Mitigation of Power Losses and Enhancement in Voltage Profile by Optimal Placement of Capacitor Banks With Particle Swarm Optimization in Radial Distribution Networks

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Abstract. *The prime purpose of placing a capacitor bank in a power system is to provide reactive power, reduce power losses, and enhances voltage profile. The main challenge is to determine the optimum capacitor position and size that reduces both system power losses and the overall cost of the system with rigid constraints. For this purpose, different optimization techniques are used, for example Particle Swarm Optimization (PSO) which converges the complex non-linear problem in a systematic and methodological way to find the best optimal solution. In this paper, the standard IEEE 33-bus and 69-bus systems are used to find the optimum location and size of the capacitors bank. These power networks are simulated in Siemens PSS®E software. For the optimum solution of capacitor banks, the PSO algorithm is used. The PSO fitness function is modelled in such a way which contains the high average bus voltage, the small size of capacitor banks, and low power losses. The fitness function used is a weighted type to reduce the computation time and multi-objective function complexity.*

Keywords

Capacitor bank, optimal placement, power losses, voltage profile and cost function.

1. Introduction

The global ongoing high penetration of Distributed Generation (DG) units within electrical power networks seem to be a consequence of the deregulation of energy markets, the reduction of pollutants, and scientific advancement. The DGs were installed mostly in distribution systems in an ill-advised and unmanaged manner over the last 20 years, providing severe concerns and hurdles. These issues include the necessity of bidirectional power flow throughout modern networks since they are opposed to unidirectional power flow from larger to reduced voltages, including the critical issues of voltage decline with power losses [1], [2] and [3].

The reduction of hazardous pollutants and unlimited fundamental electricity resources seem to be the fundamental benefits of employing renewable distributed generation sources. Unfortunately, the key drawbacks are limited performance, large expenses, and unpredictability [4] and [5]. Since the number of DGs throughout the distributing network enhances, this really remains everyone's best desire to deploy resources in the most efficient manner possible to maximize stability, eliminate unnecessary losses, and improve the voltage profile, thus maintaining the fundamental objective of electricity injection.

Nevertheless, power losses have become one of the issues that distributed systems are coping with.

According to research from earlier articles, distribution losses account for 13 % to 18 % of the overall power produced [6]. Spontaneous energy losses mostly comprise of power losses inside transformer and line elements of electrical systems. Such losses, which primarily result from current passing across various types of system equipment, are inversely linked with element resistance and indeed the square of the current passing across them. The active as well as reactive elements of the current define its intensity; lowering the reactive component while keeping the active component unchanged seems to be an efficient strategy to decrease power losses [7]. Additionally, this really seems significant to note that lower power factor values result in a decrease in systems performance, and increased losses which ultimately yield a decrease in voltage, hence high operating expenses [8].

The issue of where to deploy capacitors inside the distributed network is one that research scholars are always trying to address. The ideal arrangement of capacitors remains a challenging stochastic optimizing issue [9]. The best location of the capacitors is already suggested by a number of optimized approaches and different algorithms [10].

The $\frac{2}{3}$ rule, which was used to deploy capacitors while maintaining a balanced load upon that distribution feeder, may be the first methodology for doing this. However, it has several serious flaws, including the fact that it takes a long period and therefore seems impractical for complex systems [11] and [12].

For the purpose of loss minimization, authors in [13] have presented a parallel Tabu Search method. A graph-based technique was put into use by authors in [14]. They determine where permanent and variable capacitors should be placed inside the radial distribution systems. Authors in [15] also suggested the arrangement of the capacitors for such conservative voltage reductions over the distribution feeders. The traditional Index Vectors dependent technique for the best capacitor bank placements in the distribution system was presented by authors in [16]. Authors in [17] proposed the branch and bound strategy regarding the best arrangement of capacitor banks. Authors in [18] proposed a Fuzzy-Genetic Algorithm for the ideal position of capacitors within radial distributing systems. A Heuristic Constructive Approach was recommended by authors in [19] for the installation of the capacitors within the distribution network. Authors in [20] have designed a model for minimizing the cost of the distributed network. Authors in [21] have used the ant colony optimization strategy, to reduce overall real power losses. Arrangement of capacitors across imbalanced distributed systems becomes the focus of the researchers in [22]. The voltage stability index is being used to choose the extremely sensitive bus for optimal placement of capacitors. The paper [23] investigates a comparative analysis of power networks with and without power compensating devices like capacitors. A strategy for choosing the best location and size for capacitors on a radial distributing network has been presented in [24]. The efficiency was shown using a conventional IEEE 33-bus system.

Through the support of a previously developed sperm whale technique, the authors in [25] propose an enhanced approach for loss minimization throughout medium voltage distributing systems employing optimum capacitors arrangement. Researchers in [26] report somewhat upon optimum capacitors installation and proper sizing of the shunt capacitors in a distributed network which has undergone significant distortion. Essentially in [27], a different technique is utilized that itself decides the groups of buses for location; the sizes as well as the eventual ideal state of an individual particle have been picked once a comprehensive search was carried out in the measuring region. In order to narrow down the issues for the best buses which need to have shunt capacitors placed, a novel method for addressing the optimum shunt capacitor installation and scaling challenge across the radial distributed system has been introduced [28].

According to [29], proper capacitors' location and sizing reduce overall power losses of both distribution networks. The consistency of simulation has been tested on a 33 kV radial distributed network. simulated results are then applied to a 0.4 kV 26 bus distributed system. Findings have been examined, including power losses with voltage stability. Employing the genetic algorithm in the ETAP software, various simulated results are optimized with different capacitor locations for mitigating the power losses and enhancing the voltage profiles.

Actual and fictitious power load conditions affect the voltage profiles and power losses within the distributed networks. Besides strategically placing capacitors, this could be successfully handled via the regulated actual as well as reactive power flow [30]. Due to this, experts have developed a number of methods that might be applied while significantly altering the current structure, including the Network Reconfiguration (NR) procedure, inserting capacitors, and adding Distributed Energy resources.

Adaptive Particle Swarm Optimization successfully addresses the issue of current Distributed generation and Capacitor bank allocation within a radial distributed network to improve voltages and minimize power losses. Depending upon the particle's optimum performance from the preceding iteration, the inertial Weighted formula (W) inside the velocity updated equation has been swapped out to modify the traditional PSO [31] and [32].

Considering IEEE 33-bus system, the researchers have used various approaches such as Spring Search Algorithm (SSA), Crow Search Algorithm (CSA), Bacterial Foraging Optimization Algorithm (BFOA), Particle Swarm Optimization (PSO) for optimal sizing of capacitors and mitigation of power losses and improve voltage profile [33], [34], [35] and [36]. The optimal power loss achieved with BFOA is 144.04 kW and the sizes of capacitor banks placed at bus no. 18, 30 and 33 is 0.349, 0.821 and 0.277 MVAr. The minimum voltage achieved is 0.936 [33]. Meanwhile, CSA produces 131.5 kW with capacitor banks having values of 0.6, 0.3,0.45 and 0.6 MVAr at bus no. 11, 33, 24 and 30 respectively. The minimum voltage achieved is 0.943 [34]. Adding further, PSO yields 132.48 kW power losses and minimum voltage is 0.945. The size of capacitor banks placed at bus no. 2, 7, 31, 15 and 29 is 0.9, 0.45,0.45, 0.3 and 0.45 MVAr consecutively [35]. Spring search algorithm delivers 130.912 kW power losses with 0.951 as minimum voltage. The capacitor placement is at bus no. 14, 24, 30 with 0.3973, 0.4511 and 1.0 MVAr ratings respectively [36].

In this paper, the optimal power losses value for IEEE 33-bus system is achieved and that is 130 kW and minimum voltage is 0.99. Apart of this, the capacitor size placed at bus no. 3, 13 and 14 is 500 kvar. This signifies that lower power losses and improved voltage profile with smaller size of capacitor bank is achieved. Similarly, analysis is also carried out for IEEE 69-bus system.

In this paper, the optimal location for the placement of capacitors is found where the power losses for IEEE 33-bus system and IEEE 69-bus system reach minimum. Further, the PSO Technique is implemented on IEEE 33-bus system and IEEE 69-bus system to find out minimum cost function and optimal location of capacitors for IEEE 33 and IEEE 69 in a very efficient and cost-effective way.

This paper is organized into four sections. The introduction is explained in detail in Sec. 1. , methodology and the details of assumed systems are provided in Sec. 2. , results are represented in Sec. 3. and in the end Sec. 4. concludes this research study.

2. Methodology

In this paper, IEEE 33-bus and 69-bus system in a radial distribution system is assumed for analyzing the voltage profile and power losses by placing the capacitors with different ratings at different locations. For this analysis, two strategies have been adopted and these are the hit and trial method (without any algorithm), and the PSO algorithm. The analysis is made by using Power System Simulator for Engineering (PSS®E) software and MATLAB/Simulink software for the optimal placement and sizing of capacitors using both techniques. The standard systems IEEE 33-bus and 69-bus system are shown in Fig. 1 and Fig. 2, respectively. The bus data and line data used for these standard systems are mentioned in Tab. 1, Tab. 2, Tab. 3 and Tab. 4 [37].

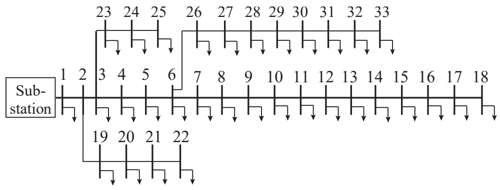


Fig. 1: SLD for IEEE 33-bus system [37].

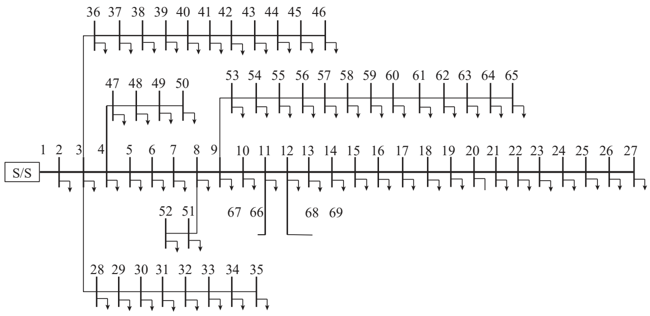


Fig. 2: SL diagram of IEEE 69-bus system [37].

Tab. 1: Bus data IEEE 33-bus system.

Bus no.	Bus type	Voltage profile (PU)	P_{Gen} (MW)	P_{Load} (MW)	Q_{Load} (MVAR)
1	Swing	1.06	3.843934	0.1	0.06
2	Load	1.0577	0	0.09	0.04
3	Load	1.0473	0	0.12	0.08
4	Load	1.0424	0	0.06	0.03
5	Load	1.0376	0	0.06	0.02
6	Load	1.0282	0	0.2	0.1
7	Load	1.0273	0	0.2	0.1
8	Load	1.0195	0	0.06	0.02
9	Load	1.0165	0	0.06	0.02
10	Load	1.0139	0	0.045	0.03
11	Load	1.0134	0	0.06	0.035
12	Load	1.0125	0	0.06	0.035
13	Load	1.0113	0	0.12	0.08
14	Load	1.0092	0	0.06	0.01
15	Load	1.0079	0	0.06	0.02
16	Load	1.0067	0	0.06	0.02
17	Load	1.0048	0	0.09	0.04
18	Load	1.0043	0	0.09	0.04
19	Load	1.0572	0	0.09	0.04
20	Load	1.0539	0	0.09	0.04
21	Load	1.0532	0	0.09	0.04
22	Load	1.0526	0	0.09	0.05
23	Load	1.044	0	0.42	0.2
24	Load	1.0377	0	0.42	0.2
25	Load	1.0344	0	0.06	0.025
26	Load	1.0272	0	0.06	0.025
27	Load	1.0259	0	0.06	0.02
28	Load	1.0184	0	0.12	0.07
29	Load	1.0131	0	0.2	0.6
30	Load	1.0107	0	0.15	0.07
31	Load	1.0099	0	0.21	0.1
32	Load	1.0091	0	0.06	0.04
33	Load	1.0088	0	0.1	0.06

Tab. 2: Line data IEEE 33-bus system.

From bus	To bus	R (PU)	X (PU)
1	2	0.057526	0.029449
2	3	0.307595	0.156668
2	19	0.102324	0.097644
3	4	0.228357	0.1163
3	23	0.281515	0.192356
4	5	0.237778	0.121104
5	6	0.510995	0.441115
6	7	0.116799	0.386085
6	26	0.126657	0.064514
7	8	1.067786	0.77061
8	9	0.642643	0.461705
9	10	0.651378	0.461705
10	11	0.122664	0.040555
11	12	0.233598	0.077242
12	13	0.915922	0.720634
13	14	0.337918	0.444796
14	15	0.36874	0.328185
15	16	0.465635	0.340039
16	17	0.80424	1.073775
17	18	0.456713	0.358133
19	20	0.938508	0.845668
20	21	0.255497	0.298486
21	22	0.442301	0.584805
23	24	0.559037	0.442425
24	25	0.61519	0.437434
26	27	0.17732	0.090282
27	28	0.660737	0.582559
28	29	0.501761	0.437122
29	30	0.316642	0.161285
30	31	0.607953	0.60084
31	32	0.193729	0.225799
32	33	0.212758	0.330805

The detailed workflow of this research is depicted in steps as follows. Steps:

1. Designing IEEE 33-bus and 69-bus systems on PSS®E and MATLAB/Simulink software and performing load flow analysis.

2. Implementation of hit and trial method to calculate voltage profile for IEEE 33-bus and 69-bus system.

3. Comparative analysis of Voltage profile for IEEE 33-bus system and 69-bus system.

4. Calculation of power losses with hit and trial method at different locations having different capacitor sizes.

5. Comparative analysis of power losses with and without capacitors for IEEE 33-bus and 69-bus systems.

6. Implementation of PSO to calculate cost function for capacitors having same capacitors, different swarm at different iterations for IEEE 33-bus system.

7. Finding the optimal location of capacitors with the same number, different swarm at different iterations with PSO.

8. Repeat steps 6 and 7 for IEEE 69-bus system.

Tab. 3: Bus data IEEE 69-bus system.

Bus no.	Bus type	Voltage profile (PU)	P_{Gen} (MW)	P_{Load} (MW)	Q_{Load} (MVAR)
1	Swing	1.0000	3.974315	0.0026	0.0022
2	Load	1.0000	0	0.0404	0.0300
3	Load	1.0000	0	0.0750	0.0540
4	Load	1.0000	0	0.0300	0.0220
5	Load	0.9997	0	0.0280	0.0190
6	Load	0.9945	0	0.1450	0.1040
7	Load	0.9891	0	0.1450	0.1040
8	Load	0.9879	0	0.0080	0.0050
9	Load	0.9872	0	0.0080	0.0055
10	Load	0.9849	0	0.0455	0.0300
11	Load	0.9844	0	0.0600	0.0350
12	Load	0.9825	0	0.0600	0.0350
13	Load	0.9796	0	0.0010	0.0006
14	Load	0.9768	0	0.1140	0.0810
15	Load	0.9740	0	0.0050	0.0035
16	Load	0.9734	0	0.0280	0.0200
17	Load	0.9726	0	0.0140	0.0100
18	Load	0.9726	0	0.0140	0.0100
19	Load	0.9721	0	0.0260	0.0186
20	Load	0.9718	0	0.0260	0.0186
21	Load	0.9714	0	0.0140	0.0100
22	Load	0.9714	0	0.0195	0.0140
23	Load	0.9713	0	0.0060	0.0040
24	Load	0.9711	0	0.0260	0.0186
25	Load	0.9710	0	0.0260	0.0186
26	Load	0.9709	0	0.0000	0.0000
27	Load	0.9709	0	0.0240	0.0170
28	Load	1.0000	0	0.0240	0.0170
29	Load	0.9999	0	0.0012	0.0010
30	Load	0.9998	0	0.0000	0.0000
31	Load	0.9998	0	0.0060	0.0043
32	Load	0.9997	0	0.0000	0.0000
33	Load	0.9994	0	0.0392	0.0263
34	Load	0.9991	0	0.0392	0.0263
35	Load	0.9990	0	0.0000	0.0000
36	Load	1.0000	0	0.0790	0.0564
37	Load	0.9998	0	0.3847	0.2745
38	Load	0.9996	0	0.3847	0.2745
39	Load	0.9996	0	0.0405	0.0283
40	Load	0.9996	0	0.0036	0.0027
41	Load	0.9989	0	0.0043	0.0035
42	Load	0.9986	0	0.0264	0.0190
43	Load	0.9986	0	0.0240	0.0172
44	Load	0.9986	0	0.1000	0.0720
45	Load	0.9985	0	1.2440	0.8880
46	Load	0.9985	0	0.0320	0.0230
47	Load	1.0000	0	0.0000	0.0000
48	Load	0.9996	0	0.2270	0.1620
49	Load	0.9989	0	0.0590	0.0420
50	Load	0.9992	0	0.0180	0.0130
51	Load	0.9878	0	0.0180	0.0130
52	Load	0.9878	0	0.0280	0.0200
53	Load	0.9854	0	0.0280	0.0200
54	Load	0.9832	0	0.0027	0.0300
55	Load	0.9802	0	0.0026	0.0022
56	Load	0.9773	0	0.0404	0.0300
57	Load	0.9581	0	0.0750	0.0540
58	Load	0.9486	0	0.0300	0.0220
59	Load	0.9449	0	0.0280	0.0190
60	Load	0.9406	0	0.1450	0.1040
61	Load	0.9334	0	0.1450	0.1040
62	Load	0.9331	0	0.0080	0.0050
63	Load	0.9327	0	0.0080	0.0055
64	Load	0.9309	0	0.0455	0.0300
65	Load	0.9303	0	0.0600	0.0350
66	Load	0.9847	0	0.0600	0.0350
67	Load	0.9847	0	0.0010	0.0006
68	Load	0.9833	0	0.1140	0.0810
69	Load	0.9833	0	0.0050	0.0035

The hit and trial method requires complete human interaction. All commands are being given manually. After that, the size and place of the capacitor bank

Tab. 4: Line data IEEE 69-bus system.

From bus	To bus	R (PU)	X (PU)
1	2	0.000310	0.000744
2	3	0.000310	0.000744
3	4	0.000930	0.002232
3	28	0.002728	0.006696
3	36	0.002728	0.006696
4	5	0.015560	0.018228
4	47	0.002108	0.005208
5	6	0.226920	0.115568
6	7	0.236220	0.120340
7	8	0.057160	0.029140
8	9	0.030560	0.015560
8	51	0.057530	0.029326
9	10	0.507780	0.167830
9	53	0.107880	0.054932
10	11	0.116060	0.038370
11	12	0.441060	0.145760
11	66	0.124744	0.037882
12	13	0.638600	0.210800
12	68	0.458428	0.151528
13	14	0.647280	0.213900
14	15	0.655960	0.216750
15	16	0.121890	0.040300
16	17	0.232120	0.076750
17	18	0.002914	0.000992
18	19	0.203110	0.067150
19	20	0.130570	0.042780
20	21	0.211790	0.069900
21	22	0.008680	0.002852
22	23	0.098640	0.032610
23	24	0.214710	0.070990
24	25	0.464250	0.153450
25	26	0.191590	0.063300
26	27	0.107380	0.035460
28	29	0.039680	0.097030
29	30	0.246630	0.081530
30	31	0.043520	0.014380
31	32	0.217600	0.071920
32	33	0.520180	0.174592
33	34	1.058960	0.350050
34	35	0.913880	0.302120
36	37	0.039680	0.097030
37	38	0.065286	0.076260
38	39	0.018840	0.022010
39	40	0.001116	0.001302
40	41	0.451546	0.527550
41	42	0.192200	0.224620
42	43	0.025420	0.029636
43	44	0.005704	0.007192
44	45	0.067518	0.085120
45	46	0.000558	0.000744
47	48	0.052760	0.129140
48	49	0.179670	0.439640
49	50	0.050960	0.124680
51	52	0.205770	0.069068
53	54	0.125860	0.064108
54	55	0.176204	0.089714
55	56	0.174406	0.088846
56	57	0.985800	0.330890
57	58	0.485894	0.163060
58	59	0.188604	0.062372
59	60	0.239380	0.072660
60	61	0.314650	0.160270
61	62	0.060388	0.030752
62	63	0.089900	0.045756
63	64	0.440510	0.224378
64	65	0.645421	0.328724
66	67	0.002914	0.000868
68	69	0.002914	0.000992

are decided where it must be placed into the system. Since this method involves manual human interaction as capacitor banks locations and their sizes are totally dependent on human desire like any random numbers. This may be considered as one of the major drawbacks of this method because these random numbers do not always provide the optimum location and size of capacitor banks. In this study, for IEEE 33-bus and 69-bus systems, capacitors are placed randomly and system voltages and power losses are analyzed. In this method, some losses of the system decreased from the nominal losses.

PSO is a population-based stochastic optimization technique inspired by the intelligent collective behavior of some animals, such as bird flocks or fish schools. To get results in PSO we utilize results from the hit and trial method. In order to enhance the system more efficiently these previous results of the hit and trial method play a vital role in deciding the output of the PSO algorithm. The losses and buses number that we have obtained in the hit and trial method is also used in PSO programming using MATLAB/Simulink, PSO updates those losses and buses and gives us new and specified the best location of the capacitors banks to be installed in the system after several iterations.

3. Results and Discussion

3.1. IEEE 33-bus and 69-bus System Voltage Profile with Hit and Trial Method

The behaviour of the Per Unit (PU) voltages at different buses with and without capacitor placement having different ratings has been discussed in detail in Fig. 4. The nominal voltages of the IEEE 33-bus system (radial distribution system) are mentioned in Fig. 4(a). These are the PU voltages without the placement of the capacitor into the system. It clearly signifies that the voltages at receiving end are less than the voltages at sending end because the load is connected at the far end buses. Since the load is inductive into the system so reactive power starts to flow and as a result, voltages are reduced at receiving. This is also evident from Fig. 4(a) that voltages at sending end are 1.06 PU while at receiving end these are almost 1 PU. Another important thing to remember is that the power factor of the system also reduces which ultimately enhances the power losses in the radial distribution network.

With the hit and trial method, random placement of capacitors at different buses with different ratings has been initiated and this is shown in Fig. 4. It is clear from Fig. 4(b) that when a capacitor of 600 kvar is placed randomly at bus no. 3, 13, 14 the some of the PU voltages are enhanced. So, by comparing Fig. 4(a) and Fig. 4(b), a small improvement in PU voltages has been observed. After that, at same buses, a capaci-

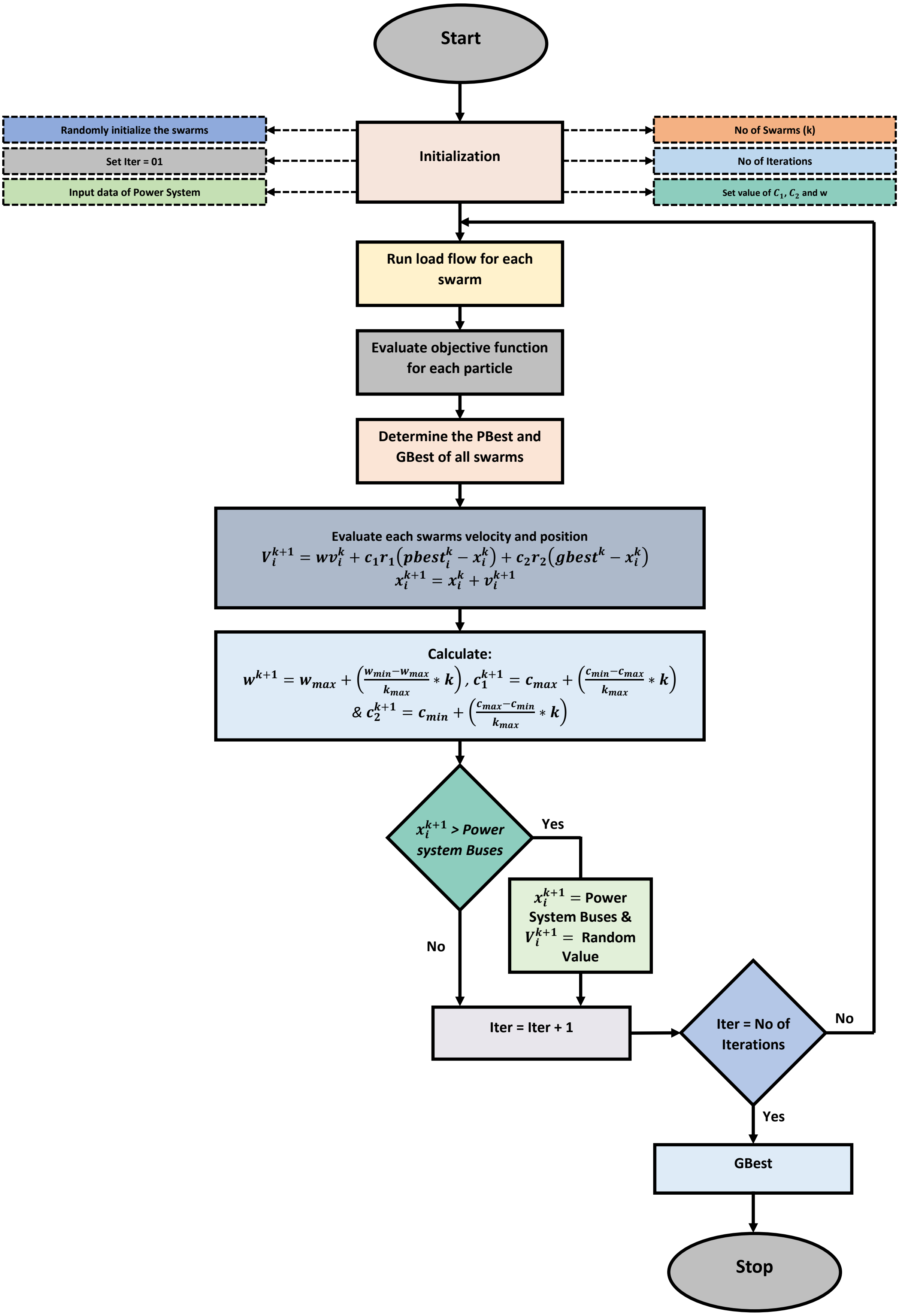
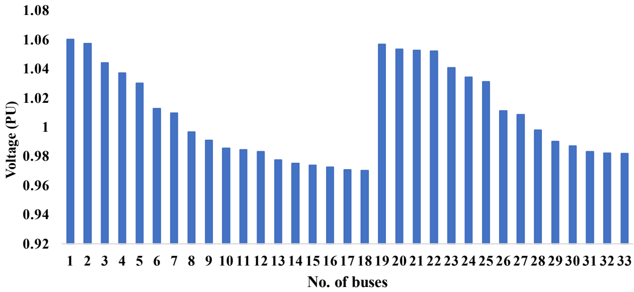
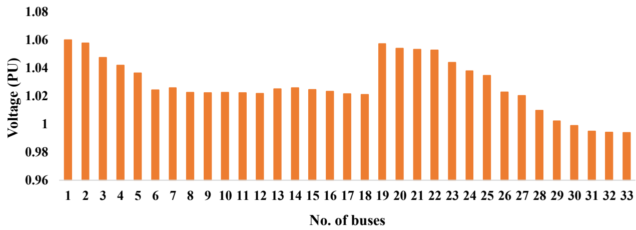


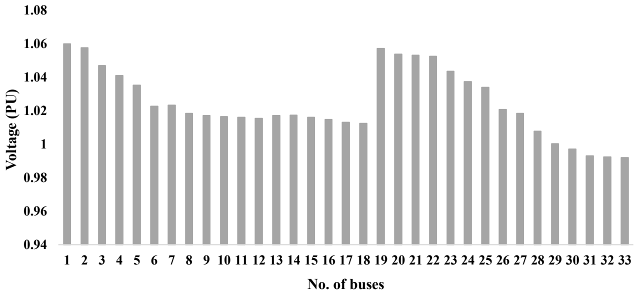
Fig. 3: PSO flow chart.



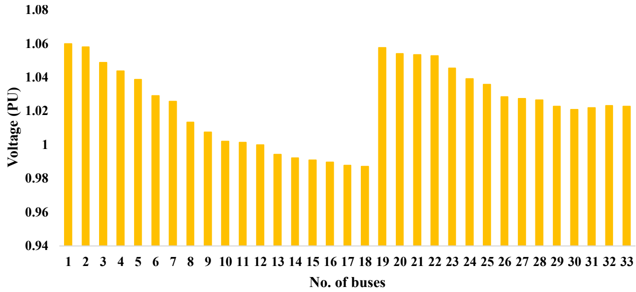
(a) Nominal voltages.



(b) Less improved voltages. Buses (3, 13, 14) 600 kvar capacitor rating.

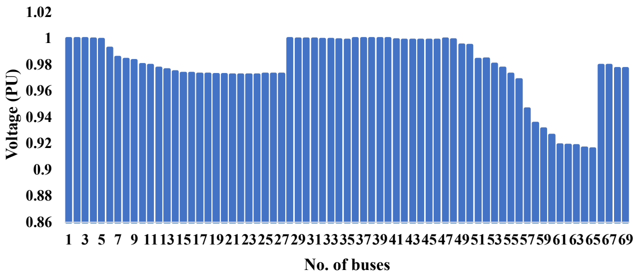


(c) Some improved voltages. Buses (3, 13, 14) 500 kvar capacitor bank.

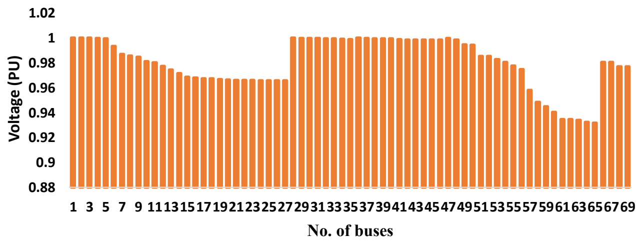


(d) Much improved voltages. Buses (3, 28, 32) 800 kvar capacitor bank.

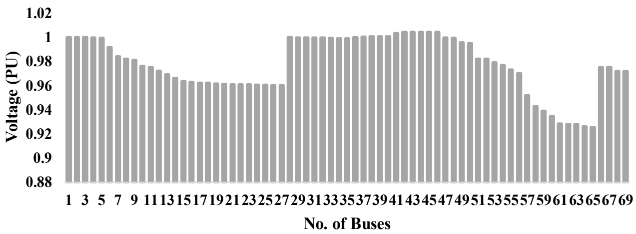
Fig. 4: PU voltages of IEEE 33-bus system with and without capacitor placement.



(a) Nominal voltages.



(b) Improved voltages. Buses (57, 66, 62) 600 kvar capacitor rating.



(c) Improved voltages. Buses (58, 48, 69, 43, 63) 600 kvar capacitor rating.

(d) Improved voltages. Buses (60, 69, 51, 65, 56, 48, 45) 500 kvar capacitor rating.

Fig. 5: PU voltages of IEEE 69-bus system with and without capacitor placement.

tor of a different rating i.e., 500 kvar, is placed and it can be said that the number of improved voltages is more than 600 kvar, although the rating of the capacitor is smaller this is clearly mentioned in Fig. 4(c). Finally, a capacitor of 800 kvar is placed at different buses i.e., 3, 28 and 32, so it is also analysed that a lot of improvement in the PU voltages has been analysed at the receiving end while comparing this location and size of the capacitor with nominal voltages and 600 kvar and 500 kvar capacitors.

Similarly, with the hit and trial method, the behaviour of the PU voltages at different buses with and without capacitor placement having different ratings has been discussed in detail in Fig. 5. The nominal voltages of the IEEE 69-bus system (radial

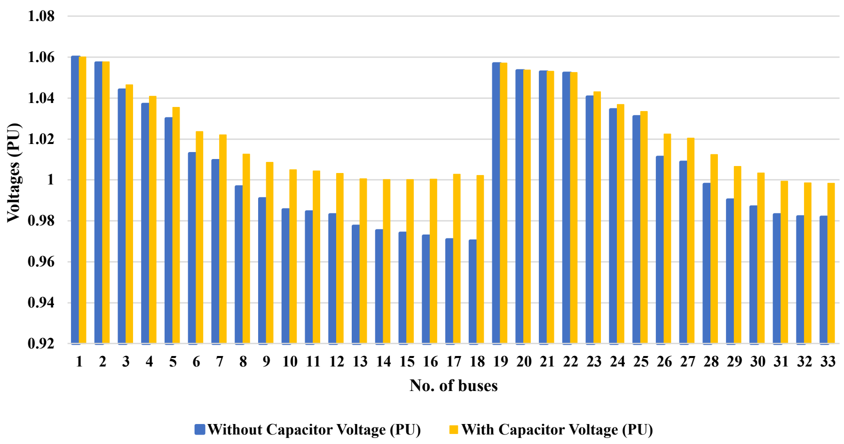


Fig. 6: Comparison of voltages with and without capacitor banks for IEEE 33-bus system.

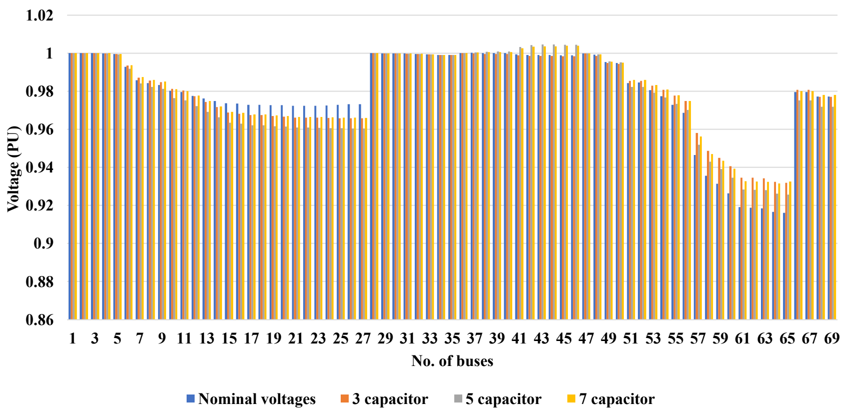


Fig. 7: Comparison of voltages with and without capacitor banks for IEEE 69-bus system.

distribution system) are mentioned in Fig. 5(a) without any capacitor. The Fig. 5(b), Fig. 5(c) and Fig. 5(d) shows the difference of PU voltage analysed into IEEE 69-bus system with different capacitor ratings and locations.

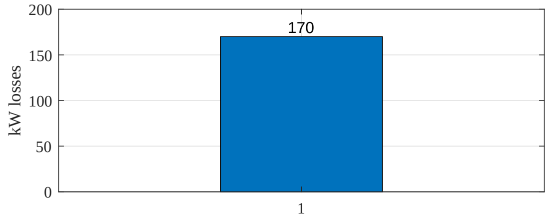
First, a capacitor bank having 600 kvar rating is placed at the bus no. 57, 66 and 62. Second, the capacitor with the same rating at different buses i.e., 58, 48, 69, 43, 63 is injected into the system and in the end capacitor with 500 kvar rating at the bus no. 60, 69, 51, 65, 56, 48 and 45 are placed to analyse the PU voltages.

1) IEEE 33-bus and 69-bus System Voltage Profile with and without Capacitors

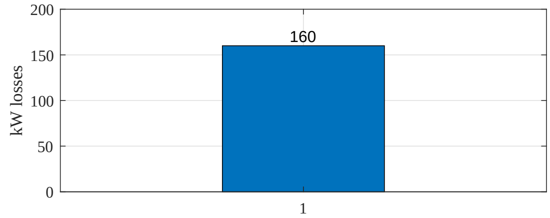
Figure 6 shows the comparison of voltages with and without capacitor banks at different locations of the IEEE 33-bus Radial Distribution System. It clearly shows that voltages are improved by injecting capacitor banks at different locations through the hit and trial method. As the capacitor feeds reactive power locally to the load which is not so far from the load, hence voltages and power factor of the system get improved. Similarly, for IEEE 69-bus system the comparison of PU voltages is depicted in Fig. 7.

2) Mitigation of Power Losses with Capacitor Bank Placement for IEEE 33-bus and 69-bus Systems

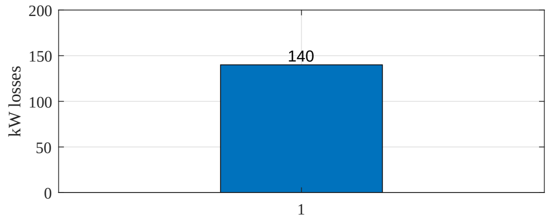
Since the capacitor supplies reactive power, it becomes necessary to measure the power losses. To mitigate power losses, capacitors with different ratings are placed on numerous buses. Figure 8 shows the detailed analysis of power losses with different capacitor ratings at different locations. It can be seen from Fig. 8(a), Fig. 8(b) and Fig. 8(d) that even capacitors with different ratings are placed at the same locations i.e., bus no. 3, 13 and 14 but, the power losses measured are different. Capacitors with 600 kvar, 400 kvar and 500 kvar ratings at the same locations produces 170 kW, 160 kW and 130 kW power losses. While capacitor with 800 kvar produces 140 kW as shown in Fig. 8(c). Therefore, a capacitor with 500 kvar produces less losses and bus no. 3, 13 and 14 are optimal locations for capacitor placement.



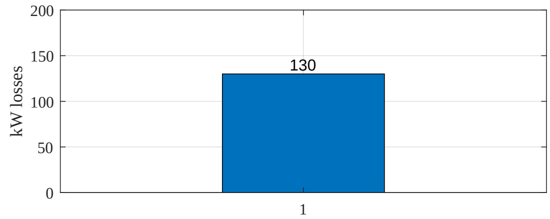
(a) Reduced kW losses. Buses (3, 13, 14) capacitor rating 600 kvar.



(b) Reduced kW losses. Buses (3, 13, 14) capacitor rating 400 kvar.

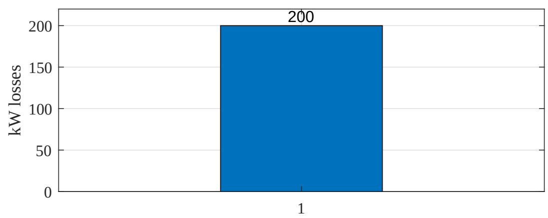


(c) Reduced kW losses. Buses (3, 28, 32) 800 kvar capacitor rating.

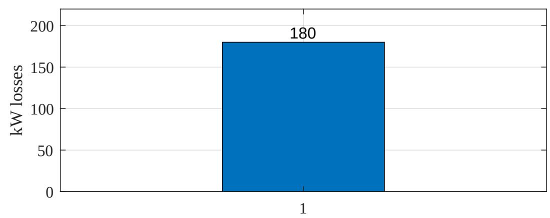


(d) Most suitable kW losses. Buses (3, 13, 14) capacitor rating 500 kvar.

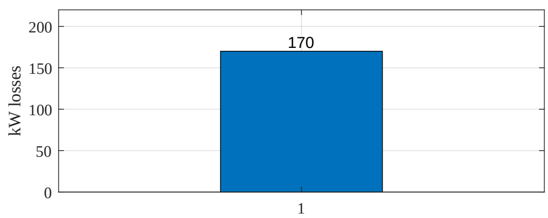
Fig. 8: Mitigation of power losses with different capacitor ratings for IEEE 33-bus system.



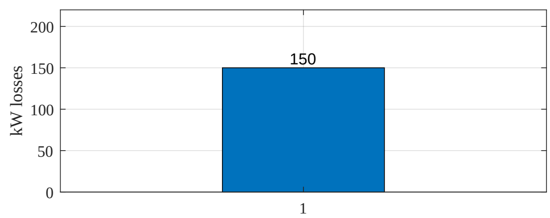
(a) Reduced kW losses. Buses(46, 52, 66) capacitor rating 700 kvar.



(b) Reduced kW losses. Buses (68, 69, 65) capacitor rating 900 kvar.



(c) Reduced kW losses. Buses (64, 21, 6) capacitor rating 600 kvar.



(d) Most suitable kW losses. Buses (61, 63, 56) capacitor rating 600 kvar.

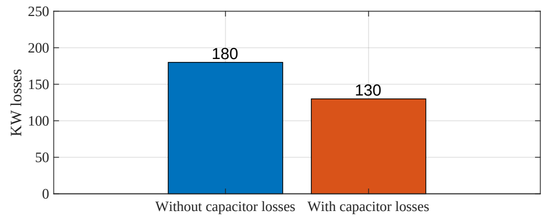
Fig. 9: Mitigation of power losses with different capacitor ratings for IEEE 69-bus system.

Similarly, power losses for IEEE 69-bus system are also mitigated by using different capacitor ratings at different allocations. Figure 9 clearly shows the comparative analysis of power losses.

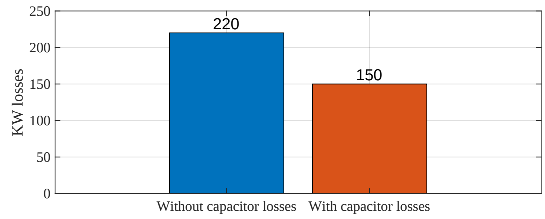
3) Power Loss Analysis for IEEE 33-bus and 69-bus System

A comparative analysis of power losses with and without capacitors has been carried out for both systems. Since it is clear from previous section that a capacitor with 500 kvar produces less losses. But it is also mandatory to measure the losses into IEEE 33-bus system without injection of capacitor banks. It can be seen from Fig. 10(a) that without capacitors placement, the system produces 180 kW losses. After a deep analysis with the hit and trial method, the capacitor with 500 kvar produces 130 kW. So, a difference of 50 kW is analysed. In general, it can be said that after the placement of capacitor, the system becomes more stable.

A similar analysis for power losses is also carried out for IEEE 69-bus system. Figure 10(b) depicts that

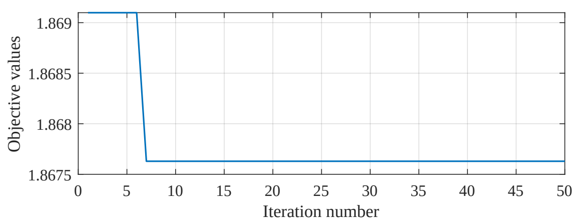


(a) IEEE 33-bus system power losses.

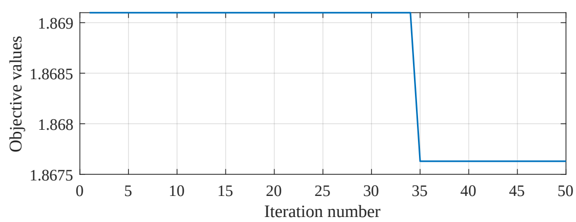


(b) IEEE 69-bus system power losses.

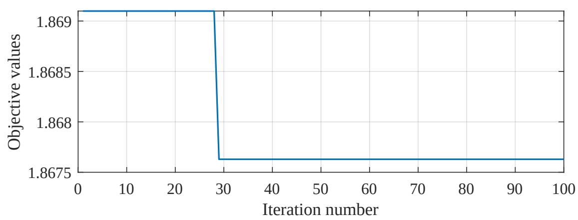
Fig. 10: Comparison of losses with and without capacitor bank.



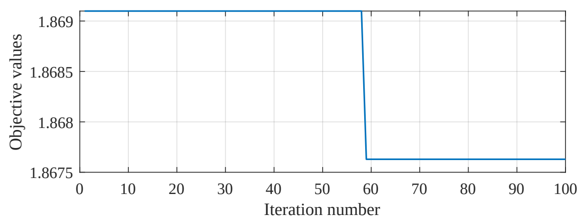
(a) 3 capacitors, 3 swarms and 50 iterations.



(b) 3 capacitors, 4 swarms and 50 iterations.



(c) 3 capacitors, 5 swarms and 100 iterations.



(d) 3 capacitors, 6 swarms and 100 iterations.

Fig. 11: Cost function with identical capacitors and different swarms at various iterations.

without the capacitor banks, the power losses are quite high (almost 220 kW), while after placing the capacitor, the losses are mitigated and reached a threshold value of 150 kW. Therefore, a difference of 70 kW in power loss is analysed after injection of the capacitor into the system.

3.2. PSO Implementation on IEEE 33-bus System

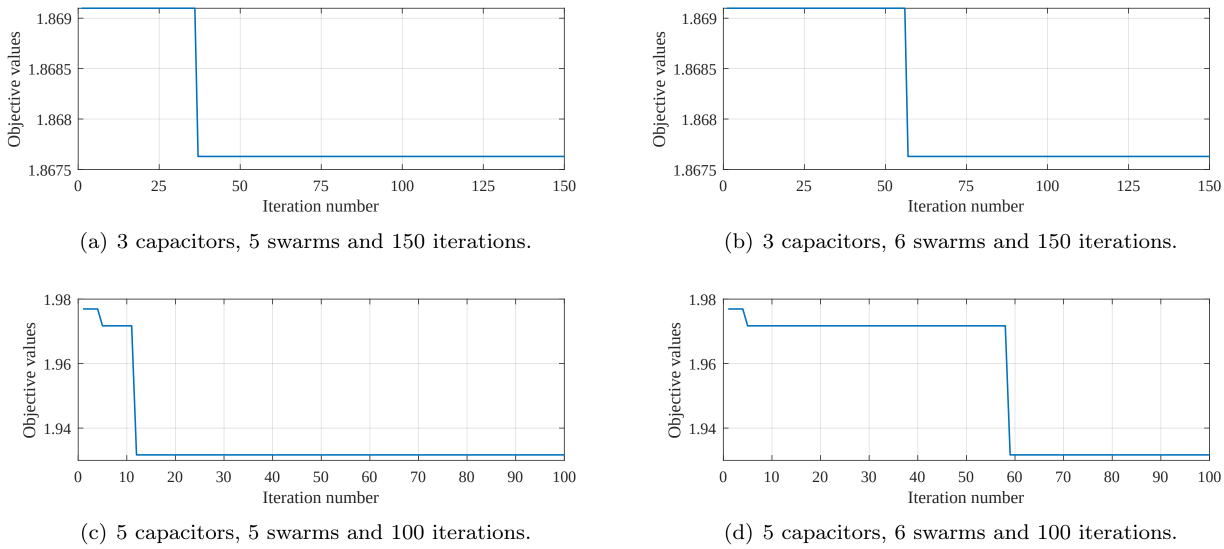
1) Analysis of Cost Function

To perform analysis on IEEE 33-bus system it becomes essential to have a minimum cost function. The cost function assumed in this study is the summation of average values of power losses, voltages (PU) at each bus and capacitor size. In order to simplify the system and to get results quickly, this summation helps in the convergence of the system.

Figure 11 shows the cost function with the same number of capacitors and different swarms at different iterations. Moreover, it is evident from Fig. 11(a) that value of the cost function is higher from 0 to 7th iteration where the system may not coverage. At iteration no. 8, the value of the cost function reaches the lower value (1.8676), where the system converges and remains stable up to 50 iterations. In Fig. 11(b), the number of swarms is increased while the number of capacitor banks and iterations remains the same. It can be seen initially; that the system may not converge due to higher values of objective function up to almost 35th iteration and at almost 36th iteration, the system becomes stable at reaches the lower value of objective function up to 50th iteration.

In a similar fashion, Fig. 11(c) and Fig. 11(d) shows the graph with 3 capacitors and 100 iterations having 5 and 6 swarms, respectively. It can be seen in Fig. 11(c) that system with 5 swarms starts converging at the 30th iteration and remains convergent continuously up to the 100th iteration while the system with 6 swarms finds optimal value at almost the 58th iteration where it seems stable and convergent up to the 100th iteration.

Figure 12 depicts the cost function with 3 and 5 capacitors having different swarms at 100 and 150 iterations. It can be distinguished between Fig. 12(a)



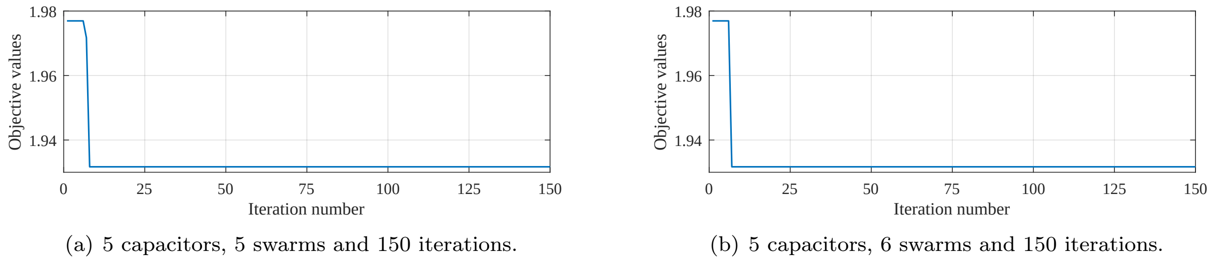
(a) 3 capacitors, 5 swarms and 150 iterations.

(b) 3 capacitors, 6 swarms and 150 iterations.

(c) 5 capacitors, 5 swarms and 100 iterations.

(d) 5 capacitors, 6 swarms and 100 iterations.

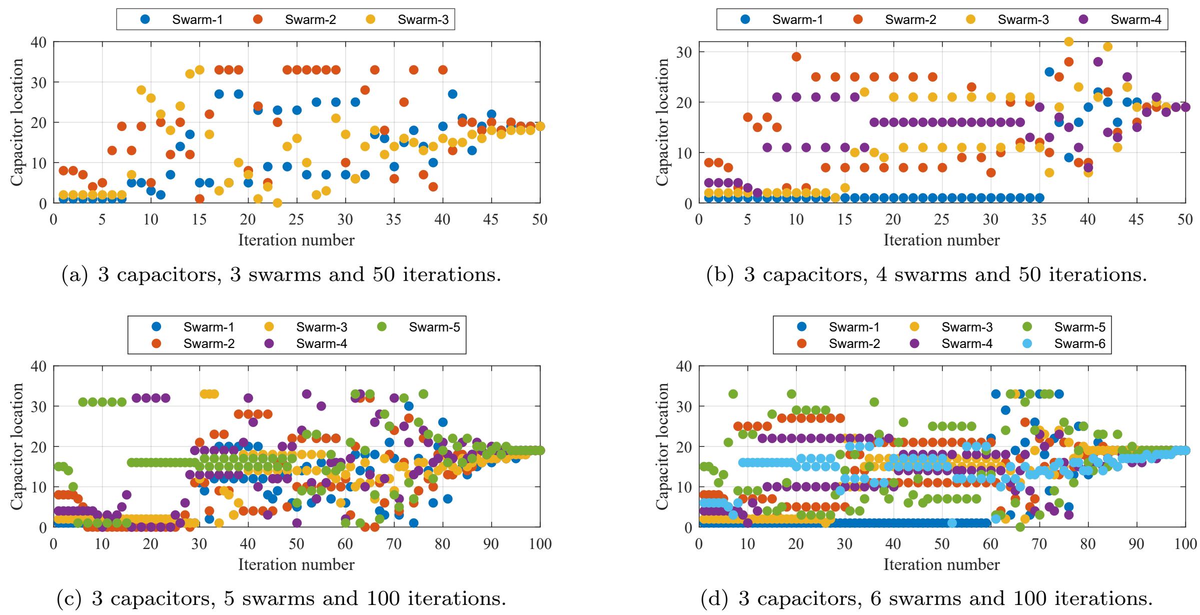
Fig. 12: Cost function with 3 and 5 capacitors having different swarms at various iterations.



(a) 5 capacitors, 5 swarms and 150 iterations.

(b) 5 capacitors, 6 swarms and 150 iterations.

Fig. 13: Cost function with identical capacitors having 5 and 6 swarms at 150 iterations.



(a) 3 capacitors, 3 swarms and 50 iterations.

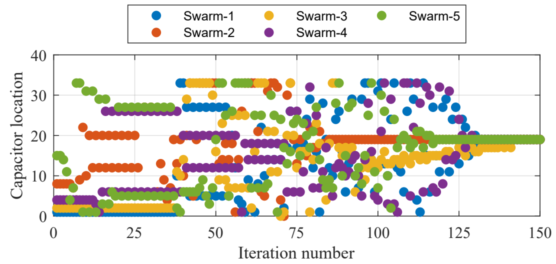
(b) 3 capacitors, 4 swarms and 50 iterations.

(c) 3 capacitors, 5 swarms and 100 iterations.

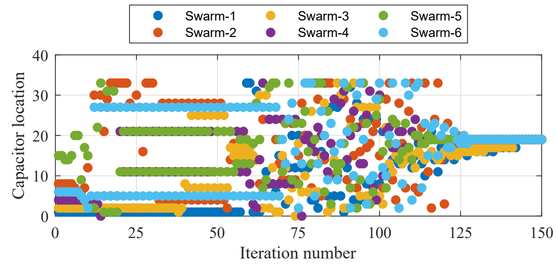
(d) 3 capacitors, 6 swarms and 100 iterations.

Fig. 14: Optimal capacitor location with identical capacitors having different swarms at 50 and 100 iterations.

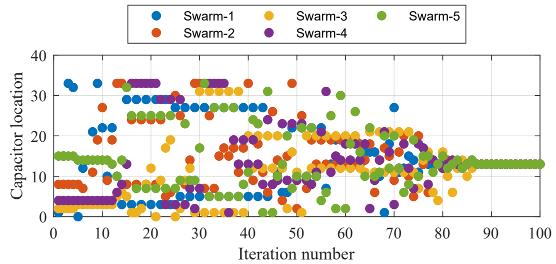
and Fig. 12(b) and between Fig. 12(c) and Fig. 12(d) that with increasing the number of capacitors, the objective value of the cost function is varying. In the case of three capacitors with different swarms, it is about



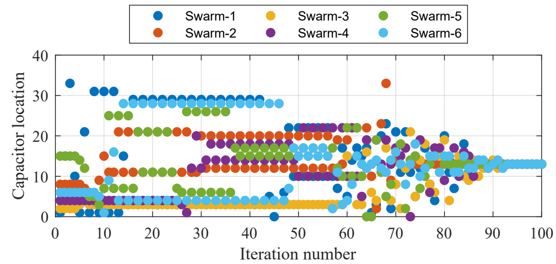
(a) 3 capacitors, 5 swarms and 150 iterations.



(b) 3 capacitors, 6 swarms and 150 iterations.



(c) 5 capacitors, 5 swarms and 100 iterations.



(d) 5 capacitors, 6 swarms and 100 iterations.

Fig. 15: Optimal capacitor location with identical capacitors having different swarms at 150 and 100 iterations.

1.8676 which is the optimum value of cost function whereas it is 1.92 in terms of 5 capacitors having different swarms.

Furthermore, it can be seen from Fig. 12(a) and Fig. 12(b) that with 5 and 6 swarms, the system is converging at 38^{th} and 58^{th} iterations. Meanwhile, in Fig. 12(c) and Fig. 12(d), the number of capacitor banks are enhanced up to 5 with 5 and 6 swarms at 100 iterations where the system is converging rapidly at the 16^{th} and 59^{th} iteration. As a result, the rate of convergence of Fig. 12(c) is faster than Fig. 12(a), Fig. 12(b) and Fig. 12(d).

It is also clear from Fig. 13(a) and Fig. 13(b) that the system has a higher cost function at the beginning and its rate of convergence is quite sharp which is almost the 9^{th} and 7^{th} iterations. Therefore, with increasing the number of iterations, i.e. 150, the system has become stable rapidly.

2) Optimal Location of Capacitors

Optimal location of capacitor banks with same number of capacitor banks and different swarms at 50 and 100 iterations is mentioned in Fig. 14. The behaviour of swarms seems interesting and the reason for using 3 swarms is to distinguish the rate of convergence. It is observed from Fig. 14(a) that swarm 1 and swarm 3 may converge up to the 7^{th} iteration while swarm 2 converges to some extent up to the 7^{th} iteration. After that, the system does not converge abruptly. Moreover, it is important to note here that the optimal location of the capacitor is bus no. 13. Similar analysis is carried out for Fig. 14(b), Fig. 14(c) and Fig. 14(d), where the optimal location of capacitor banks with different swarms at different iteration through PSO is bus no. 20, 20 and 18, consecutively.

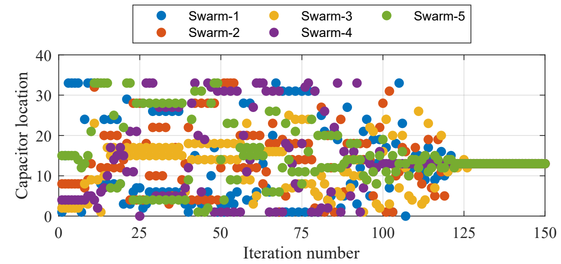
In the same way, analysis has been carried out for optimal placement of capacitor banks with 3 capacitors 5 and 6 swarms at 150 iterations. This is shown in Fig. 15(a) and Fig. 15(b) where the optimal location for the capacitor bank is suggested to be 24^{th} bus and 21^{st} bus respectively. While 5 capacitors with 5 and 6 swarms at 100 iterations have been observed in Fig. 15(c) and Fig. 15(d) and the optical location according to both figures for capacitor placement with 5 and 6 swarms at 100 iterations is to be 14 in both cases.

Figure 16 represents the optical placement of capacitor banks for 5 and 6 swarms at 150 iterations. It is clear that the best location for capacitor placement under both scenarios is bus no. 13 where losses will be lower and the system will remain stable. The important thing here to notice is the rate of convergence, which is higher for 6 swarms, although the optimal location is the same.

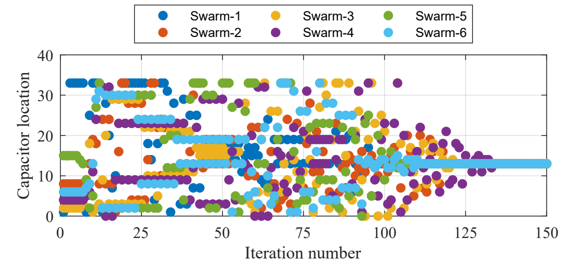
3.3. PSO Implementation on IEEE 69-bus System

1) Analysis of Cost Function

Analysis of IEEE 69-bus system is performed by implementing PSO algorithm. This algorithm has been implemented to achieve lower values of the cost func-

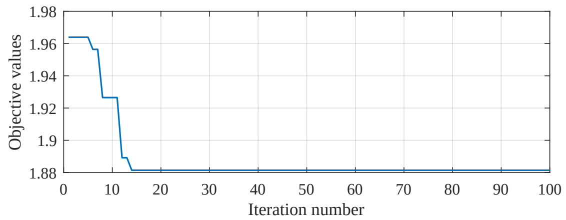


(a) 5 capacitors, 5 swarms and 150 iterations.

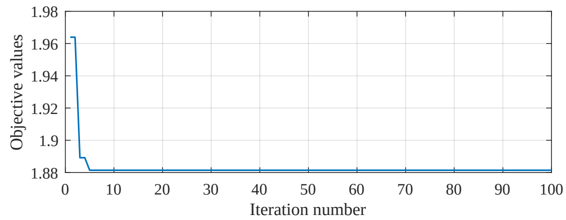


(b) 5 capacitors, 6 swarms and 150 iterations.

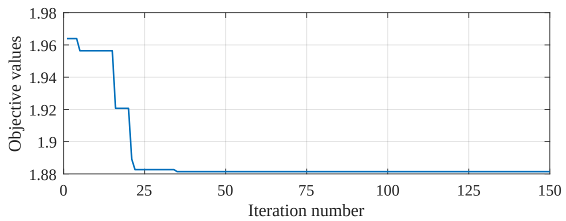
Fig. 16: Optimal capacitor location with identical capacitors having different swarms at 150 iterations.



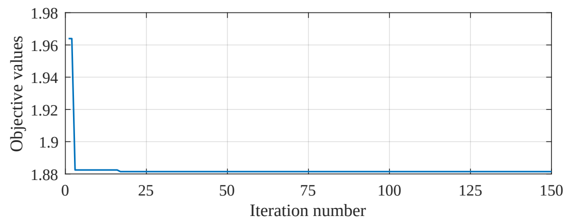
(a) 3 capacitors, 5 swarms and 100 iterations.



(b) 3 capacitors, 6 swarms and 100 iterations.

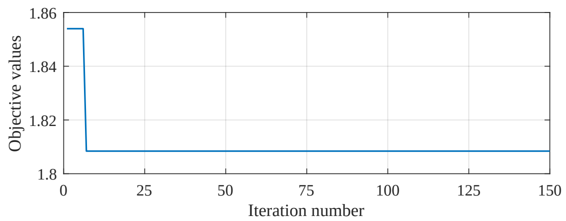


(c) 3 capacitors, 5 swarms and 150 iterations.

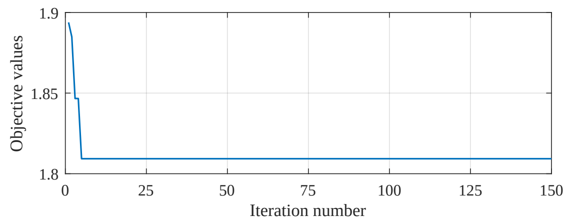


(d) 3 capacitors, 6 swarms and 150 iterations.

Fig. 17: Cost function with 3 and 5 capacitors having different swarms at various iterations.



(a) 5 capacitors, 6 swarms and 150 iterations.



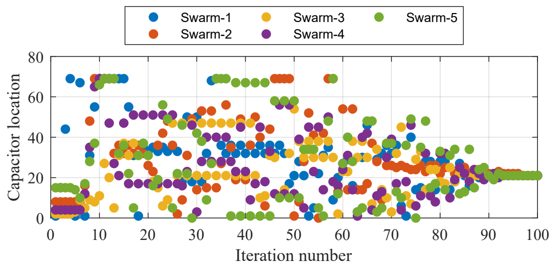
(b) 7 capacitors, 6 swarms and 150 iterations.

Fig. 18: Cost function with 3 and 5 capacitors having different swarms at various iterations.

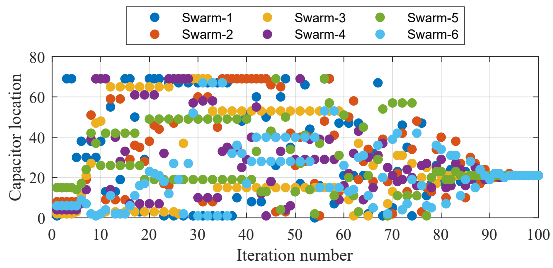
tion for better performance of the system. Like IEEE 33-bus system, the different numbers of iterations with various capacitors are also assumed to have a lower cost function in IEEE 69-bus system. The system is analyzed with an identical number of capacitors with 5 and 6 swarms at 100 and 150 iterations as shown in Fig. 17.

Furthermore, the cost function value is the same for 5 and 6 swarms at 100 iterations with 3 capacitor banks. But it is clear from Fig. 17(a) and Fig. 17(b) that the system converges at the same value which is about 1.88. However, the rate of convergence is different. With 5 swarms and 3 capacitors, the system converges at almost 17^{th} iteration while the system with 3 capacitors and 6 swarms at 100 iterations converge at almost 5^{th} iteration. Again, the number of capacitors and iterations is enhanced in Fig. 17(c) and Fig. 17(d) and these are 5 capacitor, 5 and 6 swarms at 150 iterations, respectively. The system becomes convergent almost at 35^{th} iteration with 5 swarms and at 18^{th} iteration having 6 swarms.

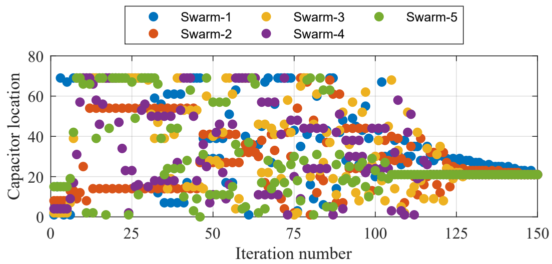
Again, a similar analysis is carried out by increasing the number of capacitors only while swarms are 6 and the number of iterations is 150.



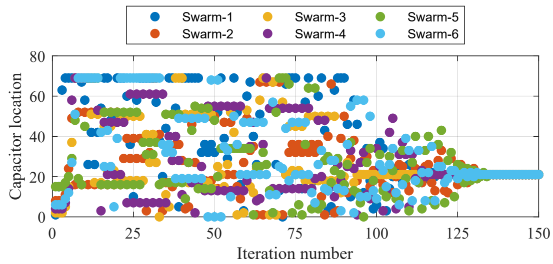
(a) 3 capacitors, 5 swarms and 100 iterations.



(b) 3 capacitors, 6 swarms and 100 iterations.

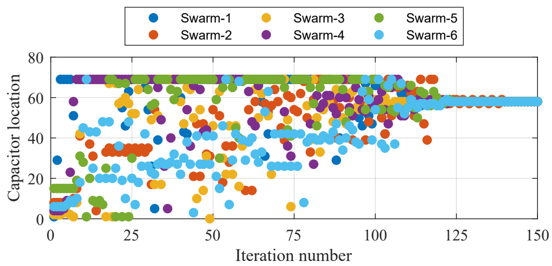


(c) 3 capacitors, 5 swarms and 150 iterations.

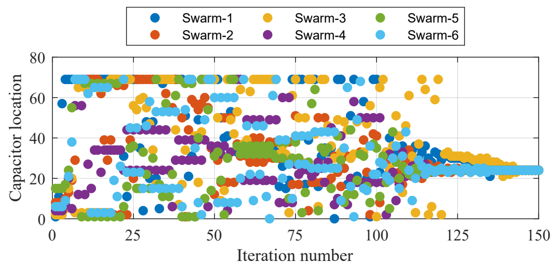


(d) 3 capacitors, 6 swarms and 150 iterations.

Fig. 19: Optimal capacitor location with identical capacitors having different swarms at 100 and 150 iterations.



(a) 5 capacitors, 6 swarms and 150 iterations.



(b) 7 capacitors, 6 swarms and 150 iterations.

Fig. 20: Optimal capacitor location with identical capacitors having different swarms at 150 iterations.

It is worthwhile to note that the value of the cost function is declined and lies below 1.81, where the system meets the convergence criteria at almost 6^{th} iteration; this is shown in Fig. 18(a). When the number of capacitor banks is enhanced up to 7 and number of iterations is the same, the objective value inclines and lies between 1.89 and 1.9. Under such a situation, the system becomes convergent at almost 4^{th} iteration having a lower value of cost function which is about 1.81 as shown in Fig. 18(b).

2) Optimal Location of Capacitors

In this IEEE 69-bus system, the optimal location for placement of capacitor banks has been achieved with particle swarm optimization technique by changing the number of capacitors, swarms, and number of iterations as represented in Fig. 19. The optimal location for the placement of capacitor banks has 3 capacitors 5 and 6 swarms at 100 iterations has been mentioned in Fig. 19(a) and Fig. 19(b) and according to that prime location is bus no. 20 and 21. However, in Fig. 19(c) and Fig. 19(d), the number of iterations is increased up to 150 while the number of capacitors and swarms remain identical. Therefore, with the implementation of PSO, the optimal location for capacitor placement is 18 and 21 for both cases.

Furthermore, it is evident from Fig. 20 that number of capacitors is increased while the number of swarms and iterations remain the same as discussed earlier. It can be seen from Fig. 20(a) and Fig. 20(b) that system slowly and gradually moves towards convergence and according to that the optimal location for 5 and 6 swarms at 150 iterations is bus number of 24 and 58 sequentially.

4. Conclusion

The vast expansion of the power system and continuously growing demand of the load every year leads to more complexity. This causes a reduction in the average buses output voltage and power losses.

To overcome these problems, different strategies are being used in the distribution systems.

In this research study, the work has been carried out on the optimal size and placement of capacitor banks at proper locations for IEEE 33 and 69 radial distribution systems. Two methods are used for the analysis and these are the hit and trial method and particle swarm optimization. With hit and trial method it was observed that with the use of a large capacitor size, the voltages are improved but power losses are enhanced due to the large charging current because in this method, the capacitor placement and size are random.

After that, the PSO algorithm is implemented where the cost function optimizes the capacitor bank in such a way that buses voltage should be as high as possible within limits, power losses should be less and capacitor bank size should be reduced. With the different numbers of capacitors bank placements, the voltage profile and power losses are generally analysed. It is observed that numbers of capacitor banks play a vital role to reduce the power losses. However, after a certain number of capacitor banks system will be uneconomical and power losses are also increased.

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Author Contributions

The contributions of M.F.S. in this research are as conceptualization and methodology, validation and, formal analysis was accomplished by A.M.S., investigation of the results was done by S.A.S., data curation is completed by R.N., writing of original draft and editing was performed by A.M.S. and A.A.K. has participated in proof reading.

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