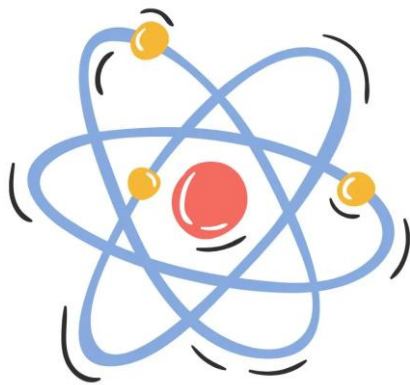




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PROFILE ENHANCEMENT

Sarfaraz Nawaz, Virendra Sangtani

Department of Electrical Engineering,
Swami Keshvanand Institute of Technology,
Management & Gramothan, Ramnagar
Jagatpura, Jaipur, India

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ABSTRACT:

In recent years, the integration of Distributed Generation (DG) units into distribution systems has emerged as an effective approach for reducing active power losses and improving overall network performance. To achieve maximum loss reduction, the optimal sizing and placement of DG units, particularly solar photovoltaic (PV)-based generators, along with capacitor units, are essential. The primary objective of this study is to maximize the percentage reduction in active power losses while maintaining an acceptable voltage profile across the distribution network. To accomplish this objective, a novel mathematical parameter termed the Loss Constant (LC) is proposed. The LC is formulated to determine the optimal rating and location of multiple solar PV-based DG units and capacitor units independently. The proposed methodology is implemented and evaluated using the standard IEEE 69-bus radial distribution system. To assess its robustness and effectiveness under varying operating conditions, three different loading levels—light, nominal, and heavy load—are considered. The obtained results demonstrate that the proposed LC-based methodology effectively identifies the optimal locations and sizes of DG and capacitor units, resulting in significant active power loss reduction and improved voltage performance. The encouraging results under different loading conditions confirm the potential of the proposed approach for efficient planning and operation of modern distribution systems.

Keywords: Distributed Generation (DG), Solar Photovoltaic (PV), Capacitor Allocation, Optimal Placement, Optimal Sizing, Active Power Loss Minimization, Loss Constant (LC), Radial Distribution System, IEEE 69-Bus System, Voltage Profile Enhancement, Load Variation.

1. INTRODUCTION

In India, distribution networks experience relatively high real power losses (RPL), which can be approximately 25% in some distribution systems. These high losses adversely affect the efficiency, voltage profile, and economic operation of power distribution networks. The integration of Distributed Generation (DG) into distribution systems has therefore emerged as an effective strategy for reducing real power losses, improving voltage performance, and enhancing overall system efficiency. DG technologies can employ both conventional and non-conventional energy resources. Conventional DG technologies include gas turbines, fuel cells, reciprocating engines, and microturbines, whereas non-conventional or renewable-based DG technologies include biomass, cogeneration, wind energy, and solar photovoltaic (PV) systems.

One of the major challenges associated with DG integration is the determination of its optimal location and capacity. Improper placement or sizing of DG units may result in inadequate loss reduction, voltage violations, reverse power flow, or increased operational costs. Therefore, optimal DG allocation requires simultaneous consideration of the location and rating of DG units while satisfying the technical and economic constraints of the distribution network.

Several optimization and analytical techniques have been reported in the literature for solving the optimal placement and sizing of DG units. Particle Swarm Optimization (PSO) has been employed to determine the optimal rating and location of DG units [1]. Analytical approaches for DG allocation in radial distribution systems (RDSs) have been presented in

[2, 3]. Genetic Algorithm (GA)-based approaches have been investigated for determining the optimal location and capacity of DG units [4, 5]. Conventional Linear Programming (LP) has also been applied to the DG placement problem [6]. A classical Kalman Filter approach was proposed in [7], while Tabu Search (TS) methodology was employed for real power loss reduction in [8]. Another GA-based method for DG allocation was presented in [9]. The Artificial Bee Colony (ABC) algorithm has been utilized to identify the optimal locations and sizes of multiple DG units [10]. Zhang *et al.* [11] proposed an integrated energy model for DG allocation. Injeti and Kumar [12] developed an optimization-based methodology for reducing real power losses in distribution systems. Evolutionary techniques, including Simulated Annealing (SA), have also been employed to determine the optimal location and rating of DG units. Sensitivity-analysis-based approaches have been investigated for solving the Optimal Placement of Distributed Generation (OPDG) problem [13], while an analytical methodology for OPDG in balanced distribution systems was presented in [14].

In addition to DG allocation, reactive power compensation plays an important role in reducing distribution losses and improving voltage profiles. Shunt capacitors are widely used for reactive power compensation because they can provide reactive power locally, thereby reducing reactive power flow through distribution feeders. Consequently, the optimal placement and sizing of capacitor units are essential for achieving effective loss reduction, voltage improvement, and efficient utilization of reactive power resources.

Various optimization techniques have been proposed for solving the capacitor allocation problem. PSO has been applied to determine the optimal location and rating of capacitor units [15]. Simulated Annealing (SA) [16], Cuckoo Search Algorithm (CSA) [17], Teaching-Learning-Based Optimization (TLBO) [18], Flower Pollination Algorithm (FPA) [19], heuristic approaches [20], and Genetic Algorithm (GA) [21] have also been employed for optimal capacitor placement and sizing. Although these techniques provide satisfactory solutions, many of them involve iterative optimization procedures and may require considerable computational effort, particularly when multiple DG and capacitor units are simultaneously considered.

The proposed methodology is evaluated using the standard **IEEE 69-bus radial distribution system** under different operating conditions. The effectiveness of the proposed approach is assessed in terms of optimal DG and capacitor allocation and the corresponding reduction in real power losses. The obtained results demonstrate promising performance and indicate that the proposed LC-based method can provide competitive, and in several cases superior, results compared with recently reported techniques in the literature.

The major contributions of this study can be summarized as follows:

1. A novel mathematical **Line Constant (LC)** is formulated for solving the optimal allocation problem of DG and capacitor units.
2. The proposed LC approach determines the **location and rating of multiple DG units and capacitor units separately**.
3. The proposed methodology aims to achieve significant **real power loss reduction** while maintaining acceptable distribution-system operating conditions.
4. The effectiveness of the proposed method is investigated using the **IEEE 69-bus radial distribution system** under different loading conditions.

5. The performance of the proposed approach is compared with existing methods reported in the literature to demonstrate its effectiveness and computational simplicity.

2. PROBLEM STATEMENT

The aim of this work is to curtail the RPL of DS. For minimizing power losses, it is essential to install the DG and capacitor units of suitable rating at best possible place.

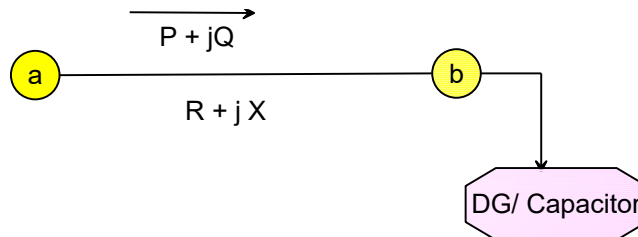


Figure 1. Line diagram of bus a & b

A simple line diagram of bus a & b is shown in figure 1. Capacitor units or DG are placed at bus b.

The RPL for n-bus system is calculated by using:

$$RPL_n = \sum_{a=1}^n \sum_{b=1}^n \frac{|V_a|^2 + |V_b|^2 - 2|V_a||V_b| \cos \theta_{ab}}{Z^2} R \quad (1)$$

It is mandatory for optimal placement of DG or capacitor units that the ratio of real power losses (after and before shunt compensation) is to be minimum.

Hence, the objective function of the problem is:

$$\text{Min. (f)} = RPL_n \quad (2)$$

Where,

P_1 : RPL for base case before compensation.

P_2 : RPL after shunt compensation.

The operational constraints:

- (a) Balancing of all power.
- (b) The total generated power of DG and capacitor units should be less than the load of the system.
- (c) Voltage profile of each bus should maintain Indian standards ($\pm 5\%$).
- (d) The line current should remain between its minimum and maximum values.

3. PROPOSED APPROACH

Motivated by the above limitations, this paper proposes a simple and effective mathematical approach for determining the optimal location and rating of multiple DG and capacitor units in radial distribution systems. A new mathematical parameter, referred to as the **Line Constant (LC)**, is formulated to address the allocation problem. The proposed LC-based methodology provides a systematic means of identifying suitable locations and ratings of DG and capacitor units separately, thereby simplifying the allocation process while targeting maximum real power loss reduction.

In this paper, a latest method is adopted to minimize RPL in DS. The RPL are reduced by inserting DG or capacitor units at appropriate positions. The ratio of P_2 and P_1 is termed as “Loss Constant (LC)” and is expressed as:

$$LC = \frac{P_2}{P_1} \quad (3)$$

Where,

P_1 : RPL for base case before compensation.

P_2 : RPL after shunt compensation.

The proposed methodology is based on minimizing the value of (P_2) and the corresponding **Loss Constant (LC)** to determine the optimal location and rating of DG and capacitor units. The LC value is evaluated at each candidate bus for different DG or capacitor capacities. The bus corresponding to the minimum LC value is identified as the **candidate bus** for installation of the DG or capacitor unit.

For a specified DG or capacitor capacity, the LC is calculated at each bus using Equation (3). By progressively increasing the size of the DG or capacitor in small increments, the variation in (P_2) and LC is evaluated. The capacity corresponding to the minimum LC value is considered the optimal rating, while the associated bus is selected as the optimal installation location.

The computational procedure of the proposed LC-based methodology is summarized as follows:

Step 1: Perform the base-case load-flow analysis and calculate the real power loss of the distribution system, denoted by (P_1).

Step 2: Initialize the DG or capacitor capacity at **1% of the total system load**, i.e., (P_D) for DG allocation and (Q_D) for capacitor allocation.

Step 3: Place the DG or capacitor unit at each candidate bus individually and perform load-flow analysis. Calculate the resulting real power loss (P_2) and the corresponding **Loss Constant (LC)** at each bus using Equation (3).

Step 4: Increment the DG or capacitor capacity by a small predefined step size. For each increment, repeat the load-flow analysis and calculate the corresponding (P_2) and LC values for all candidate buses.

Step 5: Identify the minimum LC value obtained during the iterative process. The DG or capacitor capacity corresponding to this minimum LC value is considered the **optimal rating**.

Step 6: Continue the iterative process until a change in the candidate bus number is observed or the specified termination criterion is satisfied.

Step 7: The bus associated with the minimum LC value is selected as the **optimal location** for the DG or capacitor unit.

Step 8: To determine additional optimal locations for multiple DG or capacitor units, fix the previously selected unit at its optimal location and rating, and repeat **Steps 4–7** for the remaining candidate buses.

Step 9: Repeat the procedure until the desired number of DG or capacitor units has been allocated or the predefined system constraints are reached.

Thus, the proposed LC-based procedure simultaneously facilitates the determination of the **optimal location and rating** of DG and capacitor units while targeting minimum real power losses in the distribution system.

4. RESULTS

Standard bus system, IEEE 69 bus [15] distribution system, is used to examine the above approach. The projected technique is tested by considering three different loading levels also. The code for the proposed methodology is written in MATLAB software.

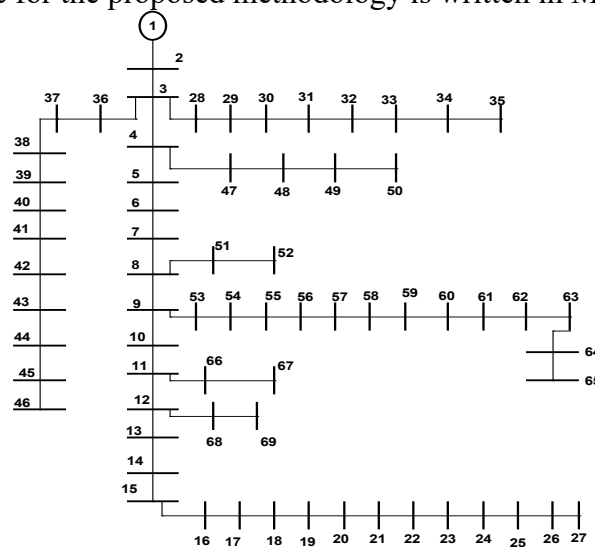


Figure 2. IEEE-69 bus DS [15]

Standard IEEE 69 Bus system

Figure 2 exhibits line diagram of test system-I. Total real and reactive load of the system is 3802 kW and 2694 kVAr [15] respectively.

Table 1. Result of Case I for 69 Bus Systems

	Load level	50%	100 %	160 %
Before Compensation	P_{loss} (kW)	53.31	225	643
	V_{min} (pu)	0.956	0.909	0.846
After Compensation with DG	Rating of DG	320 (61)	480 (17)	382(21)
	(location)	280 (64)	1200 (61)	1569 (61)
			500 (64)	749 (64)
	DG rating in kW	600	2180	2700
	P_{loss} (kilo Watt)	25	71.7	210
	V_{min} (per unit)	.98	0.98	.95

Percentage RPL reduction	54	68.13%	67
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To evaluate the effectiveness and robustness of the proposed Loss Constant (LC)-based methodology, three different allocation scenarios are considered:

- **Case I:** Optimal placement and sizing of solar photovoltaic (PV)-based DG units only.
- **Case II:** Optimal placement and sizing of capacitor units only.
- **Case III:** Concurrent optimal placement and sizing of solar PV-based DG and capacitor units.

All three cases are investigated under three different loading conditions to assess the performance of the proposed methodology under varying operating conditions:

1. **Light-load condition:** 50% of the nominal load.
2. **Nominal-load condition:** 100% of the nominal load.
3. **Heavy-load condition:** 160% of the nominal load.

Case I: Optimal Placement of Solar PV-Based DG Units

In Case I, only solar photovoltaic (PV)-based Distributed Generation (DG) units are considered for integration into the distribution system. The proposed LC-based methodology is employed to determine the optimal location and rating of the DG units with the objective of minimizing real power losses.

The candidate buses are identified while imposing a maximum **DG penetration level of 50% of the total system load**. Based on the calculated LC values, the most favorable locations for DG installation in the standard IEEE 69-bus distribution system are identified as **Bus 21, Bus 61, and Bus 64**.

The proposed methodology results in significant reduction in real power losses under all three loading conditions. The resulting real power losses after optimal DG allocation are approximately **25 kW under light-load conditions, 71.7 kW under nominal-load conditions, and 210 kW under heavy-load conditions**.

These results demonstrate that the optimal placement and sizing of solar PV-based DG units can substantially reduce real power losses across a wide range of loading conditions. The identified buses provide favorable locations for DG integration because of their influence on feeder power flow and network loss characteristics.

Table 2. Results of comparison for case-I

Method	DG rating in kW	$V_{\min}$	Percentage RPL reduction
Bacterial foraging technique (BFT) [22]	2020	0.98	62.2
Modified BFT [22]	1870	0.97	63.2
Combined GA & PSO [23]	3000	0.99	64

CTLBO [34]	2622	0.98	70
MGSA [34]	2275	0.97	68
Proposed	2180	0.98	68.13

Table 2 justifies that percentage RPL reduction is remarkable of the projected technique as compared to any technique proposed in the literature. The minimum voltage profile after applying proposed technique is 0.9708 pu which is appreciably better as the DG size is 2.02 MW. The basis of comparison is total size of DG in MW, minimum bus voltage in per unit and percentage loss reduction.

Case II: Optimal Placement of Shunt Capacitor Units

In Case II, only **shunt capacitor units** are considered for integration into the distribution system with the primary objective of reducing real power losses (RPL) and improving the voltage profile. The proposed **Loss Constant (LC)-based methodology** is employed to determine the optimal location and rating of the capacitor units. The optimal capacitor allocation is obtained by evaluating the LC values at different candidate buses for progressively increasing capacitor ratings. The bus corresponding to the minimum LC value is identified as the most suitable location, while the corresponding capacitor rating is considered the optimal size. The performance of the proposed methodology is evaluated under the three considered loading conditions, namely **light load (50%), nominal load (100%), and heavy load (160%)**. The corresponding results, including the optimal locations, capacitor ratings, and real power losses, are presented in **Table 3**.

The results demonstrate that appropriate placement and sizing of shunt capacitor units can effectively reduce real power losses and enhance the operating performance of the distribution system under varying loading conditions.

Table 3. Results of Case II for 69 Bus System

Load level		50%	100 %	160 %
After capacitor allotment only	Rating of Capacitor (kVAr) with position	420 (61)	720 (61)	1550 (61)
		70 (21)	300 (21)	220 (21)
		160 (64)	420 (64)	620 (64)
	Entire size in kVAr	640	1440	2390
	P_{realloss} in kW	37	147	400
	V_{min} (pu)	0.97	0.931	0.89
	Power Loss reduction in %	30.6	34.66	37.8

Similarly, the best location of capacitor banks is found at bus no. 21, 61 and 64. The P_{realloss} is reduced to 147 kW from 225 kW at nominal load level after installation of 1440 kVAr capacitors. The percentage loss reduction at all three loading levels is remarkable.

Table 4: Results compared with other techniques for test system-I (CASE-II)

Parameters	Without Capacitor	DSA [27] (2012)	FPA [28] (2016)	Proposed
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Real Power loss (kW)	225	147	152	147
% Loss Reduction	-	34.66	32.44	34.66
$V_{\min}$ (pu)	0.909	0.93	0.93	0.93
Rating of Capacitor (Location) in kVAr	-	900 (61) 450 (15) 450 (60)	1450 (61)	720 (61) 230 (21) 350 (64)
Total size in kVAr	-	1800	1450	1440

The results after capacitor allocation are compared with latest optimization technique like DSA [33], FPA [34]. Table 4 exhibits the comparison of results for case II on various parameters such as real power loss, percentage loss reduction, minimum voltage profile, rating and size of capacitors with other proposed techniques in the literature. It is quite evident to say that percentage loss reduction for the proposed technique accounts for 34.66 % which is better than FPA [34] which yields 32.44% of RPL reduction. Analogously the voltage profile is also enhanced considerably after placement of capacitor units.

It is clearly reported from results reported above those losses reduces significantly with simultaneously decrease in capacitor size as compared to other contemporary approaches.

Table 5. Results of Case-III

Case	Items	Loading Levels		
		Light loading (50%)	Nominal loading (100%)	Heavy loading (160%)
Base Case	P_{loss} (kW)	51.61	225	652.47
	Reactive Power Loss (kVAr)	24.28	102.15	290.25
	$V_{\min}$ (pu)	0.956	0.9092	0.845
	DG's Size (kW)	600	2180	2700
Allocation of DG and Capacitor	Capacitor's size (kVAr)	660	1440	2340
	P_{loss} (kW)	8.60	7.7	38.9
	% Real Power Loss reduction	83.33%	96.5%	94%
	Reactive Power Loss	5.04	8.4	30.23
	% Reactive Power Loss reduction	79.4%	91.76%	89.5%
	$V_{\min}$ (pu)	0.985	0.99	0.974

Case III

Table 5 exhibits brief picture of results for concurrent allotment of DG and capacitor of 69 bus system. At nominal load level, a reduction of 94.05% is observed for real power losses in table 5.

Table 6. Comparison of Results for Case-III

Parameters	IMDE [30] (2016)	BBO [31] (2016)	ICA [32] (2016)	IPSO [33] (2017)	APSO [34] (2020)	MGSA[34] (2020)	Proposed
DG's Size in MW	2.21	2.32	1.83	1.81	2.230	2.293	2.180
Capacitor's size in MVar	1.3	2.7	1.3	2.1	1.590	1.76	1.440
RPL in kW	13.9	55	23.21	17.32	6.60	8.61	7.7
% Loss Reduction	93.85%	75.6%	89.68	92.3%	97%	96.17%	96.5%
$V_{\min}$ (pu)	0.99	0.97	0.972	0.9775	0.9873	0.99	0.99

The size identified by the proposed technique for both DG and capacitor are 2020 kW and 1440 kVar respectively as shown in table 6. It can be observed from the table; the size of DG units investigated by PSO, IMDE, BBO, ICA, IPSO techniques is more than the proposed technique for nearly same loss reduction.

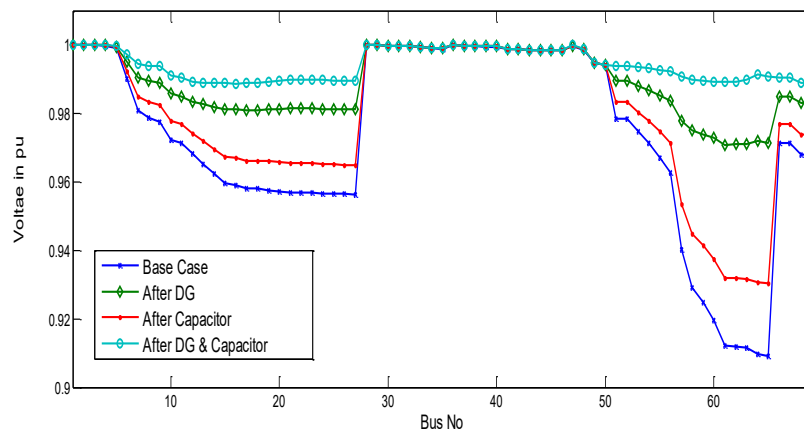


Figure 3. Voltage outline of 69 Bus system (Nominal Loading Level for Case-III)

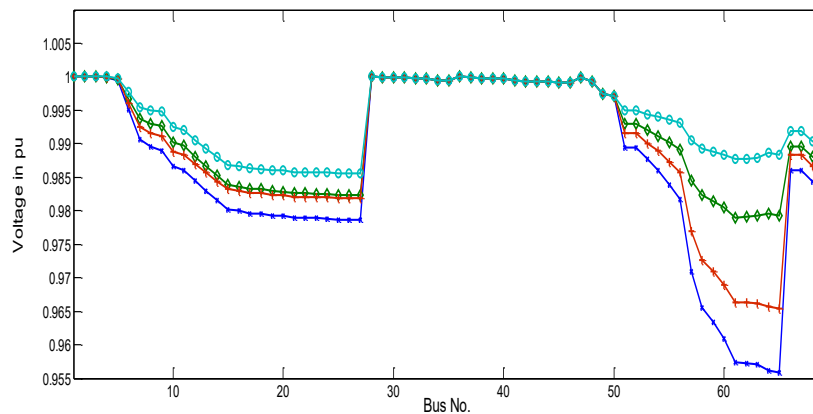


Figure 4. Voltage outline of 69 Bus systems (Light Loading Level for Case-III)

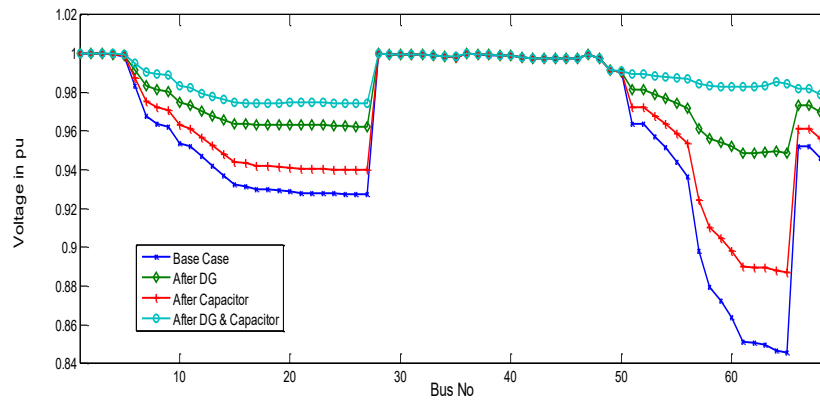


Figure 5. Voltage outline of 69 Bus systems (Heavy Loading Level for Case-III)

5. CONCLUSION

A novel, simple, and effective methodology has been proposed for minimizing real power losses (RPL) in distribution systems through the optimal allocation of Distributed Generation (DG) and shunt capacitor units. The primary objective of reducing distribution-system power losses is achieved by appropriately determining the location and rating of DG and capacitor units. A new mathematical formulation, termed the **Loss Constant (LC)**, is developed to identify suitable candidate buses and determine the corresponding ratings of DG and capacitor units. Unlike conventional iterative optimization techniques, the proposed LC-based approach provides a relatively simple computational procedure for determining optimal allocation. The effectiveness of the proposed methodology is evaluated on **two radial distribution systems (RDSs)**, comprising one standard test system and one practical Indian distribution network, under three different loading conditions: **light load (50%), nominal load (100%), and heavy load (160%)**. For the standard test system, the obtained results are compared with recently reported optimization techniques, and the proposed approach demonstrates competitive and optimal performance across the considered loading conditions.

The results further indicate that the concurrent placement of solar PV-based DG and capacitor units produces a substantial reduction in real power losses along with significant improvement in the voltage profile of the distribution network. The proposed LC-based methodology is computationally simple, flexible, and readily implementable, making it suitable for application to larger and more complex distribution systems.

Future work may focus on extending the proposed methodology to **unbalanced and three-phase distribution networks**, incorporating renewable DG intermittency, and considering additional practical constraints such as DG operating limits, capacitor switching costs, voltage stability, and annual operational costs.

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