, and distribution automation, most existing studies have primarily focused on MV distribution networks where monitoring infrastructure and control mechanisms are relatively well established. In contrast, LVDNs remain largely dependent on manual operations and lack automated restoration capability, real time monitoring, and selective load management mechanisms at the consumer level. Furthermore, conventional load control approaches such as feeder level load shedding or legacy AFLC systems do not provide the capability to prioritize consumer loads during supply interruptions. Therefore, there is a clear need for an integrated framework capable of enabling automated supply restoration, coordinated demand management, and effective integration of DERs within LVDNs.

2.2 Limitations of Existing LVDN System

The existing general arrangement of LVDN and Distribution Management System (DMS) in urban and semi urban areas is shown in Figure 1. The network typically follows a radial topology in which each feeder is protected by a fuse or a Moulded Case Circuit Breaker (MCCB). Each feeder supplies several consumer clusters, generally defined as group of consumers between two normally closed wire connected tie points, allowing manual isolation when necessary. End users are connected to the LVDN through service lines, with electricity consumption measured using electromechanical energy meters installed in series with the service connection at the consumer premises. In addition, adjacent feeders are usually interconnected through normally open tie wires that enable alternative feeding arrangements during outages or maintenance operations.

The existing DMS is operated through a DCC. Most operational decisions rely heavily on human judgment, pre network analysis results, historical records, and field data provided by consumers and field crew, as illustrated in Figure 1. However, this traditional LVDN configuration presents several operational challenges. Fault detection and isolation often require significant time, delaying the restoration of supply to healthy downstream sections even when tie points for alternative feeding are available.

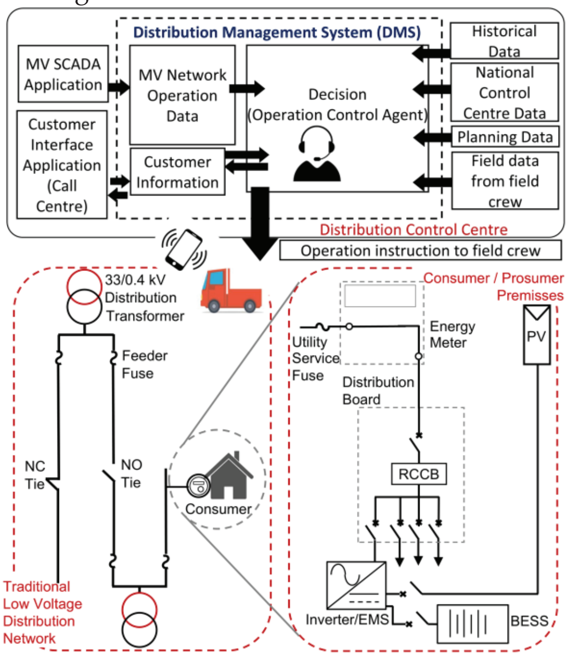

Figure 1 – Existing urban and semi urban low voltage distribution system

Demand side management is difficult to implement due to lack of real time visibility and control over individual or aggregate loads, as well as the absence of accurate demand forecasting mechanisms. As a result, zonal load shedding is primarily implemented at MV level because selective disconnection capabilities are not available at the low voltage level, thereby limiting the effectiveness of demand side management during supply shortage or emergency conditions. In addition, the dynamic operation of distributed solar generation remains largely unmanaged, raising concerns about network stability and effective integration under the current systems.

3. Proposed Methodology

3.1 Framework Development

The proposed smart LVDN architecture, illustrated in Figure 2, builds upon the existing physical infrastructure by integrating advanced smart devices and communication networks to enable intelligent load management and distributed generation coordination. Key hardware upgrades include replacing MCCBs, Fuses, wire ties with remotely controllable energy meters to dual load smart MCCBs and

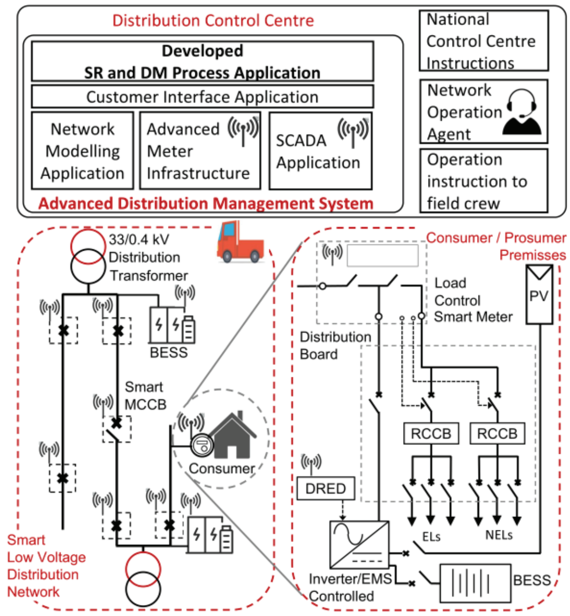

Figure 2 – Proposed smart LVDN architecture

upgrading electromagnetic control smart meters that differentiate ELs and NELs.

To support effective operational control, consumer premises wiring will be reconfigured to separate EL and NEL circuits, enabling selective curtailment during SR events or DM response. Rooftop photovoltaic (PV) systems are connected through Demand Response Enabling Devices (DREDs), facilitating coordinated integration of DERs while maintaining grid stability. Communication between smart field devices and the DCC is established through secure wireless networks and the Advanced Metering Infrastructure (AMI), forming the data backbone for real time monitoring and control. The collected data are then processed by an ADMS, which integrates existing DMS modules (see Figure 1) into a unified operational platform. This integration enables automated decision making for SR and demand management while significantly reducing the need for manual intervention.

Central to this framework is a developed algorithmic process that orchestrates SR and DM by leveraging real time data, load forecasts, network constraints, and consumer priority information. This process, detailed in the next section, dynamically optimizes load prioritization, EL and NEL switching, PV generation control, and demand response actions. The algorithm supports effective SR and DM while respecting network operational limits. Control commands derived from this process is transmitted to smart MCCBs, dual load control meters, and DREDs for seamless execution of the restoration and management strategies.

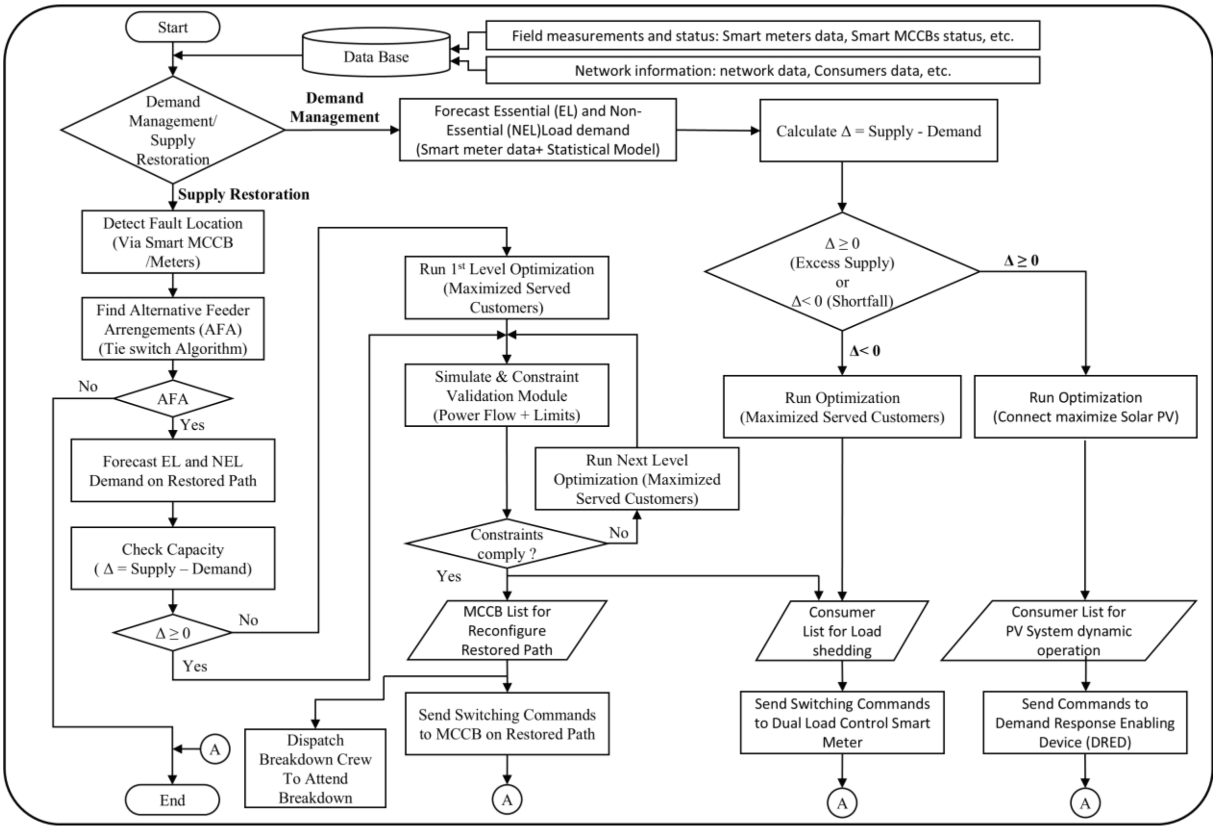

Figure 3 – Proposed algorithm for supply restoration and demand management process

3.2 Proposed Algorithm for LVDN Supply Restoration and Demand Management

Figure 3 illustrates the proposed algorithm as a sequence of structured steps aimed at maximizing the number of served consumers during both SR and DM operations.

This includes optimizing electricity supply to both consumers and prosumers, who also generate electricity, primarily through rooftop solar PV. At the final stage, a list of consumers and prosumers to be served is finalized, and control signals are transmitted to the respective smart MCCBs, dual load control smart meters and DREDs.

The methodology is carried out in multiple stages.

3.3 Data Acquisition and System Preparation

Real time field measurements and field device status data are collected from smart MCCBs and smart meters. These data are stored in a centralized database. Network models, consumer data, and system configuration data are also stored in a repository for easy retrieval. Historical consumption data from each consumer is used to estimate EL and NEL forecasts for the target time interval. Since both EL and NEL are measured through the same smart meter, they are separated using predefined EL/NEL ratios derived from case studies and statistical methods (see Figure 3). This enables separate demand forecasts for EL and NEL.

Network constraints such as transformer capacity, voltage limits, forward and reverse power flow thresholds through transformers, and ampacity limits of LV feeders, are extracted from the network model. Additionally, consumer specific data, including cluster membership, service priority level, and priority time windows, are extracted from the customer information system.

3.4 Supply Restoration (SR) Procedure

When the SR algorithm is triggered, it first receives the location(s) of the fault isolation switches. The algorithm then executes the Tie Switch Algorithm, which uses a graph theory based representation of the LVDN to identify all feasible alternative feeding configurations capable of restoring supply to the affected downstream sections. This approach is derived from the automated supply restoration framework previously proposed by the authors in [19] and is further extended in this work to support coordinated DM and DER integration.

Forecasted load values for each consumer are retrieved from the database using historical consumption data and short term demand forecasting models. The algorithm then performs a capacity verification step, where the total forecasted demand of the restoration area is compared with the available feeder and transformer capacity limits. The available supply capacity is obtained from the DCC based on real time feeder loading levels, transformer ratings, and upstream network operating conditions.

For consumers equipped with rooftop solar PV systems, the net load demand is calculated by subtracting the forecast PV generation from the forecast consumer demand. This allows the algorithm to account for the contribution of DERs while ensuring that network constraints such as feeder loading limits, transformer capacity limits, and acceptable node voltage ranges are maintained during the restoration process.

Following the capacity verification step, the candidate network configuration is evaluated using power flow analysis to ensure that all operational constraints are satisfied. These constraints include feeder loading limits, transformer capacity limits, and acceptable node voltage ranges throughout the network. If any constraint violation is detected, an optimization process is initiated to determine the most suitable restoration configuration.

The optimization process applies the modified deterministic objective function defined in Equation (1) to maximize the number of consumers served during the restoration process. The objective function considers both the normalized forecast load magnitude and the consumer priority value, thereby prioritizing critical loads while efficiently utilizing the available supply capacity. Network operational constraints, including node voltage limits and feeder power flow limits, are incorporated as defined in Equations (2)–(4) to ensure secure network operation.

For scenarios involving supply shortages or demand management operations, an additional constraint on the maximum allowable load curtailment is introduced, as defined in Equation (5). This constraint ensures that the restoration strategy maintains system stability while minimizing the impact on consumers.

$$\text{Maximize } \sum_i(\alpha(p_i/P_{max}) + \beta(c_i/C_{max})) * X_i \qquad \dots (1)$$

$$\text{Subject to, } \sum |\Delta p_i| \leq |\Delta P_{total}|$$

where α and β are weighting coefficients used to balance the contribution of normalized load demand and consumer priority value in the objective function. These parameters allow the restoration strategy to prioritize critical consumers while efficiently utilizing the available supply capacity.

Variable

$x_i = \{0,1\}$ where $x_i = 1$ consumer i served
$x_i = 0$ consumer i not served
p_i - normalized forecast load of consumer i
P_{max} - maximum normalized forecast load
c_i - priority value of consumer i
C_{max} - maximum priority value
$p \in P$ and $P_{max} \subseteq P$ $\quad c_i \in C$ and $C_{max} \subseteq C$

Power Flow Constraints

Transformer capacity, $TR_i \leq 100\%$ … (2)
Feeder capacity, $Lin_{i,j} \leq 100\%$ … (3)
Voltage drop, $u_{min} \leq u_i \leq u_{max}$ … (4)

Load Shedding Constraints

$$P_{Supply\ max} < \sum_i EL_i + \sum_i NEL_i \qquad \dots (5)$$

The final output of the SR module includes:

- The configuration of tie MCCBs for network re routing.
- EL/NEL switching matrices for each consumer.

These results are transmitted to the smart MCCBs and dual load control smart meters for automated execution of the restoration plan.

3.5 Demand Management (DM) Procedure

The DM procedure largely mirrors the SR workflow, as depicted in Figure 3, but with two key differences:

- The Tie Switch Algorithm is bypassed since the network topology is fixed.
- The available supply capacity is provided as a direct input to the algorithm.

4. Case Study and Simulation Setup

The effectiveness of the proposed framework and process is demonstrated using a simulation platform integrated with real time field data gathered from smart meters. The system used for the case study is based on the IEEE 33 bus test grid model, as shown in Figure 4. This test grid was adapted to reflect typical urban and semi urban distribution networks conforming to relevant distribution standards. It incorporates two 33/0.4 kV, 100 kVA distribution transformers, each with 4% impedance and off-load tap changers ranging from +2.5% to -7.7% in 2.5% increments. Each transformer supplies 32 consumers, including

12 prosumers equipped with rooftop solar PV systems.

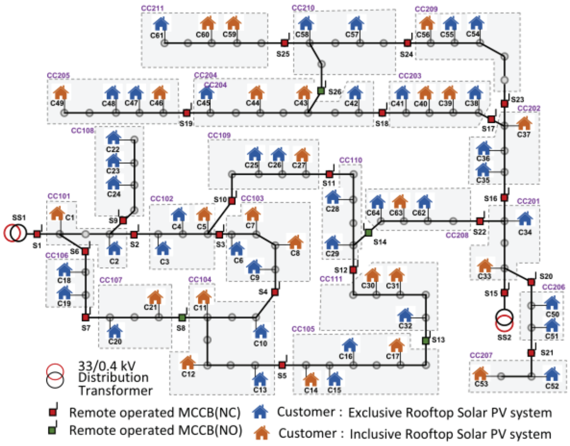

Figure 4 – Diagram of test grid

Each consumer is modelled as a single-phase load with a maximum demand of 7 kVA and a 0.9 lagging (inductive) power factor. The maximum PV power capacity is considered as 5 kVA. The network includes 21 MCCBs and 4 tie MCCBs to support various switching operations. Conductors used in the LVDN are based on CEB standards, specifically the All-Aluminium Conductor 7/7.30, known locally as "Fly" conductor type. The conductor characteristics include a resistance of 0.451 Ω/km, reactance of 0.291 Ω/km, and a current-carrying capacity of 155 A. The average span length between two poles is assumed to be 30 m.

According to the Sri Lanka Distribution Code [19], consumer voltage limits are defined between 0.94 pu and 1.06 pu, while the transformer secondary voltage is set at 1.08 pu.

4.1 Data Collection and Load Characterization

To prepare a mock database of load profiles based on real world implementation for establishing EL and NEL control under the proposed framework, 32 consumers from the western province were selected, representing domestic, commercial, and industrial categories. All participants already had utility-installed smart meters. As shown in Figure 4, each consumer's internal wiring was modified to separate the EL and NEL circuits, with a second smart meter installed on the NEL circuit. Fifteen-minute interval consumption data from both meters was collected over a three-month period. Figure 5 illustrates one such installation, while Figure 7 presents the prepared load patterns for each consumer, which were used in the simulation studies.

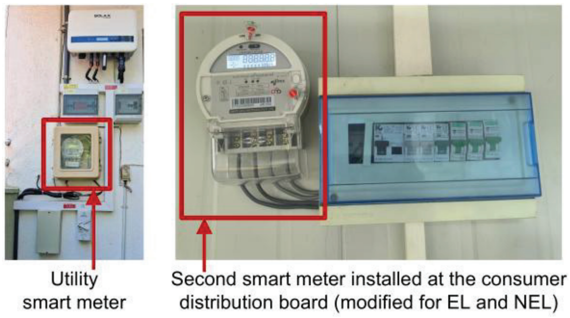

Figure 5 – Implemented dual load control method at a consumer premises

In the proposed operational configuration, consumers would typically be supplied through a single smart meter with dual load control capability, making it impossible to directly generate separate EL and NEL curves. For this study, the additional metering enabled extraction of distinct EL and NEL profiles, which were used to develop normalized forecast load profiles and derive representative EL/NEL ratios through mean based analysis. These ratios were then extrapolated to similar consumers by classification.

4.2 Simulation Platform and Algorithm Implementation

The test network was implemented in a software simulation environment to evaluate the performance of the proposed framework. The optimization algorithm was developed in Python, where the mathematical formulation of the objective function and system constraints was implemented using the PuLP optimization library. Power flow analysis and network constraint verification were carried out using DIgSILENT PowerFactory.

Consumer load data obtained from smart meter measurements were used to develop representative load profiles for the simulation study. The analysis was performed for a selected operating interval representing peak demand conditions, with load values aggregated at 15 minute time intervals to reflect realistic distribution network operation. For each simulation scenario, the algorithm first retrieves the forecast load data and determines feasible restoration configurations using the graph theory based tie switch algorithm.

The proposed optimization routine is then executed in Python to determine the optimal restoration configuration while satisfying network operational constraints. The resulting switching configuration is subsequently validated through power flow simulation in DIgSILENT PowerFactory to ensure that feeder loading limits, transformer capacity limits, and node voltage limits are maintained within acceptable operational ranges.

5. Results and Discussion

5.1 Results: Operational Scenarios

The proposed system was tested under multiple scenarios to evaluate its performance in supply restoration and demand management. The simulations were conducted using the modified IEEE 33 bus-based LVDN model described in Section 4. Two representative cases are presented here for demonstration:

Supply Restoration (SR): A fault was simulated between two sectionalizing switches in consumer cluster CC109. The algorithm isolated the fault and restored supply to healthy clusters by closing tie switches S14 (restoring CC110) and SS13 (restoring CC111), while opening S12 to split the feeder and maintain load balance.

The resulting reconfigured network topology and power flow paths used for restoration are illustrated in Figure 6, where the alternate feeding paths are highlighted. Power flow analysis confirmed that feeder loading limits, transformer capacity limits, and node voltage constraints remained within acceptable operating limits during the restoration process.

Demand Management (DM): A 3kW load-shedding requirement was imposed at Substations 1 and 2 for a duration of two hours. The system selectively curtailed NELs within the affected area while maintaining supply to ELs.

Both scenarios were simulated during peak demand conditions (Thursday, 7:00 PM).

Figure 8 presents the normal operating status of load switches (EL and NEL) for each consumer. Figure 9 illustrates the feeder reconfiguration MCCB status during supply restoration, together with the normal feeder configuration of the system. Figure 10 presents the post-restoration status of load switches (EL and NEL) for each consumer. Figure 11 shows the post-restoration voltage profile at the consumer nodes, confirming that all node voltages remain within the acceptable operating limits. Figure 12 presents the status of load switches (EL and NEL) for each consumer during the demand management scenario.

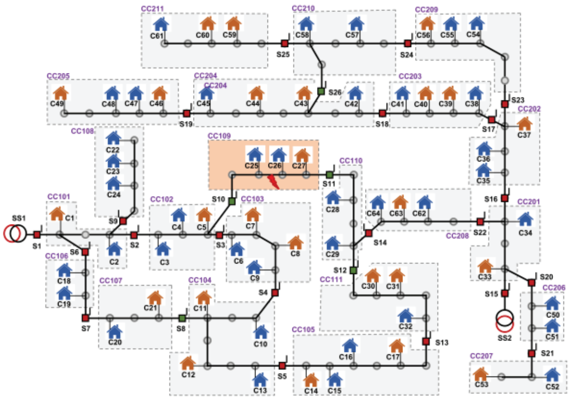

Figure 6 – Network reconfiguration path during supply restoration

Table 3 presents a comparison between the existing and proposed systems for the simulated scenario. The results show that mobilization time during the restoration process can be reduced from two and a half hours to less than five minutes. Additionally, the number of unserved consumers is significantly reduced, resulting in a substantial reduction in the ENS. Importantly, all consumers receive their essential loads, making the proposed system more beneficial socio economically than traditional zonal load shedding. These benefits were consistently observed across all tested scenarios. The benefit calculations use the latest

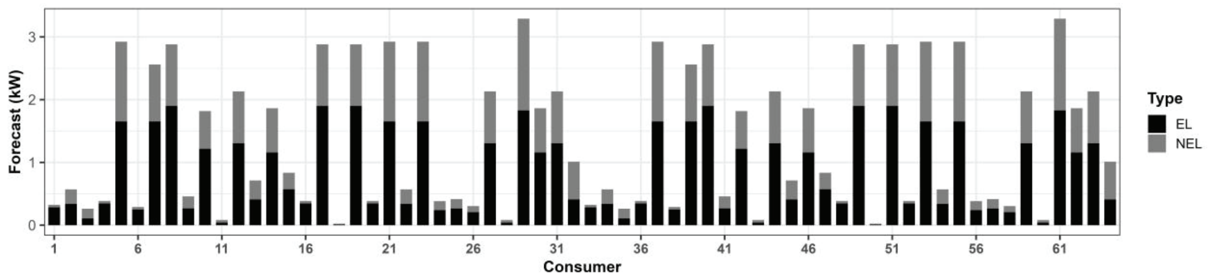

Figure 7 – Load forecast profile for EL and NEL of each consumer

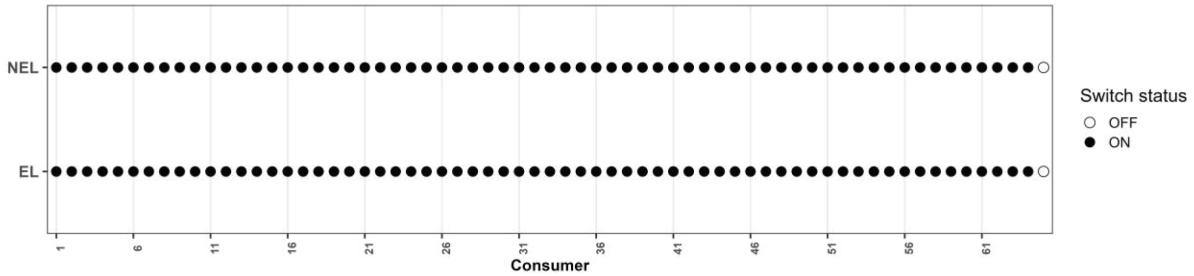

Figure 8 – Normal operating status of load switches (EL and NEL) for each consumer

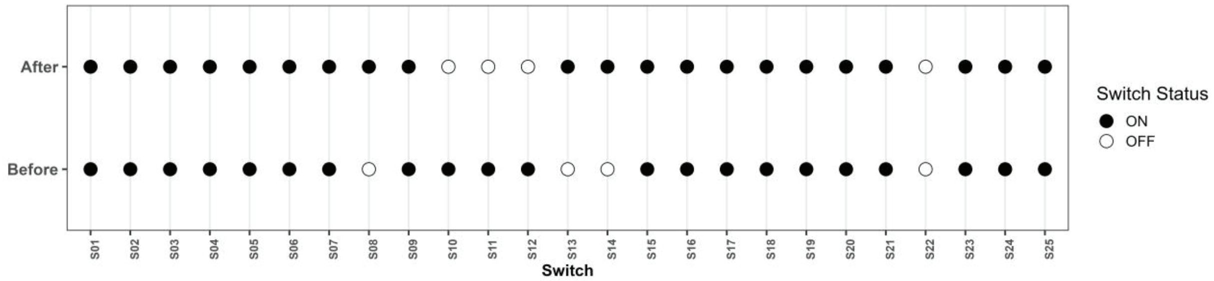

Figure 9 – Status of MCCBs before and after the fault event

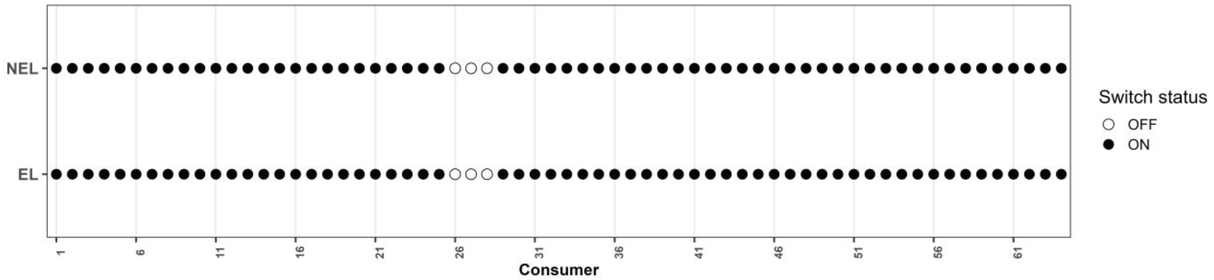

Figure 10 – Post SR status of load switches (EL and NEL) for each consumer

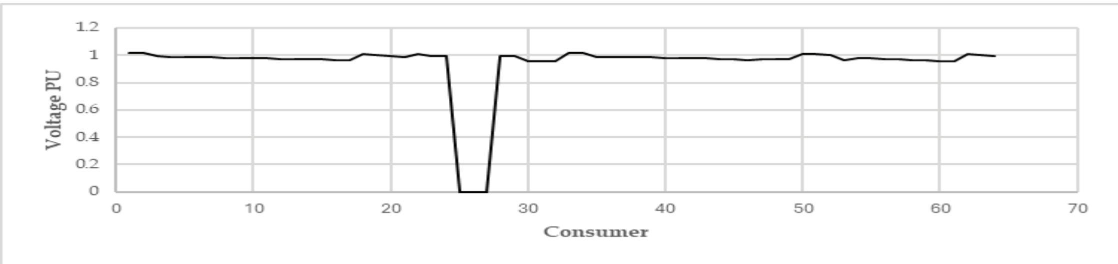

Figure 11 – Post restoration voltage profile at the consumer node

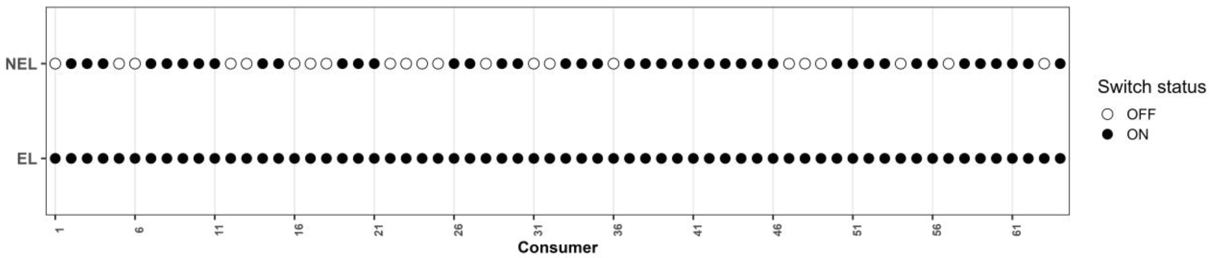

Figure 12 – Status of load switches (EL and NEL) for each consumer during the DM

ENS values published by PUCSL, as detailed in Table 4.

Table 3 – System comparison

		Existing system	Proposed system
SR	Process	Manual	Automated
	Estimated time	2.5 hours	< 3 Minutes
	Number of consumers unserved	7	3
	ENS (kWh)	18.9	8.3
	Cost of ENS (LKR)	10,834.00	4,843.00
DM	Number of consumers unserved	32	0
	ENS (kWh)	25.6	2.85
	Cost of ENS (LKR)	31,457.00	3,000.00

Table 4 – ENS values published by PUCSL

Sector	Unexpected Outages (LKR/kWh)	Expected Outages (LKR/kWh)	Combined (LKR/kWh)
Domestic	528.45	480.47	516.97
Commercial	657.67	596.18	612.74
Industrial	1,007.98	692.94	888.78

5.2 Discussion

The simulation results clearly demonstrate the effectiveness of the proposed smart LVDN framework and the underlying algorithm in improving SR and DM performance compared with conventional methods. By leveraging real time data from smart meters and integrating advanced optimization techniques, the proposed approach was able to rapidly identify and implement optimal switching configurations, thereby minimizing service interruptions and load shedding.

In the SR scenario, the algorithm efficiently reconfigured the network by selectively closing and opening tie switches, which enabled restoration of power to affected consumer clusters within a significantly shorter time frame than the traditional two and half hour restoration window. This accelerated restoration not only improves customer satisfaction but also enhances system reliability and resilience during fault events.

The separation of ELs and NELs, coupled with dynamic control of rooftop PV systems via DREDs, provided additional flexibility in managing load and generation. The ability to selectively curtail NELs while maintaining uninterrupted supply to EL ensures critical services remain powered during periods of constrained supply or network stress.

Voltage profiles and load utilization results obtained from the optimized network topology confirmed that all operational constraints, including voltage limits and feeder capacities, were satisfied. This validates the robustness of the proposed algorithm in maintaining safe and reliable grid operation while maximizing served load.

Economic analysis based on ENS and Cost of ENS metrics highlighted the cost-effectiveness of the proposed method. Reduction in unserved energy directly translates to financial savings for utilities and improved service quality for consumers. Furthermore, the algorithmic approach supports proactive demand side management, which can reduce the need for costly infrastructure upgrades.

While the simulation results are promising, practical deployment would require addressing challenges such as communication reliability, cyber security, and customer engagement. Additionally, the role of field crews remains critical for physical repairs and manual operations, underscoring the importance of a hybrid approach combining automation with human expertise.

This integration represents the key innovation of the proposed framework, facilitating a cost effective yet powerful upgrade from the existing system to a fully smart LVDN. While the developed algorithm and ADMS enable automated supply restoration and demand management to maximize service continuity, certain restoration activities such as physical repairs, reconnection of manually operated switches, and field verification remain the responsibility of field crews. The automated system thus supports and expedites the restoration process in an effective and optimized manner but does not replace the essential hands on work required on site.

Overall, the proposed framework presents a scalable and adaptable solution for modernizing distribution networks, particularly in regions with growing distributed energy resources and evolving consumer demands.

6. Conclusion and Recommendations

6.1 Key Findings

This study introduced a novel smart LVDN framework to enhance supply reliability in urban and semi-urban areas. An optimization algorithm was developed to maximize service restoration and support demand side management while respecting network operational limits. Transitioning from a manually operated, labour-intensive SR process to a technology-driven LVDN integrated with an ADMS can substantially reduce interruption duration, which currently ranges annually from approximately 40 to over 100 hours per consumer in Sri Lanka.

6.2 Recommendations

To achieve this transformation, the following key upgrades and actions are recommended:

1. Upgrade Traditional Infrastructure: Replace existing MCCBs, HRC fuses, and fixed wired tie points with smart MCCBs capable of remote operation and real time monitoring.

2. Establish a Communication Backbone: Develop a robust and secure communication infrastructure to integrate field devices with a centralized ADMS, enabling seamless data exchange and control.

3. ADMS Integration: Implement the proposed algorithms within the ADMS to enable intelligent decision making, automated feeder reconfiguration, and efficient supply restoration.

4. Consumer Side Upgrades: Encourage consumers to reconfigure internal wiring to separate Essential Loads (EL) and Non-Essential Loads (NEL), ensuring critical services remain powered during outages and load shedding.

5. Enhance Power Quality and Visibility: Deploy smart meters network wide to improve real time visibility, monitor power quality, and support a more responsive grid management approach.

These steps are essential for transforming Sri Lanka's existing LVDN into a resilient and intelligent grid infrastructure capable of meeting rising reliability expectations and operational challenges in the coming years.

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