Optimal Capacitor Placement for Minimizing Power Losses and Improve Voltage Profile on Distribution System of Dewathang Feeder

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Abstract

The strategic placement of capacitors in a distribution system is crucial for optimizing power quality, minimizing power losses, and ensuring voltage stability. Inadequate optimization of capacitor placement can result in increased power losses, voltage fluctuations, and suboptimal system performance. This paper focuses on determining the optimal location and size of capacitors in radial distribution systems to achieve minimal power loss and an improved voltage profile. A comprehensive analysis of metaheuristic algorithm techniques, such as Genetic Algorithms (GA) and Particle Swarm Optimization, is conducted to address the capacitor placement problem, with the goal of achieving the best solution. Detailed simulations using ETAP and MATLAB software demonstrate that the proposed method significantly improves voltage regulation. Additionally, the economic benefits of capacitor placement, including reduced energy costs and enhanced system reliability, are evaluated. Simulation studies on the outgoing feeders of the Nyellang substation (132/33/11 kV), particularly focusing on the Dewathang (33/11 kV) radial distribution network, show substantial reductions in power losses and notable improvements in voltage regulation. For electrical engineers, this research study provides a systematic and algorithm-driven methodology to manage power losses through optimizing the capacitor placement in transmission lines, enabling better decision-making in distribution network planning. Utility providers can also make use of these findings to achieve systems performance efficiency, minimize repair and maintenance cost, and reduce energy losses that enhance system reliability. It also assesses infrastructure upgradation and new energy efficient technology integration. The proposed approach offers a cost-effective and practical solution for optimizing the performance of distribution networks through optimal capacitor placement.

Keywords: *Capacitor placement, Power loss minimization, Genetic algorithm (GA), Particle swarm optimization, Voltage regulation*

1. INTRODUCTION

As distributed systems extend day by day being away from the generation station results in different losses which result in poor power factors and less useful power. Instability occurs in a power system when its voltages unmanageably change between load (Power demand) and generation (Power generation), due to outdated equipment, failure to control voltage and outage of controlled mechanism in the system (Izhar Ul Haq, 2023). The distribution systems are usually unbalanced and have a high R/X ratio compared to transmission systems, which results in the effect of high voltage drops and power losses in the distribution feeders.

Mostly loads are divided into two types that is industrial and domestic and these loads are inductive in nature and draw lagging current due to which power losses occurred in the power distribution system. To minimize the reactive impact of the load and power losses in the system, network reconfiguration, capacitor placement and superior optimization methods are used (M. J. Tahir, 2019). Capacitor provides leading current to the system which minimizes the lagging current impact of the load in the system. As a result, the power factor of the system can be improved, voltage profile enhanced and minimized the power losses. For simulation and analysis purposes, several optimization methods are used including modern metaheuristic techniques such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) to address these complex problems.

In this paper ETAP (Electrical Transient Analyzer Program) software is utilized to optimally locate the capacitor placement and its size in the distribution system of Dewathang feeder, aiming to reduce the power losses and improve voltage stability. The relevant literature done on capacitor placement and sizing to reduce the losses is discussed below.

Sushma Lohia, Om Prakash Mahela, and Sheesh Ram Ola discuss optimal capacitor placement in distribution systems using Genetic Algorithm (GA) for loss reduction and voltage improvement. Their literature review traces the evolution of capacitor placement methods, from heuristic techniques to advanced optimization approaches like Particle Swarm Optimization, fuzzy logic and genetic algorithm. Studies highlight economic benefits and voltage stability improvements, validated through IEEE test feeders. GA-based capacitor placement emerges as a reliable method for enhancing power transfer capacity and minimizing system losses in distribution networks.

In (Tamer M. Khalil, 2012) it presents a Selective Particle Swarm Optimization (SPSO) approach for optimizing capacitor placement and conductor sizing in radial distribution systems to minimize power losses and improve voltage profiles. Traditional methods address these issues separately, but SPSO combines them to maximize efficiency.

Recent advancements in distribution network optimization have highlighted the critical role of capacitor banks in improving voltage profiles and reducing power losses, particularly when integrated with distributed generation (DG). Ivković et al. (2024) investigated the optimal placement of capacitor banks in the medium-voltage (MV) feeder of the Gračanica distribution network, specifically analyzing the Grades feeder. Their study employed DigSILENT PowerFactory for system modeling and a genetic algorithm for optimization, demonstrating that strategic capacitor placement alongside DG integration (1–5 MVA) significantly enhances system efficiency.

The paper by M. J. Tahir et al. (2019) focuses on optimal capacitor placement in radial distribution systems using ETAP software and Genetic Algorithm (GA) to minimize power losses and enhance voltage profiles. It analyzes IEEE 4-bus, IEEE 33-bus, and NTDC 220KV grid systems, demonstrating improved efficiency and cost savings through optimized capacitor placement.

The paper "Optimal Capacitor Placement in Distribution Network for Loss Reduction and Voltage Profile Improvement" by Mirza Šarić and Jasna Hivziefendić presents a multi-objective genetic algorithm for optimal capacitor placement in medium-voltage distribution networks. It aims to reduce power losses and improve voltage profiles using fuzzy multi-criteria decision-making. Tested on a real system in Bosnia and Herzegovina, the approach benefits Distribution System Operators, customers, and regulators by enhancing efficiency and lowering costs. (Mirza Šarić, 2019).

Mahato et al. (2024) investigated the optimal placement of capacitors and solar PV-based distributed generation (DG) in radial distribution networks to minimize power losses and improve voltage profiles. Using a genetic algorithm (GA) and forward-backward sweep (FBS) method in MATLAB, the study analyzed the IEEE 33-bus system and a real-world 11 kV feeder in Nepal. Results demonstrated that combined capacitor-DG placement achieved the highest efficiency, reducing active power losses by 72.91% and reactive losses by 63.45% in the test system, while the real feeder saw an 82.72% loss reduction and 5.32% voltage improvement. The study highlighted the superiority of hybrid capacitor-DG coordination over standalone power system.

In (Simiran Kuwera, 2021), Sonwane and Kushare propose using Particle Swarm Optimization (PSO) for optimal capacitor placement in distribution systems to minimize losses and improve reliability. Their study applies PSO to the IEEE 30-bus system, optimizing capacitor placement based on reliability indices from IEEE standards 493 and 1366. The approach enhances power factors, voltage stability, and loss reduction, demonstrating PSO's advantages over traditional optimization techniques.

2. METHODOLOGY

ETAP software is used to identify the location of optimal capacitor placement through load flow analysis and MATLAB-based algorithms is employed to calculate the optimal size of the capacitor for each specified buses to enhance voltage profile, power factor correction, minimize installation and operational costs and reduction of power loses. Load flow result in ETAP provides necessary data like bus voltages and power flow in each branch, to determine where and how much capacitor capacity is needed to improve the system efficiency. Methodology for capacitor placement in Dewathang feeder starts with system modelling using single line diagram of whole Samdrup Jongkhar Dzongkha and accurate analysis of topology along with distances is done using ArcGIS earth. The system simulation in done in ETAP software for load flow analysis to study the initial state of the distribution system.

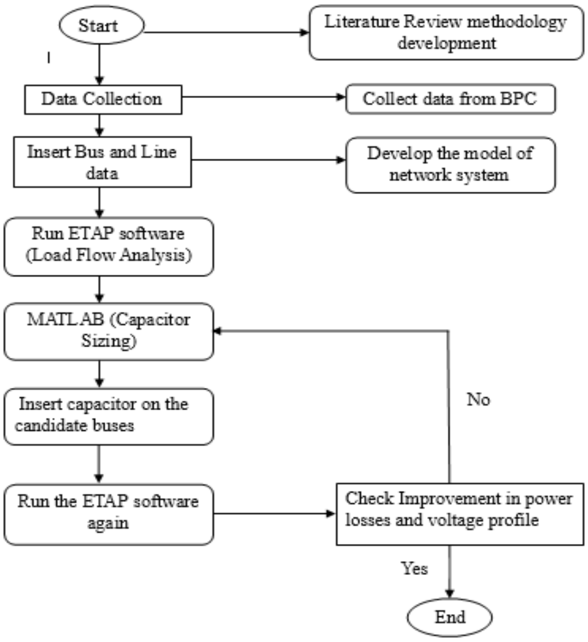


Fig. 1: *Flow chart of project procedure.*

The key parameters analysed are bus voltage, power losses and voltage profile of the system. By analysing the voltage limit and system losses helps to allocate the optimal placement of capacitor to decide the candidate buses that need system's reactive energy compensation, and its required sizing is done through MATLAB code. The IEEE 10BUS-Radial system is analysed as the sample since it is crucial for understanding power distribution efficiency, optimizing capacitor placement, and minimizing losses in electrical networks.

3. OPTIMIZATION TECHNIQUES

3.1 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a highly effective technique among population-based evolutionary algorithms. It draws inspiration from the collective behavior observed in animals like birds and fish. In PSO, a group of particles explores the search space by considering both their own best previous positions and either the best position found by the entire swarm or by nearby particles. This approach is well-suited for solving problems that are multi-dimensional, complex, nonlinear, and constrained. (Hossein Lotfi, 2016)

The velocity of a particle is updated by considering three factors: its current velocity, the influence of its own historically best position (PB), and the influence of the global best position (GB) found by the entire swarm. These influences are adjusted using specific weights, known as inertia and acceleration coefficients, along with random factors to encourage diverse exploration. The particle's position is then updated by adding the newly calculated velocity to its current position. This iterative process ensures that particles can effectively explore the search space, striking a balance between global exploration and local exploitation. (Tareq M. Shami, 2022)

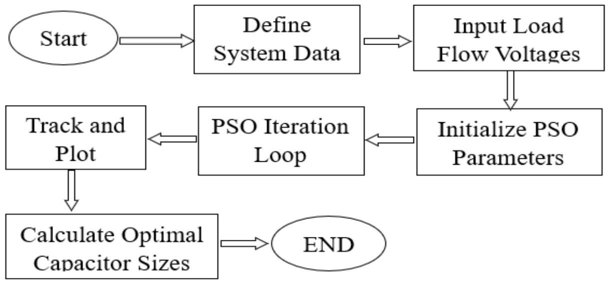


Fig.2: *Flowchart for Particle Swarm Optimization.*

4. FORMULAE

4.1 Particle Swarm Optimization

$$v_i(t+1) = \omega . v_i(t) + c_1 . r_1 (pBest_i - x_i(t)) + c_2 . r_2 (gBest_i - x_i(t))$$

$$x_i(t+1) = x_i(t) + v_i(t+1)$$

5. IEEE 10BUS-RADIAL SYSTEM

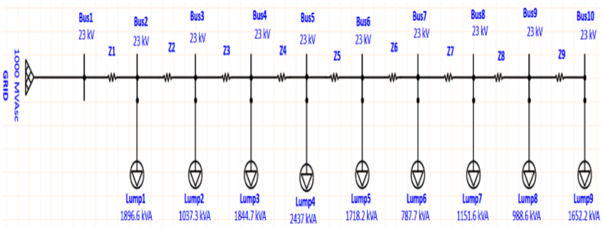


Fig 3*: Simulation of IEEE 10-BUS radial distribution system.*

The image illustrates a single-line diagram of an electrical power distribution system of IEEE 10-BUS radial distribution system in ETAP software. It includes ten buses, labeled Bus1 to Bus10, all at 23 kV, connected via impedance elements Z1 to Z9. Each bus has an attached lumped load, with power ratings ranging from approximately 787.7 kVA to 2437 kVA. The system starts with a grid with a short circuit capacity of 1000 MVA. It provides a simplified, visual representation of how electrical power is distributed across different buses in a network.

6. LOAD FLOW ANALYSIS OF IEEE 10-BUS RADIAL DISTRIBUTION SYSTEM

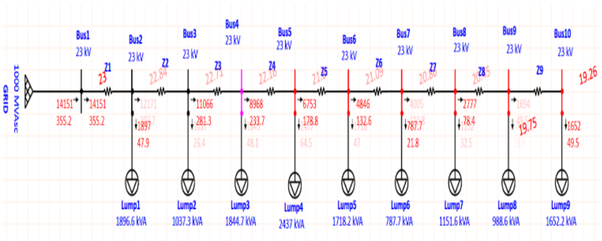
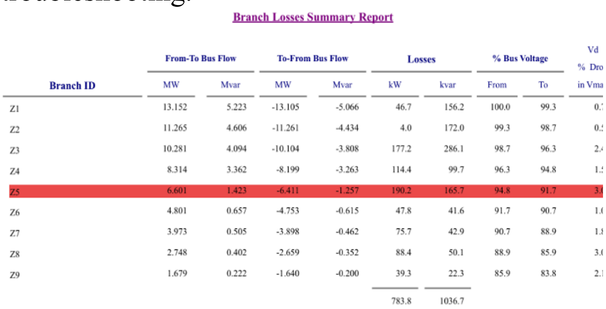


Fig. 4:*Load flow analysis of IEEE 10-BUS Radial distribution system without capacitors.*

The above SLD represents the movement of electrical power within a distribution system, illustrating how energy is transmitted from the source to various buses and loads through transmission lines. Its main purpose is to analyze power distribution and identify power losses guiding engineers in optimizing system design and operation assisting in fault detection and troubleshooting.



Branch Losses Summary Report

Branch ID	From-To Bus Flow MW	From-To Bus Flow Mvar	To-From Bus Flow MW	To-From Bus Flow Mvar	Losses kW	Losses kvar	% Bus Voltage From	% Bus Voltage To	Vd % Drop in Vmag
Z1	13.152	5.223	-13.105	-5.066	46.7	156.2	100.0	99.3	0.
Z2	11.265	4.606	-11.261	-4.434	4.0	172.0	99.3	98.7	0.
Z3	10.281	4.094	-10.104	-3.808	177.2	286.1	98.7	96.3	2.
Z4	8.314	3.362	-8.199	-3.263	114.4	99.7	96.3	94.8	1.
Z5	6.601	1.423	-6.411	-1.257	190.2	165.7	94.8	91.7	3.
Z6	4.801	0.657	-4.753	-0.615	47.8	41.6	91.7	90.7	1.
Z7	3.973	0.505	-3.898	-0.462	75.7	42.9	90.7	88.9	1.
Z8	2.748	0.402	-2.659	-0.352	88.4	50.1	88.9	85.9	3.
Z9	1.679	0.222	-1.640	-0.200	39.3	22.3	85.9	83.8	2.
					783.8	1036.7			

Fig. 5:*Losses on IEEE 10-BUS radial distribution system without capacitor.*

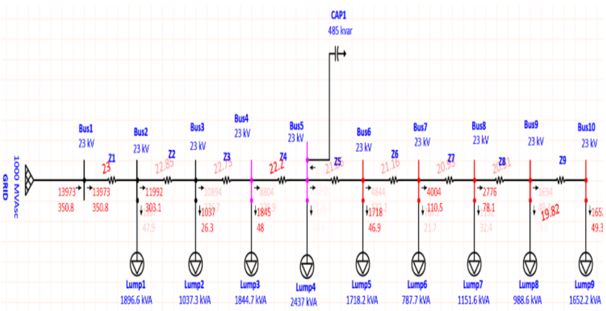
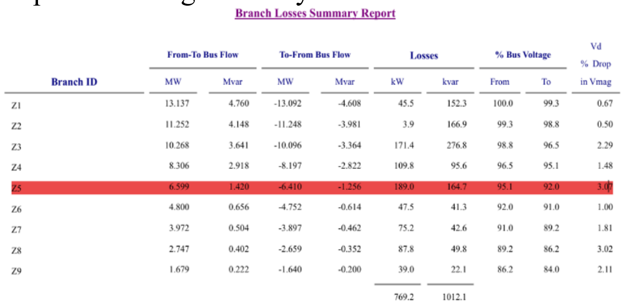


Fig. 6: *Load flow analysis of IEEE 10-BUS radial distribution system with Capacitor.*

Capacitor placement, as seen between Bus5 and Bus6, has improved system performance by providing reactive power compensation. This reduces the reactive power demand on the source, leading to minimized power losses and improved voltage stability at the buses.



Branch Losses Summary Report

Branch ID	From-To Bus Flow MW	From-To Bus Flow Mvar	To-From Bus Flow MW	To-From Bus Flow Mvar	Losses kW	Losses kvar	% Bus Voltage From	% Bus Voltage To	Vd % Drop in Vmag
Z1	13.137	4.760	-13.092	-4.608	45.5	152.3	100.0	99.3	0.67
Z2	11.252	4.148	-11.248	-3.981	3.9	166.9	99.3	98.8	0.50
Z3	10.268	3.641	-10.096	-3.364	171.4	276.8	98.8	96.5	2.29
Z4	8.306	2.918	-8.197	-2.822	109.8	95.6	96.5	95.1	1.48
Z5	6.599	1.420	-6.410	-1.256	189.0	164.7	95.1	92.0	3.07
Z6	4.800	0.656	-4.752	-0.614	47.5	41.3	92.0	91.0	1.00
Z7	3.972	0.504	-3.897	-0.462	75.2	42.6	91.0	89.2	1.81
Z8	2.747	0.402	-2.659	-0.352	87.8	49.8	89.2	86.2	3.02
Z9	1.679	0.222	-1.640	-0.200	39.0	22.1	86.2	84.0	2.11
					769.2	1012.1			

Fig. 7: Losses on IEEE 10-BUS radial distribution system with Capacitor

Table 1: *Comparison of Losses and Bus Voltage*

	IEEE 10 Bus without Capacitor				IEEE 10 Bus With Capacitor			
	Losses		% Bus Voltage		Losses		% Bus Voltage	
	kW	kvar	From	To	kW	kvar	From	To
Z 1	46.7	156.2	100	99.3	45.5	152.3	100	99.3
Z 2	4.0	172	99.3	98.7	3.9	166.9	99.3	98.8
Z 3	177.2	286.1	98.7	96.3	171.4	276.8	98.8	96.5
Z 4	114.4	99.7	96.3	94.8	109.8	95.6	96.5	95.1
Z 5	190.2	165.7	94.8	91.7	189	164.7	95.1	92
Z 6	47.8	41.6	91.7	90.7	47.5	41.3	92	91
Z 7	75.7	42.9	90.7	88.9	75.2	42.6	91	89.2
Z 8	88.4	50.1	88.9	85.9	87.8	49.8	89.2	86.2
Z 9	39.3	22.3	85.9	83.8	39	22.1	86.2	84
Total	783.8	1036.7			769.2	1012.1		

The comparison of the IEEE 10-bus system with and without capacitors shows that capacitor installation effectively reduces power losses and improves voltage profiles. Total active power loss decreased from 783.8 kW to 769.2 kW, and reactive power loss dropped from 1036.7 kVAR to 1012.1 kVAR. Additionally, voltage levels of weaker buses have been improved. Overall, the use of capacitors enhances system efficiency and stability by minimizing losses and boosting voltage performance.

Table 2: *Location and size of optimal Capacitors in IEEE 10-Bus system*

Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10
kVAR	0	0	0	400	1000	0	1000	0	1000

Table 3: *Comparison of Total Power losses in IEEE 10-Bus system*

Power Loses	Active Power (kW)	Reactive Power (kVAR)
Without Capacitor	783.8	1036.7
With Capacitor	769.2	1012.1

7. DATA COMPUTATION FOR NETWORK MODEL DEVELOPMENT

The execution of load flow analysis through software requires developing accurate models for any electrical network first. The analysis requires gathering essential information about transformer load requirements and line actual lengths. The correct values of these measurements allow transformer percentage loading calculations and line electrical parameter determination including resistance and reactance values.

Table 4: *Transformer data for the 11 kV Dewathang Distribution Feeder.*

Sl. No	Feeder code	DT Code	DT Name and Location	Capacity	PV	SV	Impedance	Loading(%)
1	SJE30	SJE30T1	Petrol Pump	125	11	0.433	4.40	61%
2	SJE30	SJE30T2	RBA Colony	250	11	0.400	4.00	51%
3	SJE30	SJE30T3	Old JNEC	315	11	0.433	4.07	28%
4	SJE30	SJE30T4	JNEC CS	500	11	0.415	4.20	24%
5	SJE30	SJE30T5	Reshore	63	11	0.420	4.20	99%
6	SJE30	SJE30T6	Bangtsho	250	11	0.415	4.00	30%
7	SJE30	SJE30T7	Khesangteri	315	11	0.415	4.00	34%
8	SJE30	SJE30T8	Kopoor	100	11	0.433	4.40	23%
9	SJE30	SJE30T9	Rekhay	100	11	0.433	4.00	39%
10	SJE30	SJE30T10	BT Tower	25	11	0.415	4.00	31%
11	SJE30	SJE30T11	Garpowoong	250	11	0.415	4.00	3.00%
12	SJE30	SJE30T12	Dewathang Baazar	500	11	0.415	4.00	22%
13	SJE30	SJE30T13	Chenari(Gayzor)	125	11	0.415	4.00	15%
14	SJE30	SJE30T14	Woongchilo	25	11	0.415	4.00	90%
15	SJE30	SJE30T15	Sip	125	11	0.415	4.00	9%
16	SJE30	SJE30T16	JNEC Thangzor	250	11	0.415	4.00	13%
17	SJE30	SJE30T17	Dewathang Hospital	2000	11	0.415	5.00	10%
18	SJE60	SJE60T12	Borvilla	63	11	0.433	4.14	13%
19	SJE60	SJE60T13	TPO Colony (10 KM)	16	11	0.415	4.00	85%
20	SJE60	SJE60T14	Dungsam Academy	250	11	0.415	4.00	58%
21	SJE60	SJE60T15	Gayzor(12KM)	63	11	0.415	4.00	7%

***Table 5**: Bus and Line Parameters for 11kV Dewathang Distribution Feeder.*

Sl. No	Line	Size(sq.mm)	From Bus	To Bus	Length(m)	R (ohm)	X(ohm)
1	line 1	50	Bus 9	Bus 10	1516	1.2152	0.5714
3	line 2	100	Bus 0	Bus 9	1000	0.4054	0.3554
4	line 3	50	Bus 10	Bus 22	698	0.5595	0.2631
5	line 4	50	Bus 11	Bus 289	708.3	0.5678	0.267
6	line 5	50	Bus 10	Bus 12	622	0.4986	0.2344
7	line 6	50	Bus 14	Bus 11	95.2	0.0763	0.0359
8	line 7	50	Bus 12	Bus 14	129	0.1034	0.0486
9	line 8	50	Bus 19	Bus 14	500	0.4008	0.1885
10	line 9	50	Bus 12	Bus 15	44	0.0353	0.0166
11	line 12	50	Bus 11	Bus 21	2605	0.2691	0.2359
12	line 13	50	Bus 25	Bus 291	147.6	0.0592	0.0278
13	line 14	100	Bus 9	Bus 13	663.7	0.262	0.2296
14	line 15	50	Bus 42	Bus 43	149.8	0.0552	0.026
15	line 16	50	Bus 290	Bus 13	108.5	0.0289	0.0136
16	line18	100	Bus 13	Bus 16	392	0.1542	0.1351
17	line 19	100	Bus 42	Bus 25	273	0.1073	0.0941
18	line 20	50	Bus 16	Bus 24	13.3	0.0043	0.002
19	line 21	100	Bus 25	Bus 27	1153	0.455	0.3988
20	line 22	100	Bus 16	Bus 26	454.7	0.1796	0.1574
21	line 23	100	Bus 27	Bus 28	720.9	0.2845	0.2493
22	line 24	100	Bus 26	Bus 29	258	0.1018	0.0894
23	line 25	50	Bus 28	Bus 47	241	0.0894	0.042
24	line 26	100	Bus 29	Bus 31	110.2	0.0435	0.0383
25	line 28	50	Bus 32	Bus 34	13.3	0.0043	0.002
26	line 30	50	Bus 31	Bus 34	223.1	0.0827	0.0389
27	line 32	50	Bus 36	Bus 34	592.7	0.2198	0.1034
28	line 34	50	Bus 37	Bus 36	100.7	0.0373	0.0175
29	line 37	50	Bus 40	Bus 473	1102	0.4086	0.1922
30	line 39	100	Bus 31	Bus 42	1084	0.4278	0.3746
31	line 41	50	Bus 27	Bus 46	147.6	0.0547	0.0257
32	line 337	50	Bus 473	Bus 36	222.4	0.0825	0.0388
33	line 497	50	Bus 473	Bus 1	100	0.0371	0.0174

7.1 Modelling of 11kV Dewathang Distribution Network

The model represents the single-line diagram of the 11 kV Dewathang distribution network, developed using ETAP software. It consists of one 132 kV main bus, one 33 kV bus, and thirty-four 11 kV buses, interconnected by thirty-three distribution lines using DOG (100 mm²) and RABBIT (50 mm²) conductors. The network includes an injection substation, with its bus designated as the Swing (Slack) bus, while the remaining thirty-four buses are configured as load (PQ) buses.

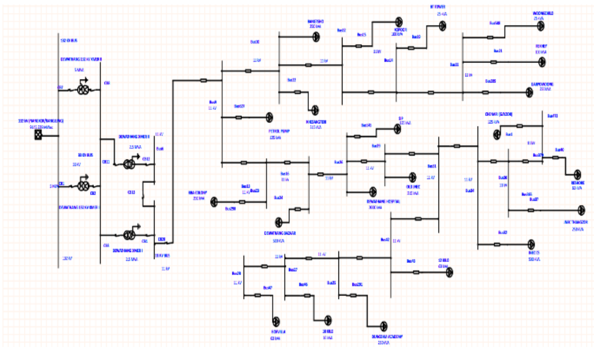


Fig. 8: *Single Line Diagram of 11KV Dewathang Distribution Network.*

8. RESULTS AND DISCUSSION

The input parameters consisting of power sources and transmission lines, transformers and connected loads allow Load Flow Analysis (LFA) to output results including voltage magnitudes and real and reactive power measurements and current flow and power loss calculations. The analysis utilizes an Adaptive Newton-Raphson method to investigate distribution network load flow conditions.

8.1 Pre-Compensation Load Flow Analysis

The load flow studies carried out on the distribution system revealed that there were marginal voltage violations at all the buses. Buses 25, 27, 28, 34, 36, and 473 were found to have lower voltage levels, while the remaining 28 buses exhibited slightly higher voltage levels.

Out of the total generated power of 1439 kW, approximately 43.80 kW were calculated as active power losses across the distribution system and transformer. This is illustrated in Figure 3 below.

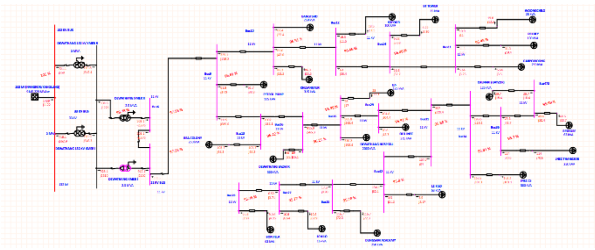
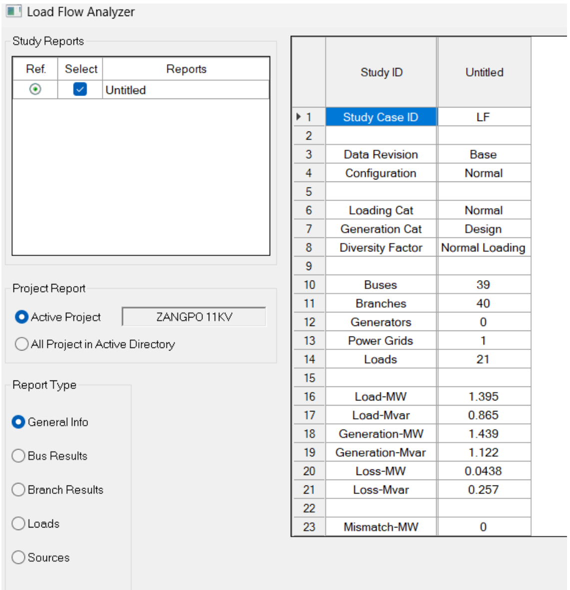


Fig. 9: *Load Flow Results of the 11kV Dewathang Distribution Feeder as Displayed in ETAP*



	Study ID	Untitled
1	Study Case ID	LF
2		
3	Data Revision	Base
4	Configuration	Normal
5		
6	Loading Cat	Normal
7	Generation Cat	Design
8	Diversity Factor	Normal Loading
9		
10	Buses	39
11	Branches	40
12	Generators	0
13	Power Grids	1
14	Loads	21
15		
16	Load-MW	1.395
17	Load-Mvar	0.865
18	Generation-MW	1.439
19	Generation-Mvar	1.122
20	Loss-MW	0.0438
21	Loss-Mvar	0.257
22		
23	Mismatch-MW	0

Fig. 10: *ETAP Load Flow Result Analyzer Prior to Compensation.*

8.2 Compensation Using Optimal Capacitor Placement via the PSO Algorithm

Particle Swarm Optimization (PSO) algorithm was employed to identify weak buses within the distribution network for the purpose of optimizing capacitor placement. The algorithm analyzed voltage profiles across all buses to detect locations where voltage levels fell significantly below the specified thresholds. These weak buses were then selected as candidates for reactive power compensation. Through iterative optimization, the PSO algorithm determined the optimal locations and appropriate sizes of capacitors to reduce power losses and enhance voltage stability throughout the network. Based on the analysis, PSO identified Bus 27 and Bus 473 as weak buses and recommended the injection of one 300 KVAR capacitor at each of these locations.

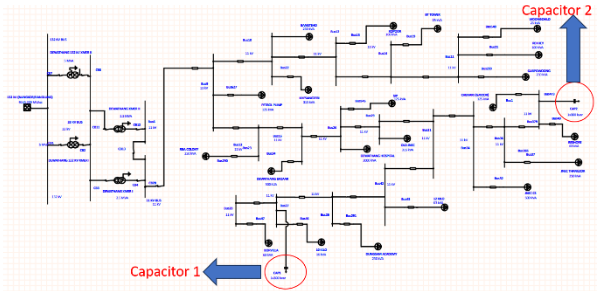


Fig. 11: *Updated ETAP Model of the 11 kV Dewathang Network Featuring Capacitor Integration.*

Load flow studies were carried out on the remodeled, compensated network to verify the improvements in system performance. The results of the load flow analysis are displayed in the ETAP view below.

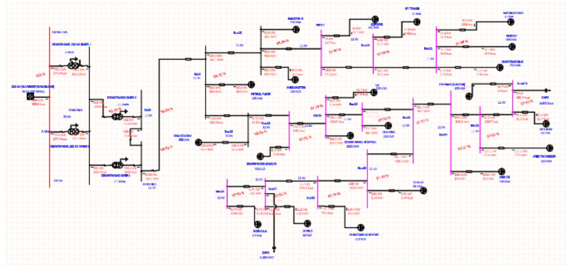


Fig. 12: *ETAP Load Flow Results after Capacitor Integration.*

Load flow studies were conducted to revalidate the remodeled 11 kV Dewathang distribution network. The analysis shows that Buses 25, 27, 28, 34, 36, and 473 which previously experiencing lower voltage levels, showed noticeable improvements post-compensation. The voltage level improvements at these buses were as follows: Bus 25: 1.689%, Bus 27: 1.688%, Bus 28: 1.690%, Bus 34: 1.710%, Bus 36: 1.767%, and Bus 473: 1.788%.

Similarly, the power factor also improved across the same buses: Bus 25: 0.34%, Bus 27: 0.35%, Bus 28: 0.45%, Bus 34: 7.03%, Bus 36: 0.45%, and Bus 473: 0.34%. Additionally, the total active and reactive power losses across the distribution lines and transformers were reduced by 9.36% and 7.4%, respectively. The Distribution system achieved its improvements in voltage profiles and power factor and loss reduction because of reactive power compensation achieved through optimally located capacitor banks. The leading reactive power injected into the network by the capacitor banks effectively offset the lagging reactive power caused by inductive loads. This compensation minimized the excessive lagging current, thereby reducing losses within the distribution lines and transformers. The total active power losses stand at 39.7 kW according to the ETAP Load Flow Result Analyzer results which are shown in Figure 13.

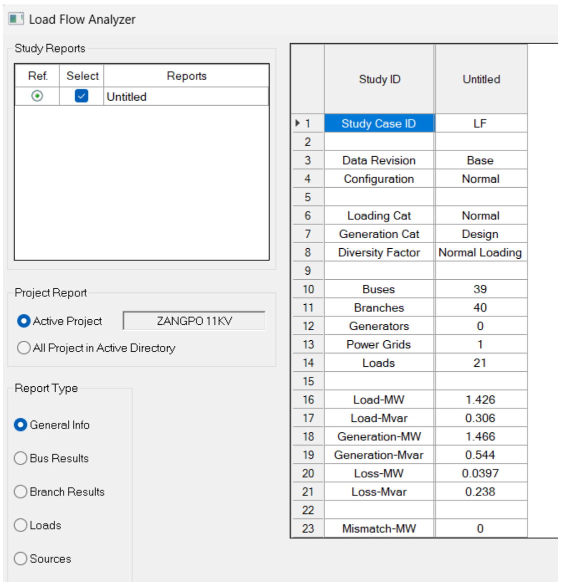


Fig. 13: ETAP Load Flow Result Analyzer after Compensation.

Table 6: Location and size of Capacitors in Candidate Buses of 11kV Dewathang.

Bus	Bus 20	Bus 21	Bus 23	Bus 25	Bus 28	Bus 30	Bus 32	Bus 34	Bus 9
kVAR	0	0	0	600	400	0	200	0	150

Table 7: Comparison of total Power losses in 11kV Dewathang distribution system.

Power losses/Status	Active Power (kW)	Reactive Power (kVAR)
without Capacitor	51.5	282.9
With Capacitor	43.3	213.2

8.3 Comparison of Bus and Line Parameters

The bus and branch parameters before and after placement of capacitor was compared to ascertain the extent of improvement. Table 4 illustrate the difference in Total Active and Total Reactive power, while Fig 14, Fig 15, and Fig 16 shows the respective graphical illustrations.

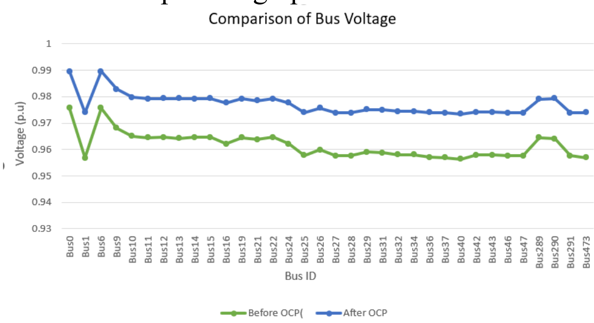


Fig. 14: Comparison of Bus Voltages prior and post Compensation.

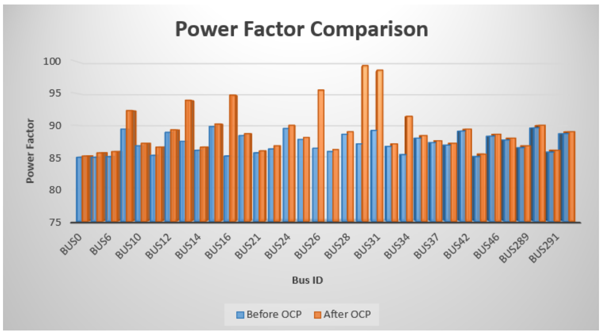


Fig. 15: Comparison of Power Factor prior and post Compensation.

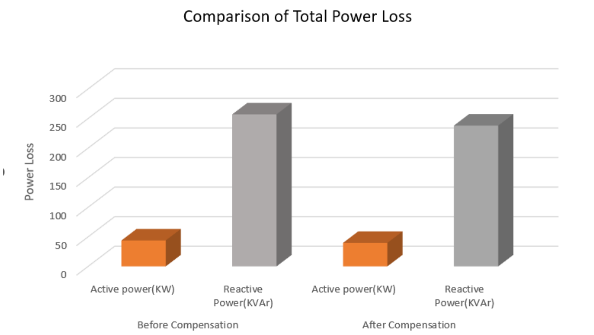


Fig. 16: Comparison of Total Power losses.

The bar chart depicts a reduction in both active and reactive power losses after compensation. This indicates the effectiveness of the compensation method in improving the efficiency of the power distribution system.

Table 2: Comparison of Bus Power Losses prior and post Compensation.

Before Compensation		After Compensation	
Active power(KW)	Reactive Power(KVAr)	Active power(KW)	Reactive Power(KVAr)
43.8	257	39.7	238

Although the collected data reflects varying load conditions, the simulation and analysis were conducted using data from a specific month, effectively representing a fixed load scenario under standard conditions. As we know in practice, load conditions vary significantly throughout the day and across seasons, influenced by factors such as residential consumption patterns, industrial demand, and climatic conditions. These fluctuations can affect the reactive power requirements of the network, potentially leading to suboptimal performance of fixed capacitors.

For instance, during low-load periods, excessive reactive power injections from capacitors could result in overvoltage issues. Similarly, during peak demand or extreme weather conditions, the initially optimized capacitor placement may not be able to provide required voltage support, increasing losses and reduce system reliability. Therefore, the effectiveness of the capacitor placement strategy may diminish over time unless adaptive or dynamic compensation methods, such as switched capacitor banks or advanced control schemes, are integrated into the system. Addressing these limitations in future work can further enhance the robustness and applicability of the proposed methodology.

9. CONCLUSION

Nowadays, there are several effective methods for determining the optimal size and location of capacitors in radial distribution systems. These methods primarily aim to reduce total power losses (kW), improve voltage profiles, and enhance the power factor (PF). Among the various available approaches, we chose ETAP software to model the 11kV Dewathang distribution feeder network and performed load flow analysis using the Adaptive Newton-Raphson method in ETAP, which provided voltage levels across different branches, along with power factor values and associated losses. Additionally, we implemented the Particle Swarm Optimization (PSO) algorithm in MATLAB to determine the optimal sizing and placement of capacitor banks.

After implementing pre-mentioned techniques and software, we were able to reduce power losses to a certain extent and consecutively improve voltage profile and power factor of different branches to some degree. Upon completion of the research work we were able to achieve our aims and objective of minimizing Distribution Line Losses by Optimal Capacitor Placement and improve voltage profiles on Dewathang Distribution system network.

For future studies, researchers can investigate the performance of various capacitor technologies, such as smart capacitors, switched capacitor banks, or static synchronous compensators (STATCOMs) and other FACTS devices, demand side management (DSM), and VAR optimization techniques. These devices and techniques can dynamically adjust reactive power compensation in response to real-time load variations, potentially offering improved performance over fixed capacitors used in the current study.

As Bhutan continues to develop its renewable energy sector, particularly in solar and wind, future research could examine how optimal capacitor placement strategies interact with distributed renewable energy generation. The intermittent nature of renewables introduces additional voltage variability, making reactive power management even more critical.

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