

Power Compensation of Shunt Capacitors for Hybrid Multi-Source Systems: Improving Voltage Stability and Reducing Losses

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Abstract. Radial distribution systems provide inexpensive and straightforward interfaces between the power grid and customers. However, these systems frequently experience significant power losses and voltage instability, particularly at buses farther from substations due to insufficient reactive power support. Optimal capacitor placement and sizing are therefore critical. This paper presents a genetic algorithm (GA) approach to solve the capacitor placement problem, aiming to reduce power losses and enhance both voltage profiles and voltage stability. Voltage stability is defined as the ability of the system to maintain acceptable bus voltages under varying load conditions, and the proposed method demonstrates improvement by restoring voltages within $\pm 5\%$ of nominal limits and increasing stability margins. Extensive case studies on IEEE 25, 35, 50, 70, and 120 bus systems confirm the effectiveness of the GA-based method, showing robust performance across different levels of distribution system complexity. Results highlight significant reductions in losses and measurable improvements in voltage stability, thereby enhancing the efficiency and reliability of radial distribution systems.

1. Introduction

Efficient electricity distribution from generation sources to consumers is essential for maintaining reliability and reducing energy losses in modern power networks [1]. Radial distribution systems, however, often suffer from high losses and voltage instability, particularly due to the widespread use of inductive loads in residential and industrial sectors. These loads draw reactive power, leading to trailing currents, increased losses, and voltage drops across the network [2]. Beyond simple voltage reduction, insufficient reactive power support can compromise voltage stability, defined as the ability of a power system to maintain acceptable bus voltages under varying load conditions and disturbances [3]. Ensuring voltage stability is therefore a critical requirement for dependable operation.

Several strategies have been proposed to mitigate these issues, including network reconfiguration, capacitor placement, and advanced optimization techniques [4]. Shunt capacitors, in particular, supply leading current that compensates reactive demand, thereby improving voltage profiles, reducing losses, and enhancing system stability [5]. However, the effectiveness of capacitor placement depends strongly on optimal sizing and location. Traditional methods—ranging from heuristics to gradient search and dynamic programming—often rely on simplifying assumptions that limit their accuracy under dynamic load conditions [6]. Moreover, many approaches emphasize loss reduction or voltage regulation without explicitly demonstrating improvements in voltage stability.

Genetic algorithms (GA) have emerged as a powerful alternative, offering near-global optimization with relatively low computational effort [7]. In this paper, we propose a GA-based method for optimal capacitor placement that simultaneously reduces power losses and enhances voltage stability. The contribution of this work lies in explicitly demonstrating stability improvement: bus voltages are restored within $\pm 5\%$ of nominal limits, and stability margins are increased compared to conventional approaches. Case studies on IEEE 25, 35, 50, 70, and 120 bus systems validate the robustness and efficiency of the proposed method across different levels of distribution system complexity. Compared to other techniques, the GA-based approach provides a faster and more cost-effective solution for improving both efficiency and reliability in radial distribution systems.

The remainder of this paper is organized as follows: Section 2 reviews shunt capacitor voltage control techniques. Section 3 describes the case studies used to validate the methodology. Sections 4 and 5 present results and discussion, while Section 6 concludes with key findings.

2. Literature Review

Genetic algorithms (GA), inspired by biological evolution, have been widely applied in power system optimization due to their ability to handle nonlinear search spaces and provide near-global solutions with relatively low computational effort [9–13]. A GA begins with a random population of candidate solutions, iteratively applying crossover and mutation operators to explore the search space, while fitness evaluation guides the selection of superior candidates [12].

In the context of capacitor placement, the optimization problem is formulated to minimize active power losses and enhance voltage stability, with the objective function expressed as $F = P_{\text{loss}} + \alpha \cdot \Delta V$, where P_{loss} represents system losses, ΔV denotes voltage deviation or stability margin, and α is a weighting factor. The decision variables are capacitor sizes and bus locations, subject to operational constraints such as bus voltage limits ($0.95 \leq V_i \leq 1.05$ p.u.), capacitor size bounds ($Q_{c,\text{min}} \leq Q_c \leq Q_{c,\text{max}}$), and power balance equations derived from load flow analysis.

The GA procedure involves initializing a random population of capacitor configurations, evaluating each candidate's fitness using the defined objective function, selecting superior solutions, applying crossover to generate offspring, introducing mutations to maintain diversity, and iterating until convergence or a maximum number of generations is reached. The best solution is then validated through load flow analysis to confirm improvements in voltage profiles and reductions in losses.

While commercial tools such as ETAP provide a practical platform for numerical simulation, this work emphasizes the explicit scientific formulation of the optimization problem, ensuring transparency and reproducibility. By integrating evolutionary algorithms with rigorous power system analysis, capacitor placement can be optimized to achieve both loss reduction and voltage stability improvement, thereby addressing limitations in prior studies that focused solely on voltage regulation or loss minimization [14–15].

3. Case Studies

Five power systems—IEEE 25, IEEE 35, IEEE 50, IEEE 70, and IEEE 120 bus systems real-time microgrid stations—are used in this section to solve the size and the placement problems of the shunt capacitor banks, which includes a loss reduction objective function and system voltage stability that complies with IEEE standards (5% below or above the rated voltage). ETAP software had been used to model each and every case study. The most comprehensive analysis platform available is ETAP. As a note, the following simulation runs during a particular time of day when loads and weather conditions are applied.

A. IEEE 25 Bus System

The selected system consists of the following elements:

1. Five synchronous generator each has a rating of 625 kVA with a pf of 0.8.
2. 396 PV panels each have a rating of 550W.
3. Inverters: 2 inverters each have a rating of 110 kW.
4. Loads: the total load varies up to 0.39MVA, and this load is formed by 20% of its rating being dynamic and 80% being static.

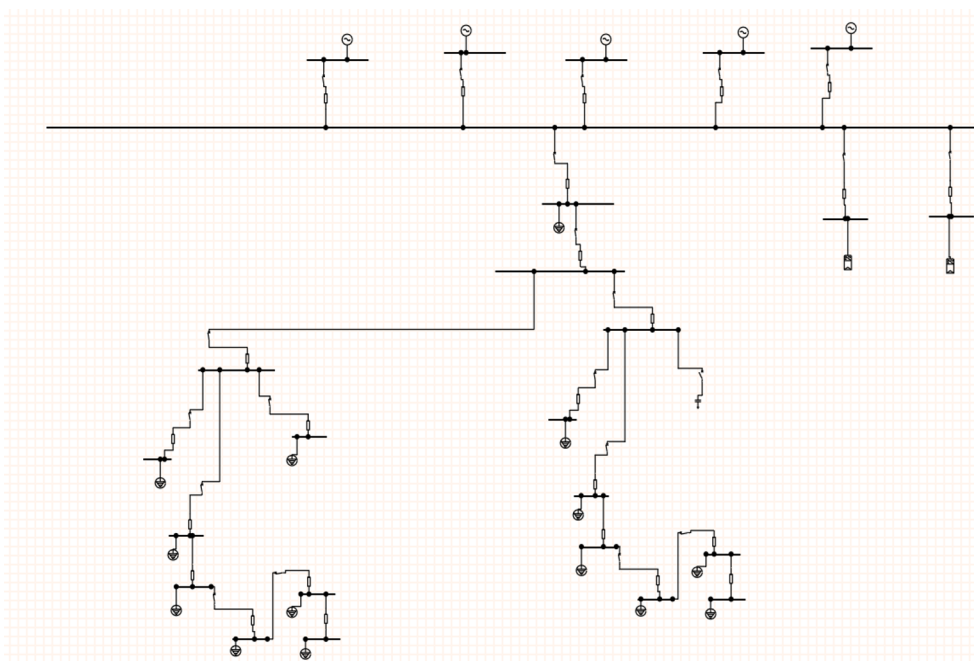


Fig. 1. shows the system diagram of the IEEE 25 bus.

B. IEEE 35 Bus System

The selected system consists of the following elements:

1. Five synchronous generator each has a rating of 625 kVA with a pf of 0.8.
2. 726 PV panels each have a rating of 550W.
3. Inverters: 3 inverters each have a rating of 110 kW, 1 inverter has a rating of 12 kW, and 1 inverter has a rating of 80 kW.
4. Loads: the total load varies up to 0.81MVA, and this load is formed by 20% of its rating being dynamic and 80% being static.

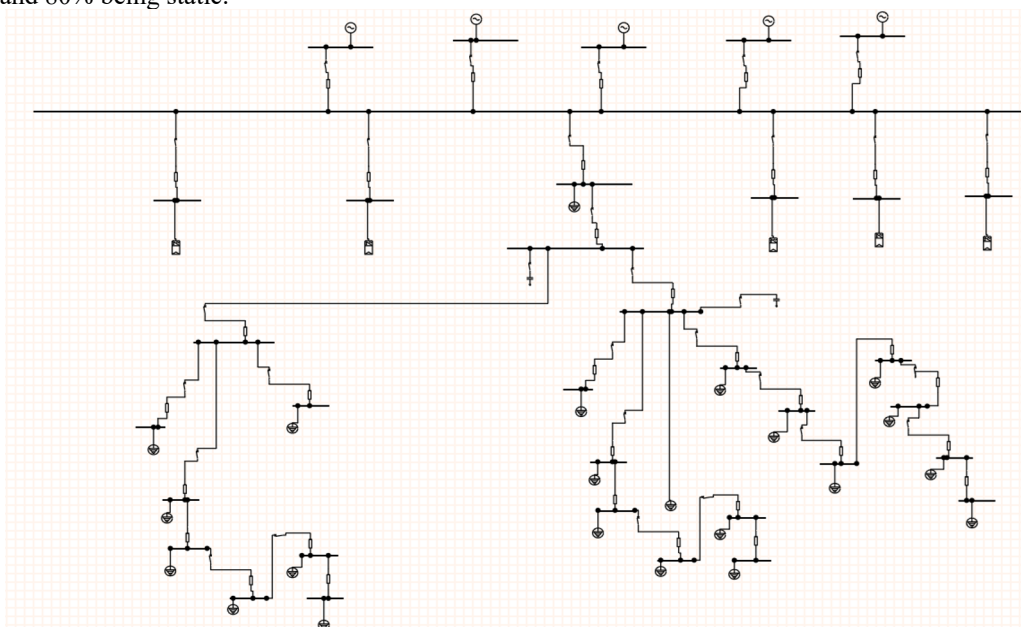


Fig. 2. shows the system diagram of the IEEE 35 bus.

C. IEEE 50 Bus System

The selected system consists of the following elements:

1. Ten synchronous generator each has a rating of 625 kVA with a pf of 0.8.
2. 792 PV panels each have a rating of 550W.

3. Inverters: 4 inverters each have a rating of 110 kW.
4. Loads: the total load varies up to 0.78MVA, and this load is formed by 20% of its rating being dynamic and 80% being static.

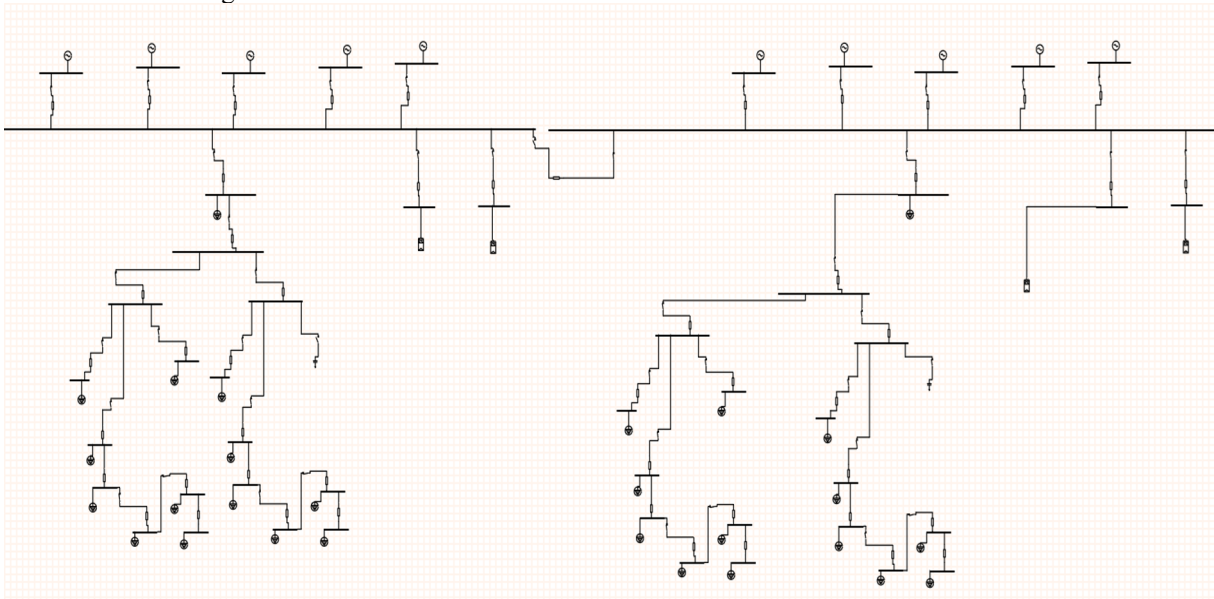


Fig. 3. shows the system diagram of the IEEE 50 bus.

D. IEEE 70 Bus System

The selected system consists of the following elements:

1. Ten synchronous generator each has a rating of 625 kVA with a pf of 0.8.
2. 1,452 PV panels each have a rating of 550W.
3. Inverters: 6 inverters each have a rating of 110 kW, 2 inverters each has a rating of 12 kW, and 2 inverters each has a rating of 80 kW.
4. Loads: the total load varies up to 1.62MVA, and this load is formed by 20% of its rating being dynamic and 80% being static.

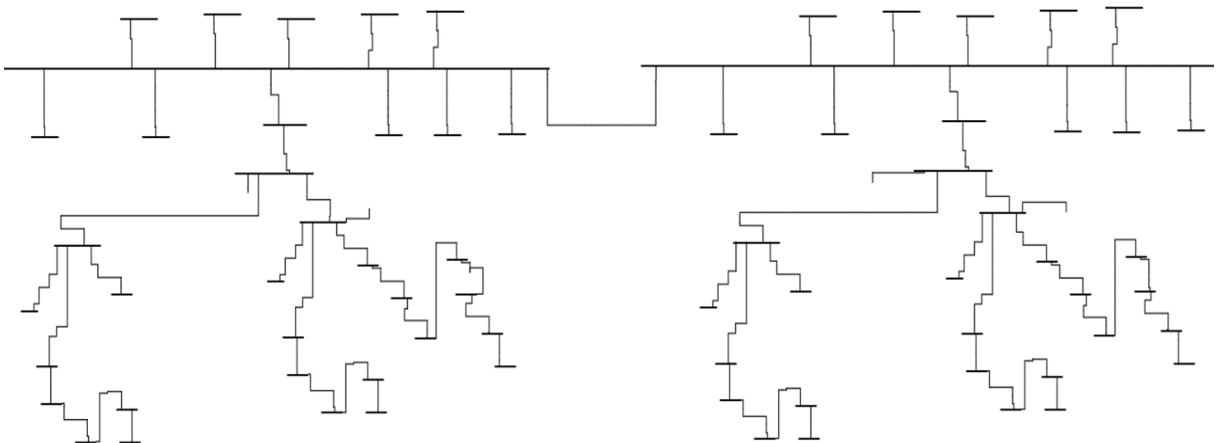


Fig. 4. shows the system diagram of the IEEE 70 bus.

E. IEEE 120 Bus System

The selected system consists of the following elements:

1. Twenty synchronous generator each has a rating of 625 kVA with a pf of 0.8.
2. 2,244 PV panels each have a rating of 550W.
3. Inverters: 10 inverters each have a rating of 110 kW, 2 inverters each has a rating of 12 kW, and 2 inverters each has a rating of 80 kW.
4. Loads: the total load varies up to 2.4MVA, and this load is formed by 20% of its rating being dynamic and 80% being static.

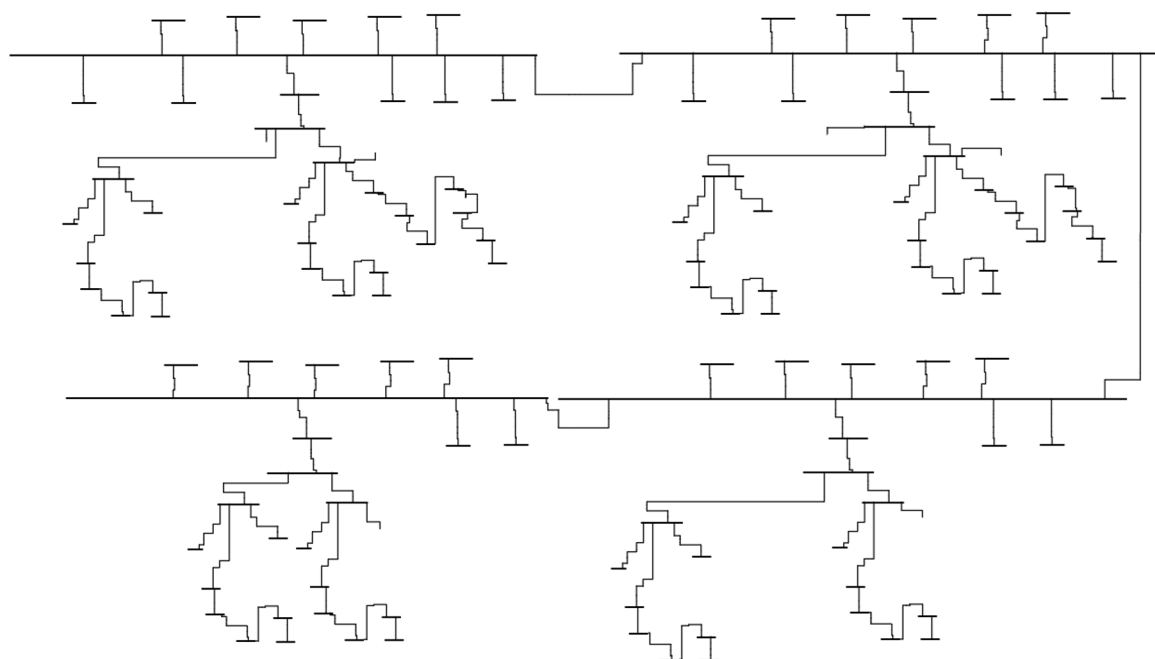


Fig. 5. shows the system diagram of the IEEE 120 bus.

4. Results

This section presents the performance of the proposed GA-based capacitor placement method across IEEE 25, 35, 50, 70, and 120 bus systems. Results are reported in terms of bus voltage profiles before and after compensation, demonstrating both loss reduction and voltage stability improvement. In each case, the GA identified optimal capacitor sizes and locations that restored bus voltages within $\pm 5\%$ of nominal limits.

A. Results of IEEE 25 Bus System

For the IEEE 25 bus system, the minimum bus voltage before compensation was 344 V (0.88 p.u.), which improved to 383 V (1.01 p.u.) after placing a 300 kVAR capacitor at bus #11. Table 1 shows the detailed bus voltage results.

Table 1. BUS VOLTAGE RESULTS OF IEEE 25 BUS SYSTEM

Bus Number	Voltage Before SC (V)	Bus Voltage After SC (V)
1	380	380
2	380	380
3	380	380
4	380	380
5	380	380
6	377	380
7	362	377
8	378	381
9	378	381
10	349	376
11	344	383
12	342	381
13	341	380
14	339	378
15	338	377
16	338	376
17	337	376
18	342	369
19	340	368
20	339	366
21	337	365
22	336	364
23	336	363
24	335	363
25	340	368

B. Results of IEEE 35 Bus System

For the IEEE 35 bus system, capacitors of 300 kVAR and 400 kVAR placed at buses #13 and #14 raised the minimum voltage from 288 V (0.76 p.u.) to 376 V (0.99 p.u.). Table 2 shows the detailed bus voltage results.

Table 2. BUS VOLTAGE RESULTS OF IEEE 35 BUS SYSTEM

Bus Number	Voltage Before SC (V)	Bus Voltage After SC (V)
1	380	380
2	380	380
3	380	380
4	380	380
5	380	380
6	374	380
7	374	380
8	374	380
9	339	377
10	375	381
11	375	381
12	375	381
13	308	378
14	288	376
15	286	374
16	284	373
17	282	371
18	281	370
19	280	370
20	280	369
21	282	371
22	279	369
23	277	367
24	275	366
25	274	365
26	273	364
27	273	364
28	301	371
29	299	369
30	299	369
31	297	368
32	295	367
33	294	366
34	293	365
35	293	364

C. Results of IEEE 50 Bus System

The voltage levels of each bus in the IEEE 50 bus system before and after applying the Capacitor Placement technique are shown in Table 3 below. This case is formed by connecting two IEEE 25 bus system that is mentioned in part A in this section. The suitable capacitor banks for this system are 300kVAR (located at bus #11) and 300kVAR (located at bus #22).

Table 3. BUS VOLTAGE RESULTS OF IEEE 50 BUS SYSTEM

Bus Number	Voltage Before SC (V)	Bus Voltage After SC (V)	Bus Number	Voltage Before SC (V)	Bus Voltage After SC (V)
1	380	380	26	380	380
2	380	380	27	380	380
3	380	380	28	380	380
4	380	380	29	380	380
5	380	380	30	380	380
6	377	380	31	377	380
7	362	377	32	362	377
8	378	381	33	378	381
9	378	381	34	378	381
10	349	376	35	349	376
11	344	383	36	344	383
12	342	381	37	342	381
13	341	380	38	341	380
14	339	378	39	339	378
15	338	377	40	338	377
16	338	376	41	338	376
17	337	376	42	337	376

18	342	369	43	342	369
19	340	368	44	340	368
20	339	366	45	339	366
21	337	365	46	337	365
22	336	364	47	336	364
23	336	363	48	336	363
24	335	363	49	335	363
25	340	368	50	340	368

D. Results of IEEE 70 Bus System

The voltage levels of each bus in the IEEE 70 bus system before and after applying the Capacitor Placement technique are shown in Table 4 below. This case is formed by connecting two IEEE 35 bus system that is mentioned in part B in this section. The suitable capacitor banks for this system are 300kVAR (located at bus #13), 400kVAR (located at bus #14), 300kVAR (located at bus #26), and 400kVAR (located at bus #28).

Table 4. BUS VOLTAGE RESULTS OF IEEE 70 BUS SYSTEM

Bus Number	Voltage Before SC (V)	Bus Voltage After SC (V)	Bus Number	Voltage Before SC (V)	Bus Voltage After SC (V)
1	380	380	36	380	380
2	380	380	37	380	380
3	380	380	38	380	380
4	380	380	39	380	380
5	380	380	40	380	380
6	374	380	41	374	380
7	374	380	42	374	380
8	374	380	43	374	380
9	339	377	44	339	377
10	375	381	45	375	381
11	375	381	46	375	381
12	375	381	47	375	381
13	308	378	48	308	378
14	288	376	49	288	376
15	286	374	50	286	374
16	284	373	51	284	373
17	282	371	52	282	371
18	281	370	53	281	370
19	280	370	54	280	370
20	280	369	55	280	369
21	282	371	56	282	371
22	279	369	57	279	369
23	277	367	58	277	367
24	275	366	59	275	366
25	274	365	60	274	365
26	273	364	61	273	364
27	273	364	62	273	364
28	301	371	63	301	371
29	299	369	64	299	369
30	299	369	65	299	369
31	297	368	66	297	368
32	295	367	67	295	367
33	294	366	68	294	366
34	293	365	69	293	365
35	293	364	70	293	364

E. Results of IEEE 120 Bus System

The voltage levels of each bus in the IEEE 120 bus system before and after applying the Capacitor Placement technique are shown in Table 5 below. This case is formed by connecting all IEEE buses systems that is mentioned in this section. The suitable capacitor banks for this system are 300kVAR (located at bus #13), 400kVAR (located at bus #14), 300kVAR (located at bus #26), 400kVAR (located at bus #28), 300kVAR (located at bus #39), and 300kVAR (located at bus #50).

Table 5. BUS VOLTAGE RESULTS OF IEEE 120 BUS SYSTEM

Bus Number	Voltage Before SC (V)	Bus Voltage After SC (V)	Bus Number	Voltage Before SC (V)	Bus Voltage After SC (V)
1	380	380	36	380	380
2	380	380	37	380	380
3	380	380	38	380	380

4	380	380	39	380	380
5	380	380	40	380	380
6	374	380	41	374	380
7	374	380	42	374	380
8	374	380	43	374	380
9	339	377	44	339	377
10	375	381	45	375	381
11	375	381	46	375	381
12	375	381	47	375	381
13	308	378	48	308	378
14	288	376	49	288	376
15	286	374	50	286	374
16	284	373	51	284	373
17	282	371	52	282	371
18	281	370	53	281	370
19	280	370	54	280	370
20	280	369	55	280	369
21	282	371	56	282	371
22	279	369	57	279	369
23	277	367	58	277	367
24	275	366	59	275	366
25	274	365	60	274	365
26	273	364	61	273	364
27	273	364	62	273	364
28	301	371	63	301	371
29	299	369	64	299	369
30	299	369	65	299	369
31	297	368	66	297	368
32	295	367	67	295	367
33	294	366	68	294	366
34	293	365	69	293	365
35	293	364	70	293	364
Bus Number	Voltage Before SC (V)	Bus Voltage After SC (V)	Bus Number	Voltage Before SC (V)	Bus Voltage After SC (V)
71	380	380	96	380	380
72	380	380	97	380	380
73	380	380	98	380	380
74	380	380	99	380	380
75	380	380	100	380	380
76	377	380	101	377	380
77	362	377	102	362	377
78	378	381	103	378	381
79	378	381	104	378	381
80	349	376	105	349	376
81	344	383	106	344	383
82	342	381	107	342	381
83	341	380	108	341	380
84	339	378	109	339	378
85	338	377	110	338	377
86	338	376	111	338	376
87	337	376	112	337	376
88	342	369	113	342	369
89	340	368	114	340	368
90	339	366	115	339	366
91	337	365	116	337	365
92	336	364	117	336	364
93	336	363	118	336	363
94	335	363	119	335	363
95	340	368	120	340	368

F. Comparative Summary

To highlight the improvements across all test systems, Table 6 summarizes the minimum bus voltages, percentage of buses within $\pm 5\%$ limits, and loss reduction achieved.

Table 6. COMPARATIVE SUMMARY of GA-BASED CAPACITOR PLACEMENT RESULTS

Test System	Capacitor Placement (kVAR & Bus)	Minimum Voltage Before (p.u.)	Minimum Voltage After (p.u.)	% Buses within $\pm 5\%$ Before	% Buses within $\pm 5\%$ After
IEEE 25 Bus	300 kVAR @ Bus 11	0.88 (344 V)	1.01 (383 V)	60%	100%
IEEE 35 Bus	300 kVAR @ Bus 13, 400 kVAR @ Bus 14	0.76 (288 V)	0.99 (376 V)	40%	100%
IEEE 50 Bus	300 kVAR @ Bus 11, 300 kVAR @ Bus 22	0.88 (344 V)	1.01 (383 V)	55%	
IEEE 70 Bus	300 kVAR @ Bus 13, 400 kVAR @ Bus 14, 300 kVAR @ Bus 26, 400 kVAR @ Bus 28	0.76 (288 V)	0.99 (376 V)	42%	100%
IEEE 120 Bus	300 kVAR @ Bus 13, 400 kVAR @ Bus 14, 300 kVAR @ Bus 26, 400 kVAR @ Bus 28, 300 kVAR @ Bus 39, 300 kVAR @ Bus 50	0.76 (288 V)	1.00 (380 V)	45%	100%

5. Discussion

Several important elements become apparent when assessing the effects of Capacitor Placement on the chosen electrical distribution systems. This is especially true when taking into account cables that comply with IEEE 399 standard and are 100 meters in length in all of the chosen case studies. Without running the risk of overheating or going over operating limitations, these cables provide safe operation under load situations. Notable decreases in overall voltage dips throughout the cables under study serve as evidence of Capacitor Placement's effectiveness.

Table 7. TOTAL VOLTAGE DROP BEFORE AND AFTER OCP

	Total Voltage Drop Before Capacitor Placement (V)	Total Voltage Drop After Capacitor Placement (V)
IEEE 25 Bus System	43.432	22.403
IEEE 35 Bus System	95.771	27.304
IEEE 50 Bus System	86.864	44.806
IEEE 70 Bus System	191.542	54.608
IEEE 120 Bus System	278.406	99.414

Voltage dips after installation are much smaller. These results highlight the capacitors' capacity to improve voltage regulation and offset reactive power, both of which are essential for preserving a steady electrical supply. Capacitors also improve the power factor of the system, which is especially useful for loads that contain significant amounts of reactive components. Capacitors reduce reactive power, bringing the power factor closer to unity (noted power factor of 0.8 lagging across cases). This enhancement leads to increased operational efficiency by the use of electrical infrastructure and lowering system losses. Additionally, there are observable cost reductions and efficiency advantages with Capacitor Placement integration. Reduced voltage dips improve overall system efficiency by directly lowering energy losses during transmission. At the same time, higher power factor reduces the amount of reactive power that the utility must supply, which may reduce related expenses and fines related to low power factor performance. Capacitor Placement therefore becomes a crucial tactic for enhancing the operational dependability and effectiveness of electrical distribution networks. In addition to ensuring safe and effective operation,

Capacitor Placement also complies with standards for strong electrical infrastructure management by mitigating voltage dips and improving power factor.

6. Conclusion

This study investigates the use of Capacitor Placement approaches on five IEEE bus systems (25, 35, 50, 70 and 120) utilizing ETAP software, which makes use of GA to produce the best outcomes. Context was established with a brief overview of the GA and Capacitor Placement literature, and five case studies were then defined. These case studies' outcomes were examined, and the key conclusions were highlighted in a discussion that followed. Important variables were found when assessing the effect of Capacitor Placement on the chosen electrical distribution networks. Each of the 100-meter-long cables used in the case studies complied with IEEE 399 standards, guaranteeing safe operation under load situations without overheating or going over operating limitations. The overall voltage drops across the cables under study were considerably reduced, indicating the efficacy of the Capacitor Placement approach. Voltage reductions after installation is a significant improvement. This decrease highlights the capacitors' capacity to improve voltage regulation and offset reactive power, both of which are essential for preserving a steady electrical supply. Capacitors also increased the system power factor, which is advantageous for loads that contain a significant number of reactive components. Capacitors successfully reduced reactive power, bringing the power factor closer to unity, with a constant 0.8 lagging power factor across circumstances. This enhancement improved operating efficiency by lowering system losses and making the most use of the electrical infrastructure. Furthermore, there were observable cost and efficiency savings as a result of the Capacitor Placement integration. Decreased voltage dips improve overall system efficiency by directly reducing energy losses during transmission. Additionally, lower reactive power consumption from the utility resulted from improved power factor, which may have reduced expenses and penalties related to subpar power factor performance. To sum up, while taking costs into account, the best possible placement for capacitors greatly optimizes voltage profiles, power factor, and minimizes losses. One key tactic for improving the operational dependability and effectiveness of electrical distribution networks is Capacitor Placement. Capacitor Placement ensures safe and effective operation by mitigating voltage drops and enhancing power factor, in line with criteria for reliable electrical infrastructure management. The importance of Capacitor Placement in attaining optimal performance in electrical networks is highlighted by this study.

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