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Allocation of distributed generation and capacitor banks in distribution system

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ABSTRACT

Voltage profile and power losses on the distribution system is a function of real and imaginary power loading condition. This can be effectively managed through the controlled real and reactive power flow by optimal placement of capacitor banks (CB) and distributed generators (DG). This paper presents Adaptive Particle Swarm Optimization (APSO) to efficiently tackle the problem of simultaneous allocation of DG and CB in radial distribution system to revamp voltage magnitude and reduce power losses. The modification to the conventional Particle Swarm Optimization (PSO) was achieved by replacing the inertial weight equation (W) in the velocity update equation, based on the particle best experience in the previous iteration. The inertial weight equation is designed to vary with respect to the iteration value in the algorithm. The proposed method was investigated on IEEE 30-bus, 33-bus and 69-bus test distribution systems. The results show a significant improvement in the rate of convergence of APSO, improved voltage profile and loss reduction.

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1. INTRODUCTION

The global increase in electrical power demand and the natural depletion in fossil fuel had necessitated the alternative sources of power generation [1]. The conventional method of transmission line upgrading is highly capital demanding with limited expansion in power capacity. In modernized distribution power system planning and operation, (DG) with microgrid (MD) had being a viable alternative and solution to power challenges [2]. DG, equally known as dispersed generation annexes small-scale technologies that can be powered by renewable energy sources for the production of electricity at users' vicinities. Technical advantages of renewable generation include reduction of pollution, power loss minimization, voltage stability enhancement and reliability improvement in distribution network. It can be modelled as induction and synchronous generators depending on its expected operation mode, either to generate reactive power only or generation of both real and reactive power [3]. DG are modeled at unity power factor to deliver active power sources. The involvement of non-programmable renewable resources raises many technical issues in the operation of modern power distribution networks. With conventional radially structured distribution networks, some technical challenges limit the integration of DG units: increase fault current magnitude, possible reserve power flow, ampacity violations and voltage variation from the operation limit [4].

Conventionally, capacitor banks (CB) are placed on distribution system for reactive power compensation. It is a reactive load generator. Its utilization benefits includes: minimization of power reduction due to losses, power factor regulation and maintenance of voltage regulations on load buses of the network [5]. Power loss reduction and voltage deviation improvement are significant and influential on the operation of distribution network, in supplying economical and high-quality power supply to consumer load [5, 6]. Sizing and allocation of DG units with capacitor banks demands thorough investigation to avoid abnormal rise in voltage on distribution feeders, line overloading and uneconomical investment cost. Therefore, evaluating the optimal penetration level, DG location along with capacitor banks for power quality improvement, while maintaining required operating condition is imperative [8].

About ten years ago, different research papers had been published on optimal location and sizing of DGs [9]. Appreciable researchers targeted integration of capacitor banks in distribution system [10]. However, some recent papers focus on optimal sizing and placement of DGs along with capacitor banks on power distribution system. In addition, PSO had been convincingly implemented in power system researches and other engineering fields [11]. It was clearly shown that PSO performed better, faster and accurate in comparison to other methods [12]. The velocity equation of PSO was modified in [13] by addition of new terms and evaluation of difference in the global best and local best of particles. It outperformed other PSO modification in term of convergence speed, quality of accuracy when tested on various system models. An adaptive PSO was presented in [14], the particle velocity is adjusted using the inertial weight strategy such that the best fitted particle navigated in comparison to speed inspired low fitted particles. In [15], the optimum simultaneous DG and capacitor placement was presented, considering power loss minimization as a fitness function. The method was tested on standard IEEE bus system. The authors in [16] presented an algorithm for optimal allocation of DG using improved Genetic for IEEE-33 bus distributed system to compute the best performing reactive power control variables for active power loss reduction and maximize voltage profile. The method reduced the multi-objective function into single objective to avoid the complexity involved in multi-objective problem. In [17], the load variations is considered to capture the system dynamic nature. The loss sensitivity factors was used to evaluate and determine the bus where compensation is required. Thereafter PSO was employed to evaluate the capacities of the capacitor banks to be placed. For the varying sensitivity factors: reduced power losses with better energy conservation was recorded. Comparative analysis of PSO and other techniques like genetic algorithm, tabu search and hybridization method shows that PSO produces better saving, reduced losses and ameliorated voltage profile.

This work presents the simultaneous DG and capacitor bank allocation in distribution network, while considering minimization of power losses and voltage profile maximization as fitness function. The voltage boundary limits are considered as system constraints. The modification was achieved by replacing the inertial weight (w) in the velocity update base on the success achieve in exploration and exploitation of the search space. The technical achievement of a particle in its current location is determined to decide choice of inertial weight for such particle for the next iteration. In addition, the particles trailed the sensitivity of the buses to enhance better convergence.

2. RESEARCH METHOD

As shown is 1 gives the proposed mathematical model for the simultaneous DG and capacitor placement considering the fitness function as minimization of total active power losses

$$Min\ f = \sum_{l=i}^{NL} K_i R_i I_i^2 \qquad i \in NL \tag{1}$$

Such that

$$K_i \left| I_i \right| \le I_{l\max} \qquad i \in NL \tag{2}$$

$$V_{i\min} \le V_i \le V_{i\max} \qquad i \in NL \tag{3}$$

$$P_i \left| P_i \right| \le P_{i\max} \qquad i \in NL \tag{4}$$

$$Q_{c_{\max}} \le Q_{total} \tag{5}$$

Where

I_i is line current in branch i
R_i is resistance of branch i
V_i is node voltage at node i
P_i is real power in branch i
Qi is reactive power in branch i
Q_{cmax} is maximum size of CB
Q_{total} is total reactive power demand
K_i represents the topological status of the branches
N is sum of branches
NL is the set of branches

The voltage stability proposes potential of distribution network within voltage limit against the variation in load demand. The fitness function is expressed as 6.

$$f_2 = \min_{i \in 2,\ldots,N} \left\{ V_s^4 - 4V_s^2 \left(R_i P_{Li} + X_i Q_{Li} \right) - 4\left(X_i P_{Li} + R_i Q_{Li} \right)^2 \right\} \tag{6}$$

Modeling of DG unit presented in PQ node mode adopted are:

a) DG as 'Negative PQ load' model of PQ mode. The DG is simply modeled as a constant active (P) and reactive (Q) power generating source. The given values of the DG model are real (P_{DG}) and reactive (Q_{DG}). The modified load at bus i with DG unit is expressed as:

$$P_{load,i} = P_{load,i} - P_{DG,i} \tag{7}$$

$$Q_{load,i} = Q_{load,i} - Q_{DG,i} \tag{8}$$

b) DG as 'Constant Power Factor' model of PQ mode. Synchronous generator and power electronic based DG units was modeled as constant power factor model. The power output was regulated by controlling the exciting current and trigger angles for synchronous generator and power electronic base DGs respectively. As shown in 9 and 10 give the reactive power and equivalent current injection of the DG respectively.

$$Q_{iDG} = P_{iDG} \tan(\cos^{-1}(PF_{iDG})) \tag{9}$$

$$I_{iDG} = I_{iDG}^r(V_{iDG}) + jI_{iDG}^i(V_{iDG}) = \left(\frac{P_{iDG} + jQ_{iDG}}{V_{iDG}} \right)^* \tag{10}$$

Where, I_{iDG}^r is real component of DG current injection,

I_{iDG}^i is Imaginary component of DG current injection.

c) The DG as PV node is commonly constant voltage model. The given values of the DG model are the real power and bus voltage magnitude. In order to maintaining constant voltage, voltage variation with time is maintained approximately zero by injecting required reactive power. In this work, the DG was configured to supply both the real and reactive power while the CB supplied the reactive power.

The backward/forward sweep (BFS) technique for load flow analysis was adopted for the work. The ratio of resistance to reactance (R/X) in distribution system is high and the conventional power flow methods like the Newton-Raphson cannot be perfectly fitted, taking into cognizance their method of derivation. Therefore, it may experience convergence difficulty in solving power flow in radial distribution network. In the BFS technique, the network system is assumed to be balanced and is represented by an equivalent single line diagram. The analysis starts from one branch to another in a sequential way until all the branches in the feeders have been traced. The bus voltages, except the source bus, are initially assumed to be one (1) pu at angle zero (0). Based on these voltages and given real and reactive power, the branch currents, proceeding from the end buses to the source, are evaluated and saved (Backward Sweep). It is however, requires a sequential procedure to ensure the network branches are rightly traced. The branch incidence table was used to avoid skipping of busses and branches. Then, branch currents, are computed to calculate the real and reactive power loss on the network. The current at the source end is now obtained using 11:

$$I = \sum_{\substack{i=1 \\ i\neq s}}^{n} P_i + \sum_{\substack{j=1 \\ i=1 \\ i\neq j}}^{n} P_{Loss.ij} + j(\sum_{\substack{i=1 \\ i\neq s}}^{n} Q_i + \sum_{\substack{j=1 \\ i=1 \\ i\neq j}}^{n} Q_{Loss.ij}))/V_s^* \quad (11)$$

$$Z_{ij} = R_{ij} + jX_{ij} \quad (12)$$

$$V_{Drop.ij} = V_j - V_i = I_{ij}Z_{ij} \quad (13)$$

$$P_{Loss.ij} = I_{ij}^2 R_{ij} \quad (14)$$

$$Q_{Loss.ij} = I_{ij}^2 X_{ij} \quad (15)$$

Where:
$\sum_{\substack{i=1 \\ i\neq s}}^{n} P_i$ is summation of active load power connected to entire consumer' end buses;
$\sum_{\substack{i=1 \\ i\neq s}}^{n} Q_i$ is summation of reactive load power connected to the entire consumer' end buses;
$\sum_{\substack{j=1 \\ i=1 \\ i\neq j}}^{n} P_{Loss.ij}$ is summation of branch (ij) real power loss across the all network branches;
$\sum_{\substack{j=1 \\ i=1 \\ i\neq j}}^{n} Q_{Loss.ij}$ is summation of branch (ij) reactive power loss across the all network branches;
V_s^* is the conjugate of the source voltage;
I is current at the source end;
Z_{ij} is impedance of branch ij;
R_{ij} is resistance of branch ij;
X_{ij} is reactance of branch ij;
$V_{Drop.ij}$ is voltage drop across branch ij
V_j *and* V_i are voltage at bus j and i respectively;
I_{ij} is current through bus i to j.

The forward sweep is then begins at the source to the end of the feeders to compute voltage drop using 13, current (I_{ij}), real and reactive power losses using 14 and 15 respectively. The evaluated total power losses are compared to initial values computed by assuming one per unit voltage for all buses. If the difference exceeds the tolerance limits, the source current is re-computed using 11, in terms of the newly obtained losses, and the path retracting operation is repeated. The computation procedure is repeated until the variation in losses between successive values of the source current is within the specified tolerance limit. The PSO particle's velocity and position is mathematically modeled as:

$$v_i^{k+1} = wv_i^k + c_1 rand_1 \times \left(pbest_i - x_i^k\right) + c_2 rand_2 \times \left(gbest - x_i^k\right) \quad (16)$$

Where v_i^k is agent i velocity at iteration k, w is weighting function, c_1 *and* c_2 are acceleration coefficients, rand is random number between 0 and 1, x_i^k and x_j^k are agent i and j current position at iteration k respectively, $pbest_i$ is the pbest of agent i, and gbest is the gbest of the group. The particle position is updated using 17.

$$x^{k+1} = x_i^k + v_i^{k+1} \quad (17)$$

The weighting factor is expressed as

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{Itre_{\max}} Itre \quad (18)$$

Where w is the weighting function, w_{max} and w_{min} are maximum and minimum weights, $Itre_{max}$ and $Itre$ are maximum and current iteration respectively. The choice of inertia weight plays a significant role in the performance of the particle swarm optimization. The modification on the inertial weight (w) in the velocity update was based on the success achieve in exploration and exploitation of the search space. The technical achievement of a particle in its current location is determined to decide choice of inertial weight for such particle for the next iteration. In addition, the particles trailed the sensitivity of the buses to enhance better convergence.

The Figure 1 shows the proposed algorithm for the adaptive base PSO for simultaneous location of DG and CB. If the P_D is the total power demand on distribution network. Q_D is the total reactive power on the network. Therefore:

$$S_D = P_D + Q_D \quad (19)$$

S_D defines the total network loading. Representing a particle by:

$$P = \left[P_1, P_2, P_{3,} P_{4,} ....P_{np} \right] \quad (20)$$

If Nb represent the number of buses on the network such that: (b = 2,3,4…Nb) represent the possible location of DG or CB on the network. Thus:

$$2 \le L_{DG} \le Nb \; and \; 2 \le L_{CB} < Nb$$

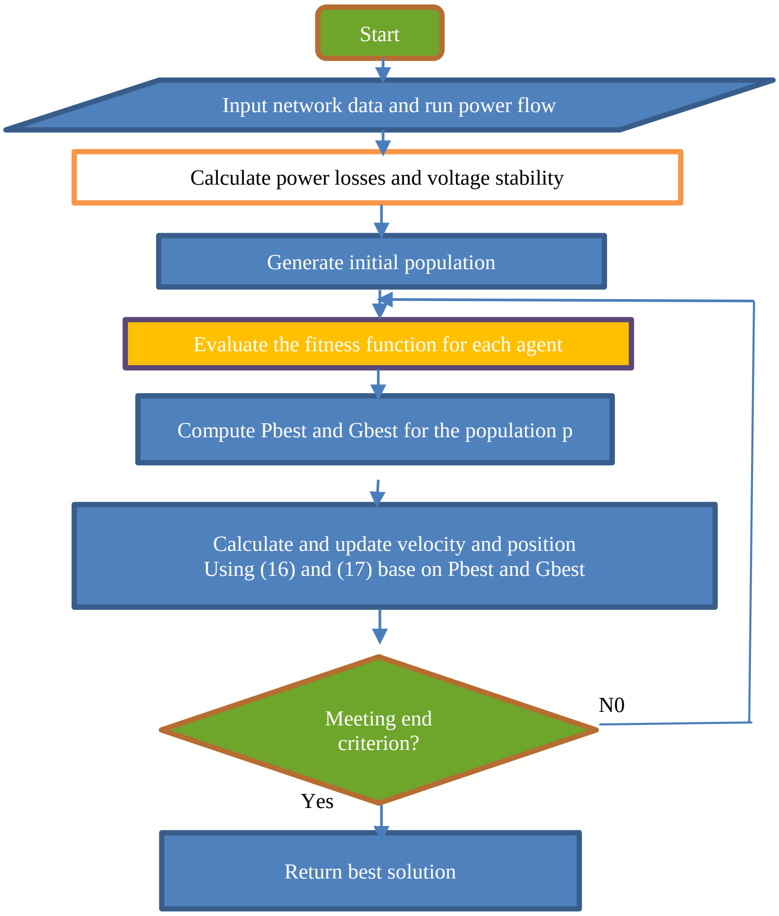

Figure 1. Flowchart of the proposed method

The structure of each particle is shown in Figure 2.

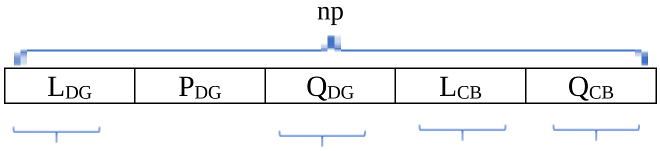

Figure 2. Structure of particle

$$np = np_1 + np_2 + np_3 + np_4 + np_5 \quad (21)$$

np represents the total number of parameters in a given particle or dimension of particle.

Where:
L_{DG} is location of DG
P_{DG} is real power of DG
Q_{DG} is reactive power of DG
L_{CB} is location of CB
Q_{CB} is reactive power of CB

3. RESULTS AND ANALYSIS

The proposed algorithm is simulated using the IEEE 30, 33 and 69-bus radial network with base voltage of 12.66kV and the base apparent power is 10MVA. Figure 3 and Figure 4 show the single line diagram of 33-bus system and 69-bus system [18].

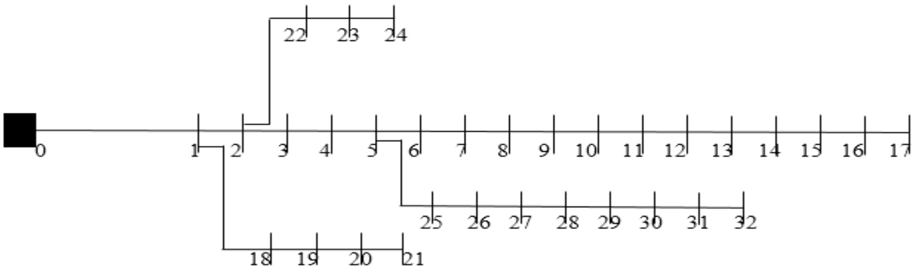

Figure 3. Single line diagram of 33-bus distribution test system

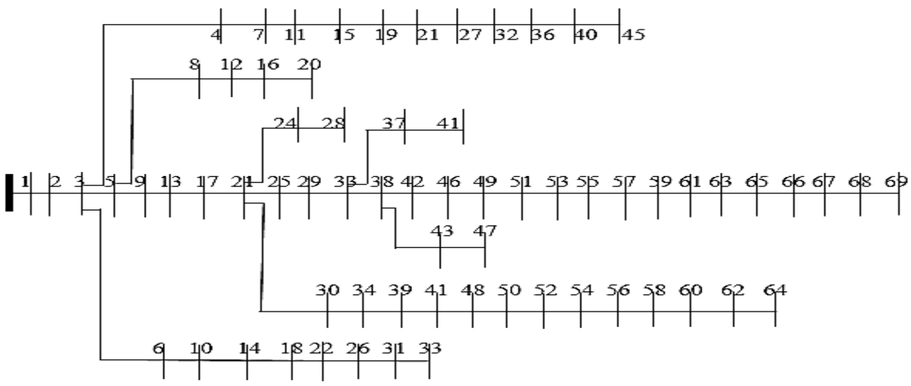

Figure 4. Single line diagram of 69-bus distribution test system

3.1. Base Case System Analysis

Initially, load flow analysis was carried out on 30-bus system for the determination of voltage profile and power loss. Total power loss is 0.0087 + 0.0026i (0.0091) in per unit. For 33-bus system, the total power loss of the system is 0.0027 + 0.0011i (0.0029) in per unit. The base case voltage of the 33-bus system before the integration of DG and CB into the network is presented in Table 1. The voltage magnitudes in Table 1 is plotted against their respective bus numbers is shown in Figure 5.

Table 1. Base Case Voltage for 33 Bus Network

Bus no	Voltage without DG&CB	
1	0.9860 + 0.0228i	0.9863
2	0.9752 + 0.0301i	0.9757
3	0.9696 + 0.0338i	0.9702
4	0.9642 + 0.0375i	0.9649
5	0.9489 + 0.0431i	0.9499
6	0.9440 + 0.0420i	0.9449
7	0.9404 + 0.0452i	0.9415
8	0.9348 + 0.0479i	0.9360
9	0.9295 + 0.0503i	0.9309
10	0.9288 + 0.0509i	0.9302
11	0.9277 + 0.0519i	0.9292
12	0.9220 + 0.0543i	0.9236
13	0.9195 + 0.0547i	0.9211
14	0.9182 + 0.0554i	0.9199
15	0.9169 + 0.0561i	0.9186
16	0.9146 + 0.0565i	0.9163
17	0.9140 + 0.0568i	0.9158
18	0.9855 + 0.0230i	0.9858
19	0.9820 + 0.0244i	0.9823
20	0.9812 + 0.0246i	0.9815
21	0.9805 + 0.0248i	0.9808
22	0.9719 + 0.0318i	0.9724
23	0.9655 + 0.0345i	0.9661
24	0.9624 + 0.0359i	0.9631
25	0.9476 + 0.0440i	0.9486
26	0.9460 + 0.0452i	0.9471
27	0.9382 + 0.0482i	0.9394
28	0.9328 + 0.0503i	0.9342
29	0.9307 + 0.0518i	0.9321
30	0.9265 + 0.0529i	0.9280
31	0.9255 + 0.0531i	0.9270
32	0.9252 + 0.0531i	0.9267

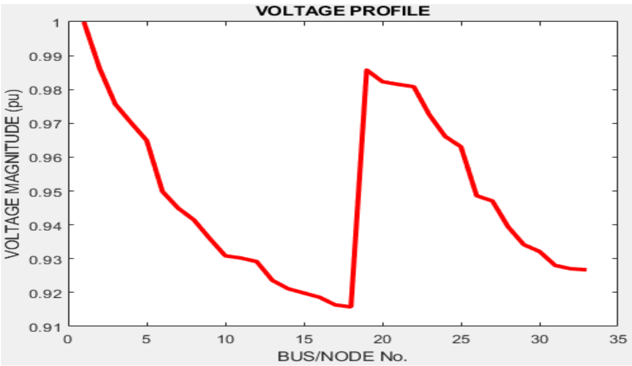

Figure 5. Voltage profile for 33-bus network

The branch profile for 33-bus system by plotting the current magnitude against their respective branch is shown in Figure 6. For 69-bus system, initial load flow was simulated to get the base voltage at each bus and the base total power loss of the system without placement of devices. The base case total power loss is 0.0238 + 0.0107i (0.0261) in per unit. The base case voltage magnitudes is plotted against their respective bus and that of the branch current profile is shown in Figure 7 and Figure 8.

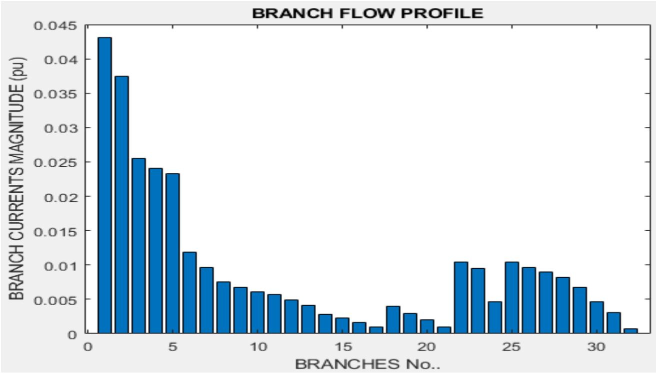

Figure 6. Current magnitude for 33-bus network

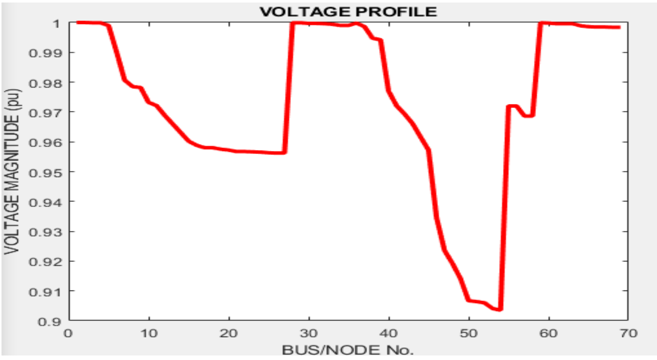

Figure 7. Voltage profile for 69-bus network

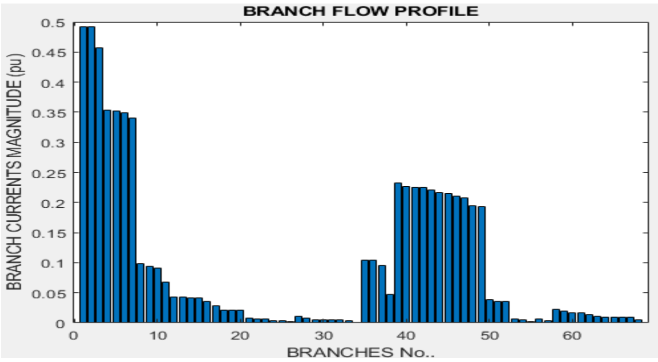

Figure 8. Current magnitude for 69-bus network

3.2. Effects of DG and CB Placement

Applying the proposed method for the optimum DG and CB locations with their corresponding sizes, the computed results are presented in Table 2. The effect of DG and CB placement is also evaluated by calculating the power system losses reduction and system voltage improvement. Table 3 shows effect of DG placement on network performance. The base case of 33-bus system and the improved voltage magnitude is shown in Figure 9.

There is an improvement in voltage profile after the placement of DG and CB on bus 26 and bus 21 respectively. The lowest voltage that is bus 17 with it voltage increases from 0.9158 to 0.9481 per unit voltage. This is an indication that the DG and CB installed has improved the voltages at each bus of the network. The blue line point out the base case voltage trend while the red line point out the voltage profile after DG and CB placement. The 69 bus base case voltage magnitude, and the corresponding improved voltage were plotted against their respective buses. The voltage profile plot is shown in Figure 10.

Table 2. Application of Proposed Algorithm for Simultaneous DG and CB Placement and Sizing

Test System	Proposed Method				
	DG Position	DG Size		CB Position	CB Size (kVar)
		P(kW)	Q(kVar)		
30-Bus	12	37.2	22853.9	17	3808.9
33-Bus	26	1.04	7356.6	21	2908.3
69-Bus	36	891.0	275340.8	42	209229.2

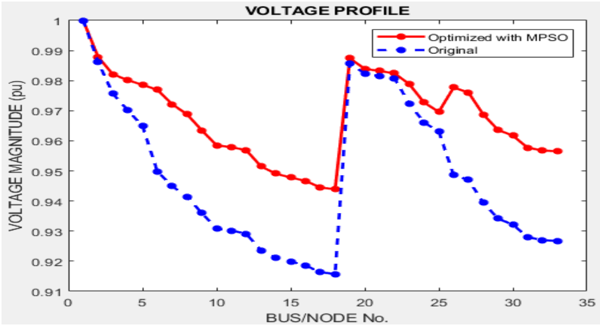

Figure 9. Voltage profile for 33-bus after placement

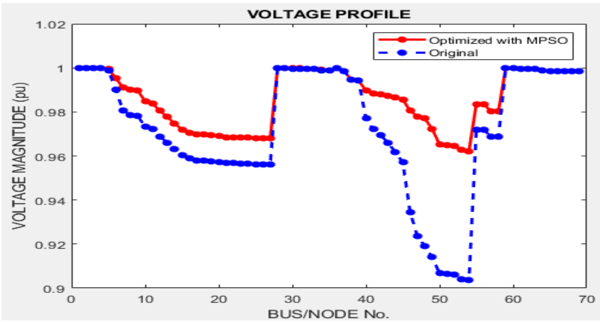

Figure 10. Voltage profile for 69-bus after placement

Table 3. Impact of Proposed Algorithm for Simultaneous DG and CB Placement and Sizing

Test System	Proposed Method						
	Power loss Without DG & CB		Power loss With DG & CB		% Total loss reduction	% Voltage improvement	Simulation Time
	Ploss(kW)	Qloss(kVar)	Ploss(kW)	Qloss(kVar)			
30-Bus	874	256	402	84	55.1%	35%	1.4816s
33-Bus	266	108	102	57	60.2%	42%	3.4909s
69-Bus	2383	1074	1191	482	50.9%	45%	11.1885s

A significant improvement is observed in Figure 10 after DG and CB placement. Bus 53 has the smallest voltage of 0.9322 before DG and CB placement and have increased to 0.965 after the placement. The blue line point out the base case voltage trend while the red line shows the trend of the voltage after placement.

3.3. Comparison of the Method with Existing Method and Network without DG and CB

A comparative examination of the proposed method is further made with other optimization techniques in previous works for establishing its efficiency. More specifically, salient features such as convergence and technical improvement predicated the approach adopted in this work. This MPSO version was given enabling parameters to achieve optimal solution by extending iteration number as high as 1000 with population of 200 particles, and equally achieve a better and fast convergence time of 1.4816sec, 3.4909sec and 11.1885s for 30-bus, 33-bus and 69-bus system respectively compare to [19]. PSO, multi objective genetic algorithm (MOGA) and biogeography based optimization (BBO) technique were used in [20]. The proposed DG and CB allocation method is also helpful for reduction of network power loss and voltage improvement with highest value of 60.2% and 45% respectively.

4. CONCLUSION

Optimal DG and CB placement problem has been solved by using Adaptive particle swarm optimization (APSO) technique. The modification was achieved by replacing the inertial weight (w) in the velocity update. The proposed location and size of active power and reactive power of DG with reactive power of CB had been computed by summing up the loads and losses of all the branches on the distribution network. Through the optimal allocation of DG and CB by the proposed technique, the active and reactive power losses are reduced and the system voltage profile improved.

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