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Optimal Capacitor Allocation in Radial Distribution Networks for Annual Costs Minimization Using Hybrid PSO and Sequential Power Loss Index Based Method

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Abstract- *In the most recent heuristic methods, the high potential buses for capacitor placement are initially identified and ranked using loss sensitivity factors (LSFs) or power loss index (PLI). These factors or indices help to reduce the search space of the optimization procedure, but they may not always indicate the appropriate placement of capacitors. This paper proposes an efficient approach for the optimal capacitor placement in radial distribution networks with the aim of annual costs minimization based on sequentially placement of capacitors and calculation of power loss index. In the proposed approach, initially, the number of capacitors location is estimated using the total reactive power demand and average range of capacitors available in the market. Then, the high potential buses can be identified using sequential power loss index based method. This method leads to achieve the optimal or near optimal locations for the capacitors and decrease the search space of the optimization procedure significantly. The particle Swarm Optimization (PSO) algorithm takes the final decision for the optimum size and location of capacitors. To evaluate the efficiency of the conducted approach, it is tested on several well-known distribution networks, and the results are compared with those of existing methods in the literature. The comparisons verify the effectiveness of the proposed method in producing fast and optimal solutions.*

Keyword: Annual costs minimization, Capacitor allocation, Particle swarm optimizarion, Power loss reduction, Sequential power loss index.

1. INTRODUCTION

Installation of shunt capacitors at appropriate locations in distribution networks improves the feeder voltage profile via power factor correction. The capacitors decrease the demand current, system losses, and voltage drop, leading to voltage profile improvement [1]. Numerous methods for solving optimal capacitor placement problem with a view to minimize the power losses have been suggested in the literature based on both traditional mathematical methods and more recent heuristic approaches [2]. Heuristic approaches can decrease the mathematical complexity. Also these methods have rapid responses. Several heuristic methods have been developed in the last decade for the optimal capacitor placement. A comprehensive analysis of the recent heuristic optimization techniques that solve the optimal capacitor placement problem is presented in [3]. Choosing the whole buses of network as the potential (candidate) locations for the capacitor placement will result in the optimal solutions, but the computation time increases significantly instead, and the probability of convergence decreases with increasing the size of distribution network. In more recent heuristic based methods, the high potential buses for the capacitor placement are initially identified and ranked using loss sensitivity factors [2,4-8] or power loss index [6,9,10]. In these methods, some of the network buses are nominated initially for capacitor placement after ranking of buses based on LSF or PLI. Although using LSF or PLI significantly leads to the reduction of search space for the optimization procedure, but they have been proven less than satisfactory, and may not always obtain the appropriate places of capacitor installation, especially, when the distribution network requires more than one capacitor for the reactive power compensation. For example, both LSF and PLI methods are used in [6] to

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identify the candidate locations for the reactive compensation; the obtained results clearly indicate that the PLI and LSF methods based capacitor placement gives better results, and neither of LSF nor PLI guarantees the maximum net savings. The authors highly recommended applying both PLI and LSF indicators to get the optimal or near optimal operating costs and maximum savings. In LSF and PLI methods, the impact of reactive power injected by capacitors is not considered to identify the location of them. Consequently, the buses are not properly ranked for multiple capacitor placement by performing these methods. Injection of reactive power by one capacitor bank changes the reactive power flow in distribution networks, and it may change the rank of buses for placement of the next capacitor, which have been initially found by LSF or PLI methods. Thus, the appropriate locations of the capacitors should be identified by adding capacitors and ranking of the buses sequentially.

In this paper, initially, the number of capacitors' locations is approximated using total reactive power demand and the average range of capacitors available in the market. Then, the high potential buses are identified using the sequential power loss index based method. Finally, the PSO algorithm is used to find the optimal size and location of capacitors. The validity and effectiveness of the proposed approach is tested on 34-bus, 85-bus, and 94-bus radial distribution networks, and the results are compared with those of existing heuristic based methods like Artificial Bee Colony (ABC) [2], PSO [4], Genetic Algorithm (GA) [11], Cuckoo Search Algorithm (CSA) [12], Evolutionary Algorithm (EA) [13], Teaching Learning Based Optimization (TLBO) [14] and Direct Search Algorithm (DSA) [15]. The noteworthy contributions of the current paper can be outlined as follows:

- Proposing an efficient approach for optimal capacitor allocation with the aim of annual costs minimization;
- Determining the potential (candidate) locations for capacitors using sequential placement of capacitors and calculation of power loss index;
- Using a PSO algorithm to optimally select among the potential buses for the capacitor installation;
- Fast convergence and optimal solutions of the conducted approach compared to the existing methods.

The remainder of this paper is organized as follows: The load flow method is summarized in the next section. Section 3 presents the sequential PLI based method for optimal capacitor allocation. The objective function and PSO algorithm are respectively described in sections 4 and 5. Section 6 provides the simulation results for the application of the proposed approach on three distribution networks. Finally, the last section concludes the paper.

2. LOAD FLOW METHOD

The traditional load flow methods used in transmission systems, such as the Gauss-Seidel and Newton-Raphson techniques, may become inefficient in the analysis of distribution systems due to the high ratio of R/X in distribution systems. The distribution power flow method suggested in [16] is used in this study to calculate the voltage of buses and power flow of lines. This method solves the load flow problem directly based on calculation of two matrices obtained from the topological characteristics of distribution systems. For complete formulation and description of this load flow method, the readers are referred to [16].

3. SEQUENTIAL PLI BASED METHOD

3.1. Estimating the number of capacitors' location

The proposed approach is implemented by providing an estimate for the number of capacitors' location. These locations can be approximated using total reactive power demand and average range of capacitors available in the market. This number is used to identify high potential buses for the capacitor installation. From the practical point of view, to avoid cases of leading power factor, and to maintain the power factor within higher lagging values, the injected reactive power must be limited to 75% of total reactive load demand [6]. Using this limitation and considering 750 kVAr as the average value of available capacitors, the approximated number of capacitors location is calculated as Eq. (1):

$$N_{loc} = ceil\left(\frac{0.75\sum_{i=1}^{N_{bus}} Q_d(i)}{(Q_{C\max} + Q_{C\min})/2}\right) + 1 \tag{1}$$

where, the *ceil*() function rounds a number to the next larger integer, N_{bus} and Q_d are the number of buses and reactive power demand, respectively; $Q_{C\max}$ and $Q_{C\min}$ are the maximum and minimum range of injected reactive power. Equation (1) yields an approximate number of capacitors location. The optimal number of capacitors location may be higher or lower, which has to be set manually by the user.

3.2. Identification of buses using sequential PLI based method

To identify high potential buses, the procedure of PLI calculation must be run N_{loc} times by sequentially adding the capacitors to the network. In each time, after ranking of buses by PLI, the best location is identified and then excluded for the next time. The PLI is calculated by the following expression [6]:

$$PLI(i)=\frac{LR(i)-LR_{min}}{LR_{max}-LR_{min}} \quad , \; i=2,3,\dots,N_{bus} \qquad (2)$$

where, *LR* is the power loss reduction compared to initial power loss due to injection of reactive power to i^{th} bus. Unlike PLI calculation in [10], the reactive power injection is not equal to reactive power demand of each bus. After intensive trials, step changes of reactive power injection around an average value of capacitors are led to achieve the optimal or near to optimal locations for capacitors. The reactive power injection in each time is calculated as follows:

$$Q_C(j)=\frac{0.75\sum_{i=1}^{N_{bus}}Q_d(i)}{N_{loc}}+F(j)*\frac{0.75\sum_{i=1}^{N_{bus}}Q_d(i)}{N_{loc}} \qquad (3)$$
$$j=1,2,\dots,N_{loc}$$

The first term of Eq. (3) shows the average value for N_{loc} capacitors. $F(j)$ is decreased linearly according to Eq. (4).

$$F(j)=\frac{2X}{100}*\frac{(N_{loc}-1)/2-j+1}{N_{loc}-1} \qquad (4)$$

where, *X* is a percentage of tolerance around the average value. There is a direct relation between the optimal value of *X* and the ratio of maximum/average of loads' reactive power. The following steps identify the buses for capacitor placement using the sequential PLI based method:

(a) Run the load flow and obtain initial real power loss;

(b) Do for all estimated location (for *j* = 1:N$_{loc}$):

(b.1) Do for all buses, except slack bus:

(b.1.1) Inject capacitive reactive power equal to (3);

(b.1.2) Run load flow and obtain the real power loss;

(b.1.3) Calculate the loss reduction (*LR* = initial real power loss – real power loss);

(b.2) Calculate PLI using Eq. (2);

(b.3) Sort the values of PLI in descending order;

(b.4) Set $HPB(j)=PLI(1)$;

(b.5) Set $Q_d^{new}(HPB(j))=Q_d(HPB(j))-Q_C(j)$.

In the above steps, HPB (*j*) stores the high potential buses for capacitor allocation.

4. OBJECTIVE FUNCTION AND PROBLEM CONSTRAINTS

4.1. Objective function

The objective of capacitor allocation in distribution networks is to minimize the annual network costs including the installation cost, annual cost of real power loss, and also, the operation cost. Mathematically, the objective function of problem can be formulated as Eq. (5), where, P_{loss} is real power loss, N_c is the number of compensated buses where the capacitors are installed. The constant parameters of the objective function are listed in Table 1 [10]. Moreover, the objective function can be matched to maximize annual net saving. Annual net saving is obtained by subtracting the *Cost* after compensation from the *Cost* before compensation.

Table 1. The constant parameters of the objective function

Parameter description	Value
Average energy cost (K_e)	$0.06/kWh
Depreciation factor (α)	20%
Purchase cost (C_p)	$25/kVAr
Installation cost (C_i)	$1600/location
Operating cost (C_o)	$300/year/location
Hours per year (T)	8760

4.2. Constraints

The objective function is subjected to the following operational constraints:

- Reactive power compensation limits as Eq. (7).
- Buses voltage limit as Eq. (8).
- The apparent power flow of lines as Eq. (9).

In these expressions, $V_{\min}$ and $V_{\max}$ are the minimum and maximum voltage limits, *V(i)* is the voltage amplitude of i^{th} bus, N_{bus} is the number of network buses, and N_{line} is the number of network lines.

5. PSO ALGORITHM

PSO algorithm is used in this work to find the optimal size and location of capacitors. PSO is a population based stochastic optimization technique developed by Kennedy and Eberhart [17]. This algorithm has been widely used for optimization of various power system problems [18-

20]. Some special advantages of the PSO over other optimization algorithms can be outlines as below:

$$Cost\ /\ year = K_e.P_{loss}.T + \alpha.[C_i.N_c + C_p.\sum_{i=1}^{N_C} Q_c(i)] + C_o.N_c \quad (5)$$

$$Saving\ /\ year = Cost_b - Cost_a = K_e.(P_{lossb} - P_{lossa}).T - \alpha.[C_i.N_c + C_p.\sum_{i=1}^{N_C} Q_c(i)] - C_o.N_c \quad (6)$$

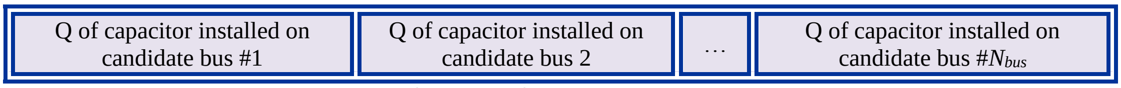
$$Q_{C\,min} \le Q_C(i) \le Q_{C\,max} \qquad i = 1,2,\dots,N_{bus} \quad (7)$$

$$V_{min} \le V(i) \le V_{max} \qquad i = 1,2,\dots,N_{bus} \quad (8)$$

$$S(i) \le S_{\max} \qquad \mathrm{i} = 1,2,\dots,\mathrm{N}_{\mathrm{line}} \quad (9)$$

$$v_i^{t+1} = w.v_i^t + r_1.c_1.(x_{pbesti} - x_i^t) + r_2.c_2.(x_{gbest}^t - x_i^t) \quad (10)$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \quad (11)$$



Q of capacitor installed on candidate bus #1	Q of capacitor installed on candidate bus 2	…	Q of capacitor installed on candidate bus #N_{bus}

Fig. 1. Configuration of the particles in PSO algorithm

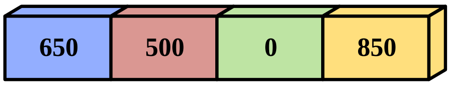


Fig. 2. A typical particle for 4 candidate buses

- The PSO algorithm is easy to implement in MATLAB programming environment;
- It has high convergence speed;
- It is from the family of intelligent optimization algorithms;
- The PSO does not have genetic operators like crossover and mutation; the particles update themselves with the internal velocity and they also have memory which is important to the algorithm.
- PSO actually has two populations, personal bests, and current positions; this allows greater diversity and exploration over a single population (as it is genetic algorithm);
- The momentum effects on particle movement can allow faster convergence (e.g. when a particle is moving in the direction of a gradient), and more variety/diversity in search trajectories.

In the current paper, the sequential PLI based method reduces the search space of the problem by determining potential (candidate) locations for the capacitors; in this way, the problem optimization becomes easier, so that the PSO obtains accurate results by having high convergence speed.

The standard PSO algorithm employs a population of particles. The particles fly through the n-dimensional domain space. The state of each particle is represented by its position $x_i = (x_{i1}, x_{i2}\dots x_{in})$ and velocity $v_i = (v_{i1}, v_{i2}\dots v_{in})$. The modified velocity and position of each individual particle can be calculated using the formulas Eq. (10) and (11).

In Eq. (10) and (11), x_{pbesti} is the personal best position of the particle *i*; x_{gbest}^t is the position of the best particle of the swarm; v_i^{t+1} is the velocity of *i*th particle at (*t*+1)th iteration; x_i^t is the current particle position; r_1 and r_2 are random numbers between 0 and 1; c_1 is the self-confidence (cognitive) factor, and c_2 is the swarm confidence (social) factor; *w* is the inertia weight which is set to decrease linearly from about 1 to 0.6 over the iterations.. After that the high potential (candidate) buses for the capacitor installation are identified, the particles of PSO algorithm are configured as the Fig. 1. In this figure, the *i*th part of each particle shows the value of installed capacitor on the corresponding bus. For example, if the candidate buses determined by the sequential PLI method are as 10, 18, 21, 25, a typical particle may be as Fig. 2. According to this figure, three capacitors with the capacities of 650, 500, and 850 kVAr have been installed respectively on the buses 10, 18, and 25; and also, no capacitor has been installed on bus 21. The implementation flowchart of the proposed method is depicted in Fig. 3.

6. SIMULATION RESULTS

In accordance with the presented equations in the previous section, a program is developed in MATLAB software and the analyses have been carried out on a computer with Intel(R) Core(TM) 2 Duo CPU @2.2 GHz, 4 GB RAM. To investigate the performance and applicability of the proposed approach, it has been tested on several distribution networks (15-bus, 33-bus, 34-bus, 69-bus, 85-bus, and 118-bus), and an actual 94-bus radial distribution network. Only three distribution networks: the 34-bus, 85-bus, and the 94-bus have been selected for reporting in this article. To observe the effectiveness of the proposed approach, the obtained results are compared with the other methods. Due to the impact of loss in the objective function calculation, all of the existing methods

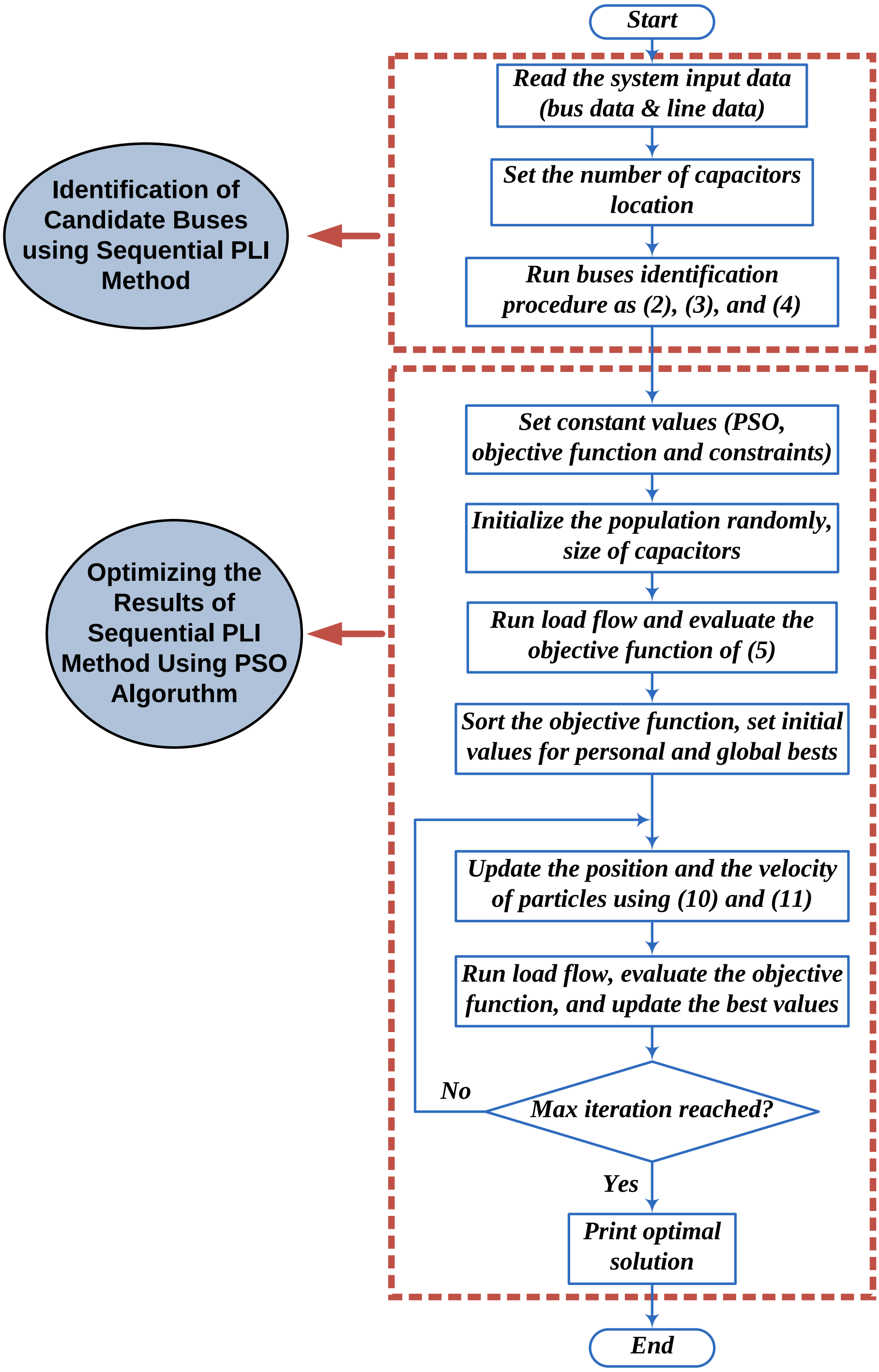


Fig. 3. The implementation flowchart of hybrid PSO and sequential PLI-based method

results are recalculated by the load flow technique of this paper. The control parameters of PSO algorithm and constraints are shown in Table 2. For producing non-similar populations, the initial population, as reported in Fig. 3, has been generated randomly. Off course, the algorithm is executed several times to make sure that no better result can be found. Also, the authors put the best result in the initial population, and executed the program for several times to make sure that the obtained result is optimal. The bus voltage constraint is (1 p.u. ± 5%) for 34-bus and (1 p.u. ± 10%) for 85-bus and 94-bus test cases, respectively. The proposed method can obtain the optimum solution by setting the number of

high potential buses (N_{loc}) to 4, 5, and 3 for 34-bus, 85-bus, and 94-bus test cases, respectively. Different results are obtained by adjusting the value of X from 0 to 90 in the proposed approach.

6.1. The 34-bus network

The 34-bus radial distribution network consists of a main feeder and 4 sub-feeders, as shown in Fig. 4. The line and load data of this system are given in [21]. The total load and the rated voltage of this system are (4636.5 + j2873.5) kVA and 11kV, respectively. The active power loss before the compensation is 221.7235 kW. By adjusting the value of X, i.e. the value of tolerance percentage, the numerical results for the 34-bus network have been reported in Table 3. It is observed that the high potential buses and the objective function change by adjusting the value of X. The results have been obtained in two scenarios (with and without voltage limit) for the 34-bus test network. The convergence behavior of the proposed approach in these two scenarios has been shown in Figs. 5 & 6.

Table 2. The control parameters of PSO algorithm and constraints

Item	Setting
Population size	30
c_1	1.6
c_2	1.9
Number of iteration	50
Bus voltage constraint	$0.95 \le V_i \le 1.05$ & $0.90 \le V_i \le 1.10$
Allowable capacitor range	0-1500 kVAr with steps of 50 kVAr

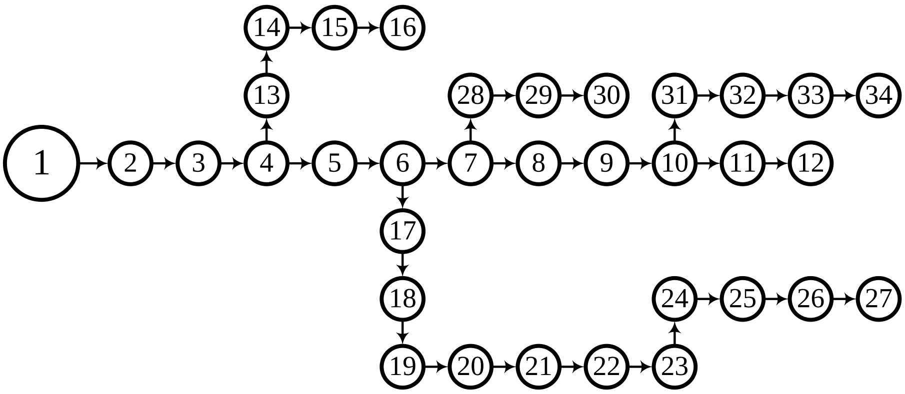


Fig. 4. The single-line diagram of 34-bus radial distribution network

Table 3. Results for 34-bus, 85-bus, and 94-bus networks with different values of *X*

X	34-bus without voltage limit		34-bus with voltage limit		85-bus		94-bus	
	Cost	High potential buses	*Cost*	High potential buses	*Cost*	High potential buses	*Cost*	High potential buses
0	96726	25,21,10,18	97245	25,21,10,18	91065	48,68,30,12,60	154163	21,58,15
10	96726	25,21,10,17	97245	25,21,10,17	91042	48,68,29,12,60	153993	20,58,15
20	96726	25,10,21,18	97245	25,10,21,18	91042	48,68,29,12,60	153993	20,58,14
30	96726	25,10,21,18	97245	25,10,21,18	91063	48,68,12,28,60	153993	20,58,13
40	96791	24,10,20,17	97451	24,10,20,17	91150	35,68,12,28,60	153993	20,58,12
50	96791	24,10,20,17	97451	24,10,20,17	91283	35,67,12,27,61	153993	20,58,11
60	96791	24,10,20,17	97451	24,10,20,17	91401	34,67,12,27,61	153706	20,58,25
70	96872	24,10,19,29	97480	24,10,19,29	91366	34,67,12,26,61	153718	20,58,26
80	96872	24,10,19,29	97480	24,10,19,29	91366	34,67,12,26,76	153787	20,58,28
90	96872	24,10,19,30	97480	24,10,19,30	91366	34,67,12,26,76	153993	20,58,90

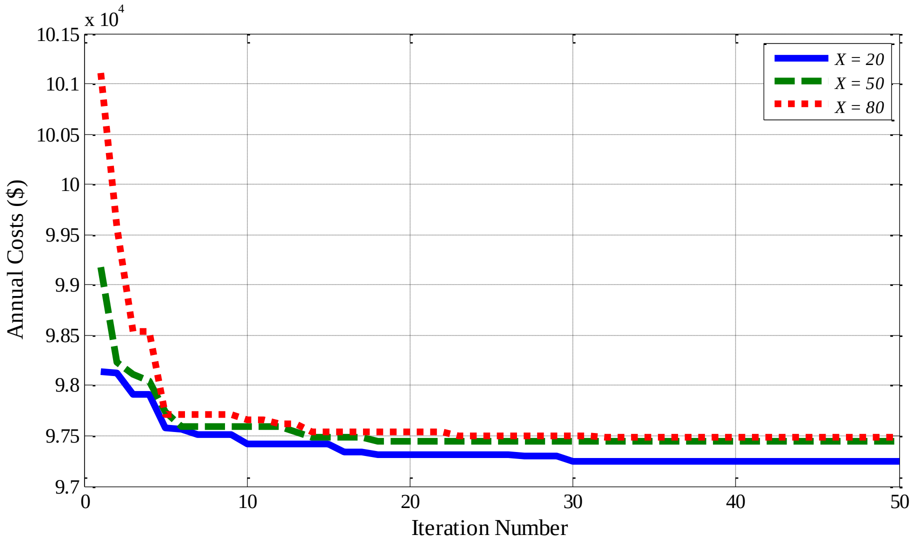


Fig. 5. The convergence behavior of proposed method based on annual cost minimization for 34-bus network (without voltage limit)

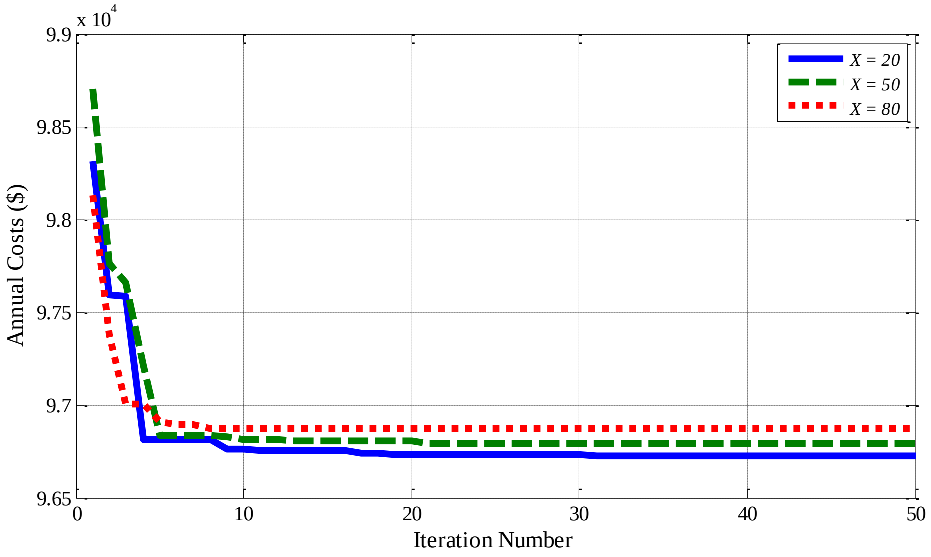


Fig. 6. The convergence behavior of the proposed method for 34-bus network (with voltage limit)

Table 4. Optimal locations and sizes of capacitors for 34-bus system

Proposed method (X= {0,10,20,30})				Existing methods									
Without voltage limit		with voltage limit		Discrete size						Continuous size			
				ABC [2]		EA [13]		CSA [12]		CSA [12]		PSO [4]	
Bus	kVAr	Bus	kVAr	Bus	kVAr	Bus	kVAr	Bus	kVAr	Bus	kVAr	Bus	kVAr
10	600	10	600	19	950	8	1050	9	750	9	767.04	19	781
21	650	21	700	24	900	18	750	20	900	20	834.50	20	479
25	600	25	750			25	750	25	600	25	648.45	22	803

The optimal locations and sizes of capacitors obtained by the proposed approach along with existing methods are listed in Table 4 for the 34-bus network. The technical and economic benefits of the proposed approach are provided in Table 5 for comparison with the existing methods. From Table 5, it is observed that the net yearly saving using the proposed approach in “with voltage limit” scenario is $97245 which is less than that obtained by the other methods. Furthermore, the annual cost is reduced 16.55% with 2050 kVAr installed at 3 locations (10, 21, and 25). However, in “without voltage limit” scenario, the annual net saving increases to $19812 by 0.001 p.u. decrease in the minimum voltage level than instance of “with voltage limit”. One of the remarkable aspects of the proposed approach is that the computational time for finding the optimal solution reduces considerably. The voltages profiles of the 34-bus network with and without compensation for the two scenarios have been shown in Fig. 7. The minimum voltage of the test system improves from 0.9417 to 0.9500 and 0.9490 p.u., respectively for “with” and “without voltage limit” scenarios. The voltage of the slack bus is excluded from the report.

Table 5. Comparing the results of optimal capacitor placement in 34-bus network

Parameter	Without Capacitor placement	Proposed approach (X= {0,10,20,30})		Existing methods				
		without voltage limit	with voltage limit	Discrete size			Continuous size	
				ABC [2]	EA [13]	CSA [12]	CSA [12]	PSO [4]
ΣQ_C (kVAr)	-	***1850***	**2050**	1850	2550	2250	2250	2063
P_{loss} (kw)	221.723	***162.891***	**161.977**	167.989	161.261	160.660	160.620	168.898
P_{loss} reduction (%)	-	***26.53***	**26.95**	24.23	27.27	27.54	27.56	23.83
PF_{overall}	0.8556	***0.9760***	**0.9839**	0.9760	0.9970	0.9904	0.9904	0.9844
V_{min} (p.u.)	0.9417	***0.9490***	**0.9500**	0.9497	0.9502	0.9500	0.9500	0.9496
V_{max} (p.u.)	0.9941	***0.9949***	**0.9950**	0.9949	0.9952	0.9950	0.9951	0.9950
Cost/year ($)	116538	***96726***	**97245**	98785	99369	97553	97532	100948
Cost reduction (%)	-	***17.00***	**16.55**	15.23	14.73	16.29	16.31	13.38
Saving/year ($)	-	***19812***	**19293**	17753	17169	18985	19006	15590
Computational time (s)	-	***6.75***	**6.67**	N/A	N/A	34.16	36.83	N/A

Note: The bold/bold italic values represent the results of proposed approach with/without voltage limit scenarios

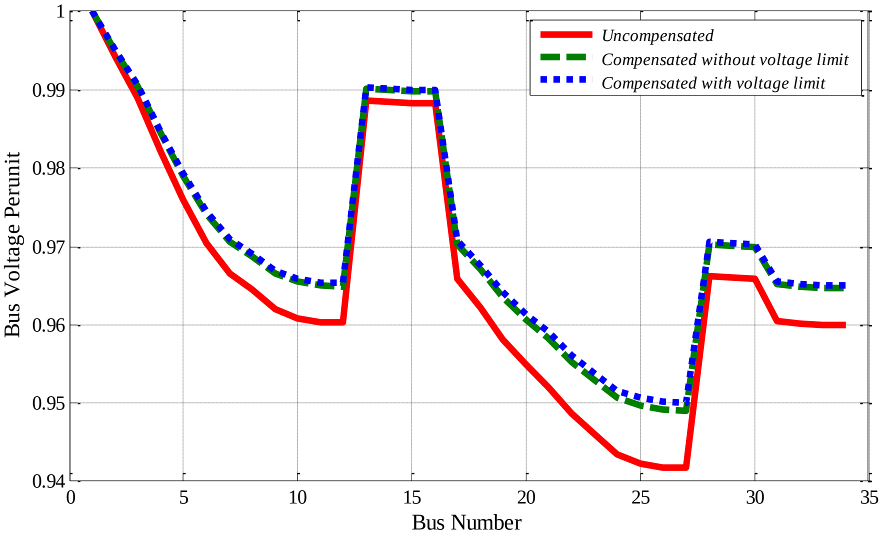


Fig. 7. Voltage profile of the 34-bus network

6.2. The 85-bus network

To show the applicability of the proposed approach for large-scale distribution networks, it is implemented on 85-bus test network. Fig. 8 shows the single-line diagram of this network. The line and load data of this system are taken from [22]. The total load of system is (2570.28 + j2622.21) kVA, and the active power loss without compensation is 316.136 kW. By adjusting the value of X, the numerical results for the 85-bus network are tabulated in Table 3. It is observed that the optimum solution is obtained when X is equal to 60. The convergence trend of the proposed approach for the 85-bus network is illustrated in Fig. 9.

Table 6 shows the optimal locations and sizes of capacitors obtained by the proposed approach along with the existing methods for the 85-bus network. The proposed approach suggests 2000 kVAr compensation installed on five locations (10, 21, 25, 48, and 25). The technical and economic benefits of the proposed approach in the case of 85-bus network are provided in

Table 7 in comparison with the existing methods. From Table 7, it is observed that the proposed approach achieves the minimum annual cost ($91042), and consequently, the maximum net yearly saving ($75119). The active power loss is reduced to 148.292 kW. Furthermore, the overall power factor has been enhanced from 0.7152 to 0. 9671. The voltage profile of the network with and without compensation has been shown in Fig. 10. The minimum voltage of this test system improves from 0.8713 to 0.9187 p.u.

6.3. The 94-bus network

The 94-bus test case is an actual radial distribution network with the total load of (4797 + j2323.9) kVA. This system is illustrated in Fig. 11. The line and load data of this system are obtained from [23]. The active power loss of this system before the compensation is 362.8587 kW. By adjusting the value of *X*, the numerical results for 94-bus networks are presented in Table 3. Similar to 34-bus and 85-bus networks, the high potential buses and the objective function for the 94-bus network change by variation of *X*. The proposed approach achieves the minimum cost when *X* equals to 60. The convergence curve of this case is presented in Fig. 12. Table 8 shows the optimal locations and sizes of capacitors obtained by the proposed approach along with the ABC based method for the 94-bus network. The proposed approach suggests 3 locations (20, 25, and 58) with the total reactive power of 1800 kVAr. The technical and economic benefits of the proposed approach are provided in Table 9 along with the results of existing method in case 94-bus network. From Table 9, it is observed that the proposed approach leads to 19.41% reduction in the annual cost. The active power loss is reduced to 271.777 kW.

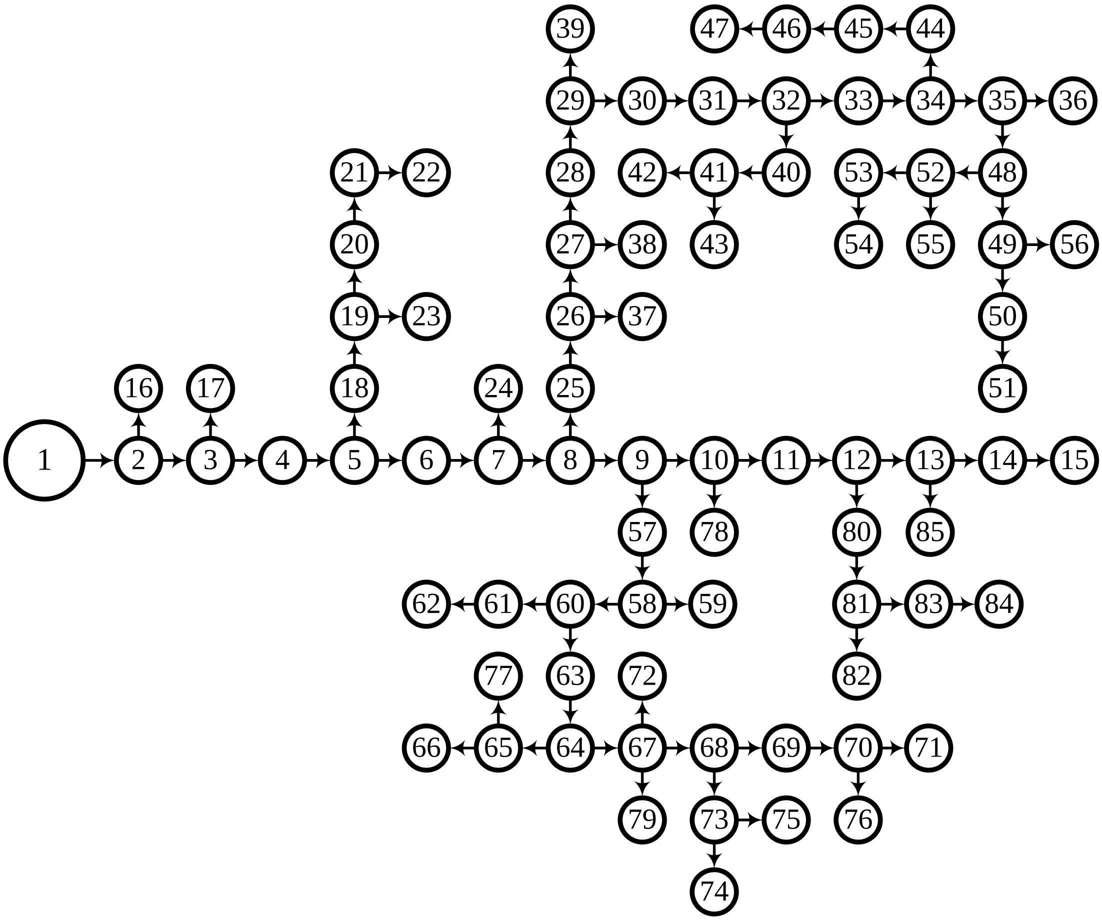


Fig. 8. The single-line diagram of 85-bus radial distribution network

Table 6. Optimal locations and sizes of capacitors for 85-bus network

Proposed approach	Existing methods

(*X*= {10,20})		Discrete size						Continuous size					
		TLBO [14]		DSA [15]		CSA [12]		PSO [4]		GA [11]		CSA [12]	
Bus	kVAr	Bus	kVAr	Bus	kVAr	Bus	kVAr	Bus	kVAr	Bus	kVAr	Bus	kVAr
12	400	4	300	6	150	18	150	7	324	26	48.437	8	367
29	450	7	150	8	150	27	150	8	796	28	214.06	68	356
48	400	9	300	14	150	29	300	27	901	37	103.12	32	220
60	400	21	150	17	150	42	150	58	453	38	120.31	63	313
68	350	26	150	20	150	48	300			39	178.12	12	337
		30	0	26	150	60	450			51	100	44	175
		31	300	30	150	69	300			54	212.5	48	347
		45	150	36	450	80	450			55	101.56	21	134
		49	150	57	150					59	4.687		
		55	150	61	150					60	157.81		
		61	300	66	150					61	112.5		
		68	300	69	300					62	104.68		
		83	150	80	150					66	9.375		
		85	150							69	100		
										72	67.18		
										74	112.5		
										76	71.87		
										80	356.25		
										82	31.25		

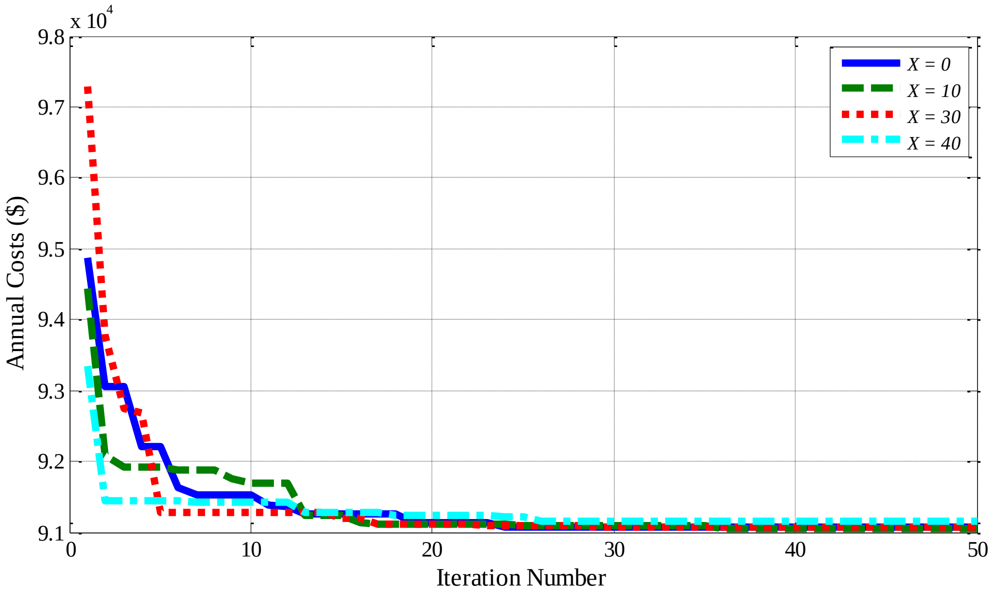


Fig. 9. Convergence trend of the proposed method for 85-bus network

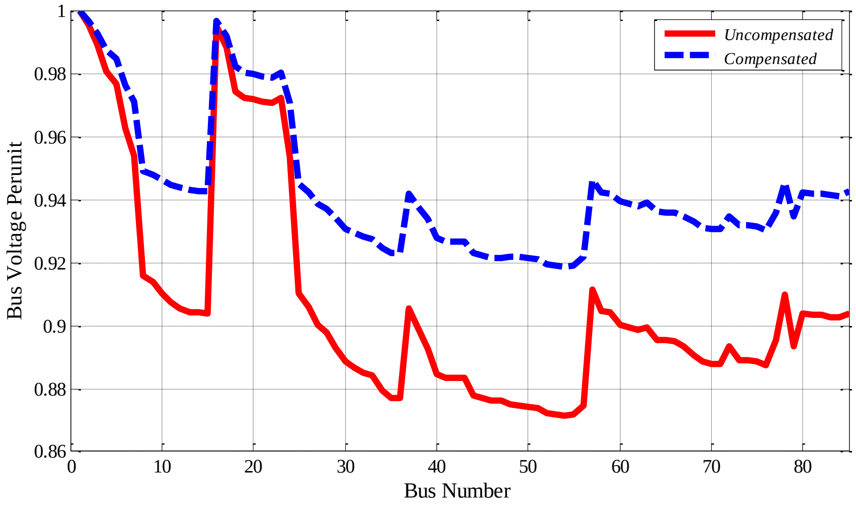


Fig. 10. Voltage profile of the 85-bus network

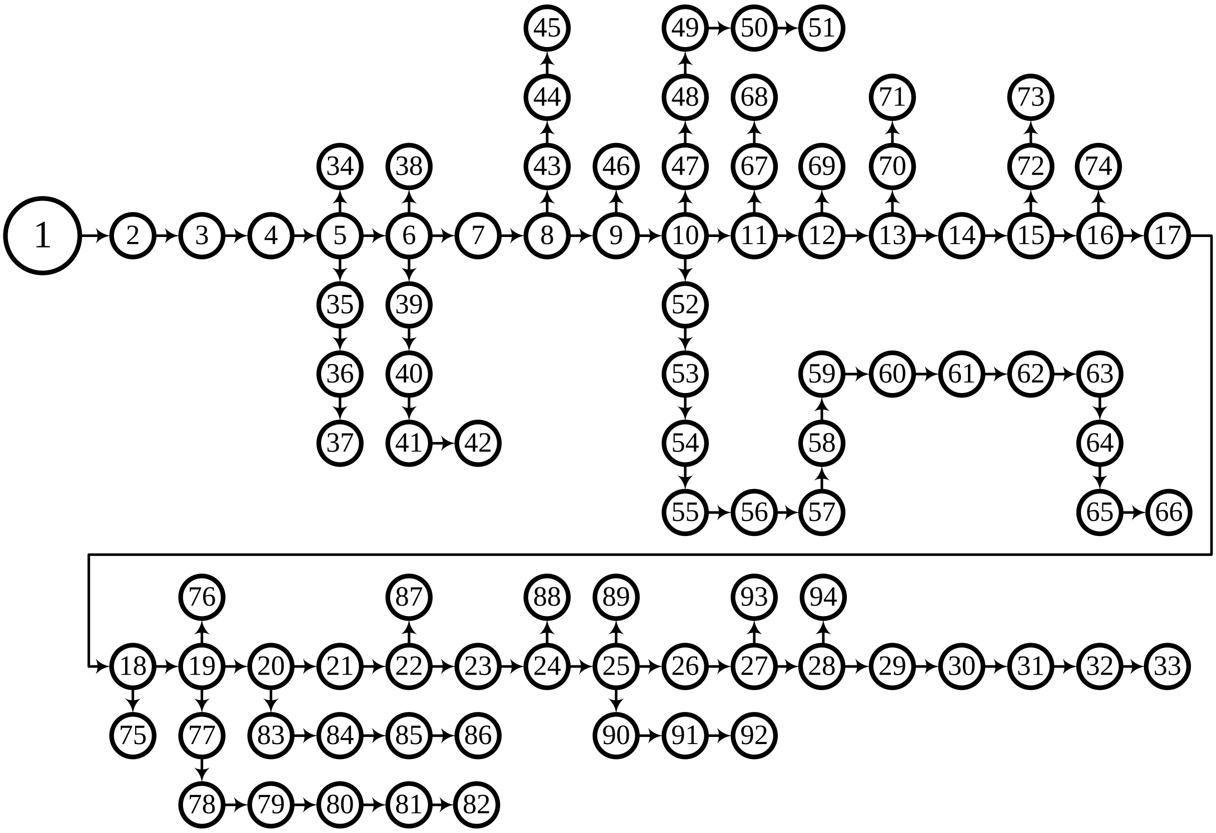


Fig. 11. The single-line diagram of 94-bus radial distribution network

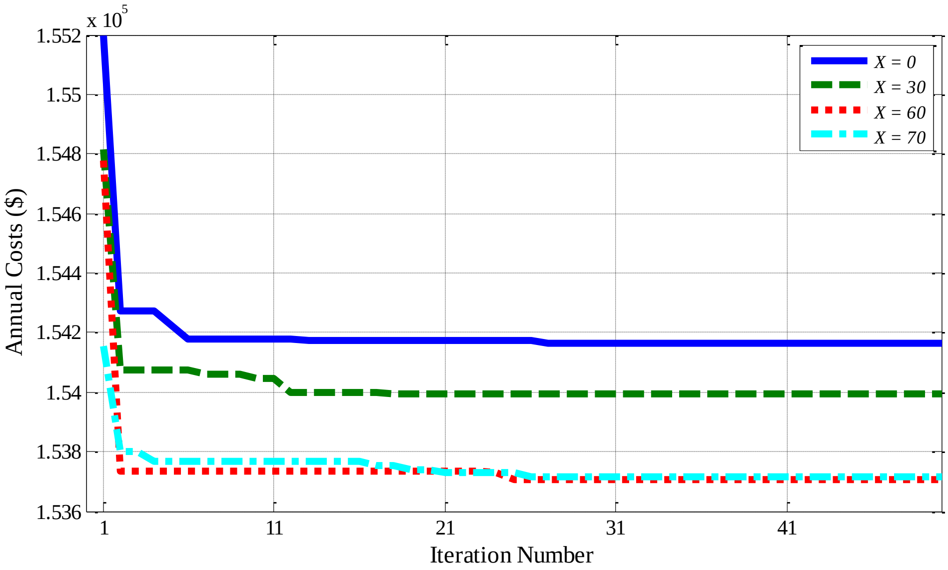


Fig. 12. The convergence trend of the proposed method based on annual costs for 94-bus network

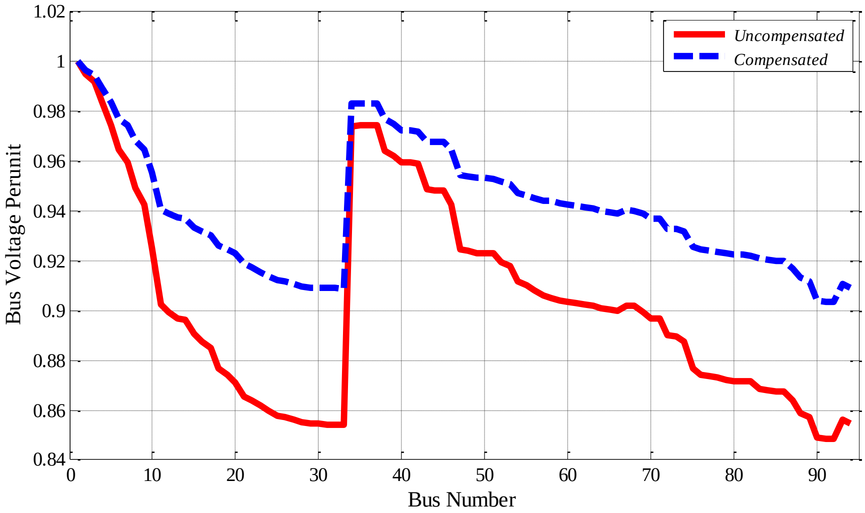


Fig. 13. Voltage profile of the 94-bus network

Table 7. Comparing the results of optimal capacitor placement in 85-bus system

Parameter	Without Capacitor placement	Proposed approach (X= {10,20})	Existing methods					
			Discrete size			Continuous size		
			TLBO [14]	DSA [15]	CSA [12]	PSO [4]	GA [11]	CSA [12]
ΣQ_C (kVAr)	-	**2000**	2700	2550	2250	2473	2206.25	2250
P_{loss} (kw)	316.136	**148.292**	143.191	145.863	146.094	163.545	146.247	145.221
P_{loss} reduction (%)	-	**53.09**	54.71	53.86	53.79	48.27	53.74	54.06
PF_{overall}	0.7152	**0.9671**	0.9999	0.9934	0.9858	0.9959	0.9830	0.9857
V_{min} (p.u.)	0.8713	**0.9187**	0.9242	0.9179	0.9201	0.9156	0.9246	0.9216
V_{max} (p.u.)	0.9957	**0.9971**	0.9976	0.9974	0.9973	0.9974	0.9973	0.9973
Cost/year ($)	166161	**91042**	96821	97475	92997	100804	99679	92538

Cost reduction (%)	-	**45.21**	41.73	41.34	44.03	39.33	40.01	44.31
Saving/year ($)	-	**75119**	69340	68686	73164	65357	66482	73623
Computational time (s)	-	**13.25**	18.38	N/A	174.86	N/A	N/A	199.32

****Note***: The bold values indicate the results of proposed approach

Table 8. Optimal locations and sizes of capacitors for 94-bus system

Proposed approach (*X*=60)		Existing method	
		ABC [2]	
Bus	kVAr	Bus	kVAr
20	750	18	600
25	250	21	450
58	800	54	1050

Table 9. Comparing the results of optimal capacitor placement in 94-bus system

Parameter	Without Capacitor placement	Proposed approach (*X*=60)	Existing method
			ABC [2]
ΣQ_C (kVAr)	-	**1800**	2100
P_{loss} (kw)	362.858	**271.777**	271.359
P_{loss} reduction (%)	-	**25.10**	25.22
PF_{overall}	0.8769	**0.9846**	0.9931
V_{min} (p.u.)	0.8485	**0.9036**	0.9072
V_{max} (p.u.)	0.9951	**0.9967**	0.9970
Cost/year ($)	190718	**153706**	154986
Cost reduction (%)	-	**19.41**	18.74
Saving/year ($)	-	**37012**	35732
Computational time (s)	-	**13.54**	N/A

****Note:*** The bold values indicate the results of proposed approach

Moreover, the overall power factor has been enhanced from 0.8769 to 0.9846. The voltage profile of the 94-bus network with and without compensation has been depicted in Fig. 13. The minimum voltage of this system improves from 0.8485 to 0.9036 p.u.

7. CONCLUSION

In this paper, a novel and simple approach named hybrid PSO-sequential PLI has been presented and successfully applied to the capacitor allocation problem in radial distribution networks. The objective function is to minimize the annual network costs. In the proposed approach, after estimating the number of capacitors locations, these locations have been identified by adding capacitors and calculating PLI (Power Loss Index) sequentially. This approach can determine the buses for the capacitor installation by tuning the value of tolerance percentage (*X*). Finally, the optimal locations and sizes of the capacitors have been obtained by the PSO algorithm. The validity and effectiveness of the proposed approach is tested on 34-bus, 85-bus, and 94-bus radial distribution networks. The numerical results confirm that the proposed method is capable of finding optimal solution better than the other methods reported in the literature. Furthermore, due to restriction of the optimization search space to the number of estimated locations, the proposed approach has a fast convergence toward the optimal solutions. Implementation of the proposed approach results in more power loss reduction, more power factor correction, better voltage profile, and the increase in annual network saving.

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