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Optimal Distributed Generators and Capacitor Sitting and Sizing in Distribution Systems with Modified Particle Swarm Optimization

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Abstract: To ensure the good quality of power in electrical distribution systems, voltages at the different nodes should be within reasonable limits. Shunt capacitors banks installed along with the distribution feeders can supply part of the reactive power required by the inductive loads and hence reduces the voltage drops. Further distributed generators (DGs) also improve the voltage profile as well as provide the local real power generation. The improvement in voltage profile in the system is very much sensitive to the locations and sizes of the shunt capacitor banks as well as distributed generators. In this work, the optimal sitting and sizing of capacitors and DG units are found by the proposed algorithm based on modified particle swarm optimization (MPSO). Loss sensitive factors are used to determine the optimal location of DG units and Shunt capacitor units and their size is obtained by M PSO. The proposed algorithm has been solved by considering multiple objective functions viz., minimization of power loss, minimization of cost function and minimization of deviation of bus voltage. The proposed algorithm has been tested on two test systems i.e., IEEE-33 and IEEE-69 bus systems and results are presented and analyzed.

Keywords: Distributed Generators (DGs), Shunt capacitors, Multi objective function, and Modified particle swarm optimization.

I. INTRODUCTION

In a practical power system network especially in distribution system the system operators are always obligated with voltage levels of each customer bus within the satisfied limits. To ensure good voltage profile in distribution systems, several standards have been established to provide recommendations and stipulations. In general many electrical power supply companies try to maintain/control the distribution voltage variations within the range of $\pm 5\%$. One of the most commonly used methods to improve the voltage profiles of distribution systems is connecting shunt capacitor banks along the feeders. Due to the recent advances DGs came into picture to better the voltage profiles further. Distributed Generators (DGs) and Shunt capacitor bank modifies and improves the voltage profile by changing the power flow patterns. Therefore locations of DGs and Shunt capacitor banks have a significant role and impact on the enhancement of voltage profile. In the past two decades, great effort has been contributed to solve the optimal capacitor placement problem that utilizes different methods/algorithms that is based on different objectives.

The optimal capacitor placement problem generally formulated as a mixed integer optimization problem. Several algorithms can help in getting the solution of optimal capacitor placement problem. For instance, a heuristic constructive algorithm (HCA) is presented in [1] where in the integer variable are denoted by a sigmoid function. Another heuristic method is used in [2] to get a near optimal solution for realistic sized systems with an objective function of minimizing harmonic levels, capacitance costs and power losses. This method is extended to unbalanced loads in [3]. Ant colony search algorithm (ACSA) is used in [4] to get solution to optimal capacitor placement problem and network reconfiguration problem.

The Optimal Capacitor placement and its sizing problem in [5] has an objective function of minimizing the cost subjected to voltage profile limits, capacitor sizes at each bus and power quality limits of harmonics. The effect of placement of capacitor on distribution system reliability is considered in [6] by defining multi objective function i.e. reliability cost, investment cost and cost of power losses. Considerable amount of research has also been done on optimal placement of DG as well. An analytical method is presented in [7] to obtain the optimal location of DG units in radial and networked systems to minimize the power loss. Optimal placement of DGs in [8] is fixed by using exhaustive search to optimize the efficiency and system reliability. In this work the system SAIDI is used to represent the reliability. An iterative based algorithm is given in [9], where in continuous power flow is used to find the most sensitive bus to voltage collapse or maximum loading for DG installation. The objective functions of this include the power loss reduction, power transfer capability improvement and to increase the voltage stability margins.

Genetic algorithm (GA) is used in [10] to find the optimal DG location with various load models. The objective function here is based on multi objective index that considers real and reactive power losses, voltage profile and capacity of DG. Immune Algorithm (IA) is used in [11] to optimize the voltage profiles by changing the location of DGs with the constraints of bus voltage limits and line current limits.

An algorithm based on GA is used in [12] to find the location, size and type of DGs used in distribution system based on benefit and cost of the DGs. Ch. Chang et al. [13] presented an Ant Colony Search Algorithm for Capacitor and Reconfiguration problem for loss reduction in distribution networks. I. Ch. Silva et al. [14] reported a heuristic constructive algorithm for optimal capacitor placement in distribution system for voltage profile improvement. M. Kalantari et al. [15] proposed a method to find the DG and Capacitors to reduce the losses and improve the voltage profile using GA. M. Wang et. al. [16] presented two optimization models to improve the voltage profile, first the DG placement is considered and then the optimal capacitor placement is modeled and solved. It has been presented in literature that the reactive power injected by the shunt capacitor banks can effectively reduce the system energy losses and relieve feeder loading [17] and improves the system reliability [18].

E.G. Carrano et al. [19] reported a method for optimal capacitor placement problem based on Genetic Algoirthm to reduce the voltage drops in the distribution system. A. Ahuja et al [50] presented a network reconfiguration and capacitor placement based on Ant Colony Algorithm to reduce the losses and to improve the voltage profile. J.M. Nahman et al. [20] presented an algorithm for optimal capacitor placement problem based on Simulated Annealing (SA) to improve the voltage profile.

II. MODIFIED PARTICLE SWARM OPTIMIZATION (MPSO)

In fundamental PSO, the velocity of an agent or element can be updated by using equation

$$V_{id}^{k+1} = \omega . V_{id}^{k} + c1 . rand * (Pbest_{id} - S_{id}^{k}) + c2 . rand * (Gbest_{id} - S_{id}^{k}) \quad \ldots(1)$$

The velocity update equation given above has three components:

i) The first term is used to referred as "Momentum" or "Inertia". It causes the particle to continue in the same path it has been traveling.

ii) The second term is meant for local attraction in the direction of the best position of a given particle whose corresponding fitness value is called the particles best (P_{best}) scaled by a random weight factor (C_1, rand1). This component is referred as "Self knowledge" or "Memory".

iii) The third term is used to represent attraction towards the best position of any particle whose corresponding fitness value is called global best (G_{best}) scaled by another random weight factor (C_2, rand2). This component is referred to "cooperation", "group knowledge" or "shared information". In MPSO in addition to the particles with best solution, particles having worst solution are also considered and the velocity update equation is modified as

$$V_{id}^{k+1} = \begin{bmatrix} \omega . V_{id}^{k} + c1 \times r1 \times k1 \times (Pbest_{id} - S_{id}^{k}) + \\ c2 \times r2 \times k2 \times (Gbest_{id} - S_{id}^{k}) + \\ c3 \times r3 \times k3 \times (Pworst_{id} - S_{id}^{k}) + \\ c4 \times r4 \times k4 \times (Gworst_{id} - S_{id}^{k}) \end{bmatrix} \quad \ldots (2)$$

Where, C1 and C3 are the cognitive acceleration coefficients, C2 and C4 are the social acceleration coefficients, Gbest is the global best of the entire swarm, G_{worst} is the global worst of the entire swarm, K is the previous iteration number, K+1 is the current iteration number, K=[k1,k2,k3,k4] is switch matrix and its value is [1,1,0,0] for best particles and[0,0,1,1] for worst particles, P_{best} is the particle's best, P_{worst} is the particle's worst r1,r2,r3 and r4 are the random numbers between 0 to 1, S_{id}^{k} is the position of i^{th} particle V_{id}^{k} is the velocity of i^{th} particle. The individual element's position in $(k+1)^{th}$ iteration can be modified according to

$$S_{id}^{k+1} = S_{id}^{k} + V_{id}^{k+1} \quad \ldots (3)$$

i = 1,2,……,n. d = 1, 2,…..,m.

Where s^k is current searching point, s^{k+1} is modified searching point, v^k is current velocity, v^{k+1} is modified velocity of agent i, v_{pbest} is velocity based on Pbest, v_{gbest} is velocity based on gbest, n is number of particles in a group, m is the number of members in a particles, pbest is pbest of agent i, gbest is gbest of the group, ω_i is weight function for velocity of agent i, c_i is weight coefficient for each term.

2.1 Generation of a particle:

Initialization: Following algorithm is used to generate a particle consisting of real and reactive power outputs of DG units and reactive power rating of capacitor units

Step 1: Set i=1

Step 2: Select the active power rating of first DG within the active power generation limits of the respective DG

Step 3: Repeat step 2 for all DG units

Step 4: Select the reactive power rating of first DG within the reactive power generation limits of the respective DG

Step 5: Repeat step 4 for all DG units

Step 6: Select the reactive power rating of first capacitor rating within the limits of its rating

Step 7: Repeat step 6 for all the capacitors

Step 8: increment the particle number i.e., i=i+1

Step 9: If all particles are generated stop the initialization process, otherwise go to step 2.

2.2 Algorithm for optimal sizing

The algorithm to find the optimal sizes of DGs and capacitors is:

Step 1: Read the line and load data of the system and DG units data

Step 2: Calculate the power loss and other objective function values using the distribution load flow for the network before placing

Step 3: Initialize the particles according to the algorithm given above

Step 4: For each particle find the objective function according to equation (7)

Step 5: If the objective function of each particle is better than the previous experience, then update its P_{best}

Step 6: Find the G_{best} by considering the fitness value of all the particles

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Step 7: Find the velocity of each particle according to the equation (2)
Step 8: Update the velocity and position by using equations (3)
Step 9: If the iteration number reaches the maximum limit print the results,
Step 10: Otherwise set increase iteration count by one and go back to step 4.
Finally the optimal size (Real and reactive power outputs) of DGs and rating of capacitors can be observed from final G_{best}

III. PROBLEM FORMULATION

The main aim of the proposed MPSO algorithm is to determine the optimal locations and their optimal sizes of the DGs and capacitor units by minimizing the different objective functions. Three objective functions of minimization of power loss, cost function and deviation of bus voltage are considered in this work.
Based on the sensitivity analysis, loss sensitive factors are calculated for all the buses and these are arranged in the decreased order and top order buses are chosen to install DGs and capacitors. The optimal sizes of these units are determined by determining multi-objective function with modified particle swarm optimization subjected to practical constraints.

3.1 Objective Functions:
3.1.1 Minimization of real power loss:
Minimization of power loss is considered as first objective function for the placement of DG.

$$f_1(x) = Minimizing \sum_{l=1}^{N_l} \left[|I_l|^2 \times R_l \right] \quad \dots (4)$$

Where I_i is the current through branch 'i' and R_i is the resistance of branch 'i'.

3.1.2 Minimization of cost function
Cost function minimization is considered as second objective function. Cost function consists of cost of DG units, cost of substation, cost of capacitor units and cost of energy loss. This cost function is considered for 15 years.

$$f_2(x) = Minimizing \sum_{i=1}^{N_{DG}} C(DG_i) + P_{sub} \times T \times price_{sub} + C(E_L) + \sum_{i=1}^{cn} C(CB_i) \quad \dots (5)$$

Where
N_{DG} is the number of dg units used
$C(DG_i)$ is cost of energy generated by the i^{th} DG units ($)
$C(E_L)$ is the cost of energy loss
P_{sub} is the real power supplied by the substation bus (kWh)
$Price_{sub}$ is the price of energy at substation in ($/kWh)
$C(CB_i)$ is the cost of i^{th} capacitor bank

In this work three DGs (Fuel cell, photo voltaic and wind turbines) are used and their cost function has taken from [21].

3.1.3. Minimization of deviation of bus voltage (D.V.B)
Minimization of deviation of bus voltages is considered as third objective, mathematically it is given as

$$f_2(x) = Minimizing \sum_{i=1}^{N_b} |V_r - V_i| \quad \dots (6)$$

Where Nb is the number of buses or nodes
Vi is the voltage magnitude at i^{th} bus
Vr is the rated voltage magnitude at i^{th} bus (1 p.u.)
Finally multi-objective function can be developed as

$$f(X) = Min \begin{bmatrix} W_1 \times \sum_{l=1}^{N_l} \left[|I_l|^2 \times R_l \right] + \\ W_2 \times \begin{pmatrix} \sum_{i=1}^{N_{DG}} C(DG_i) + P_{sub} \times T \times price_{sub} \\ + C(E_L) \\ + \sum_{i=1}^{cn} C(CB_i) \end{pmatrix} + \\ W_3 \times \sum_{i=1}^{N_b} |V_r - V_i| \end{bmatrix} \quad \dots (7)$$

W_1, W_2 and W_3 are the weighing factors and $W_1+W_2+W_3=1.0$.
3.2 Constraints:
The above objective function is solved by considering a set of practical constraints.
(i) Voltage magnitude constraint
(ii) Feeder capability constraint
(iii) Distributed generator constraint
(iv) Capacitors constraints

IV. RESULTS AND ANALYSIS

The effectiveness of the proposed MPSO algorithm has tested on IEEE-33 and IEEE-69 radial distribution systems for two cases.
Case-1 system with DG units only
Case-2 system with both DG and capacitor units
The objective function values are calculated by considering a single objective values, three combinations of two objective functions and three objective functions for different weight factors. Weight factors are obtained based on non-dominated solutions that are obtained from Pareto set dominance criterion.

Based on sensitivity analysis three DG units are installed at buses 11, 29 and 31, capacitors are installed at buses 6, 8, 29, 30, 9 and 13 for IEEE-33 bus radial distribution system. Three DG units are installed at buses 60, 63 and 62, capacitors are installed at buses 57, 58, 61, 60, 59 and 15 for IEEE-69 bus radial distribution system.
The simulation results of MPSO for IEEE-33 bus system for single objective of minimization of loss, minimization of cost function and minimization of deviation of bus voltage are given in table 1. From these results it is observed that the objective function values have been reduced for the system after placing shunt capacitor units along with the DG units when compared to the system with DG units only. It is also identified from this multi objective MPSO results that, giving importance or priority (allocating higher weight factor) for one objective function does not show much improvement in the other two objective function values.

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TABLE 1: RESULTS OF IEEE-33 BUS SYSTEM FOR SINGLE OBJECTIVE FUNCTIONS

S.No.	Control Parameter	Min. of power loss		Min. of Cost unction		Min. of D.V.B	
		Case-1	Case-2	Case-1	Case-2	Case-1	Case-2
1	P_{DG1}(kW)	154.32	146.22	162.5	125.29	147.43	151.36
2	P_{DG2}(kW)	59.81	59.36	59.24	46.67	64.25	71.11
3	P_{DG3}(kW)	614.38	652.97	611.20	542.84	595.24	648.25
4	Q_{DG3}(kVAr)	407.38	468.31	411.68	424.19	404.38	672.81
5	Q_{c1}(kVAr)	-	164.44	-	158.36	-	164.25
6	Q_{c2}(kVAr)	-	214.32	-	207.69	-	198.69
7	Q_{c3}(kVAr)	-	138.77	-	142.36	-	154.22
8	Q_{c4}(kVAr)	-	78.29	-	88.21	-	88.64
9	Q_{c5}(kVAr)	-	91.14	-	92.45	-	102.47
10	Q_{c6}(kVAr)	-	126.36	-	109.33	-	112.36
11	T.P.L	142.14	120.71	149.48	124.97	154.37	128.71
12	Cost function (Million $)	27.7999	27.6011	27.4890	27.3917	27.8384	27.7168
13	D.B.V	0.924	0.802	0.942	0.814	0.926	0.782

TABLE 2: RESULTS OF IEEE-69 BUS SYSTEM FOR SINGLE OBJECTIVE FUNCTIONS

S.No.	Control Parameter	Minimization of power loss		Minimization of Cost function		Minimization of D.V.B	
		Case-1	Case-2	Case-1	Case-2	Case-1	Case-2
1	P_{DG1}(kW)	164.22	154.98	156.55	138.87	151.66	168.24
2	P_{DG2}(kW)	56.41	56.77	76.22	49.64	61.25	74.61
3	P_{DG3}(kW)	689.35	662.28	671.66	608.58	628.36	632.44
4	Q_{DG3}(kVAr)	411.47	601.25	471.58	614.73	438.59	621.58
5	Q_{c1}(kVAr)	-	102.37	-	106.78	-	108.26
6	Q_{c2}(kVAr)	-	116.27	-	135.77	-	127.45
7	Q_{c3}(kVAr)	-	138.57	-	155.78	-	148.38
8	Q_{c4}(kVAr)	-	74.25	-	62.78	-	61.27
9	Q_{c5}(kVAr)	-	107.87	-	121.22	-	106.72
10	Q_{c6}(kVAr)	-	81.87	-	71.58	-	84.74
11	T.P.L (kW)	158.78	138.26	159.44	139.62	166.24	142.49
12	Cost Function (Million $)	28.6998	27.2618	27.6598	27.2611	27.8622	27.2806
13	D.B.V	1.9652	1.7043	2.0017	1.7297	1.9647	1.5257

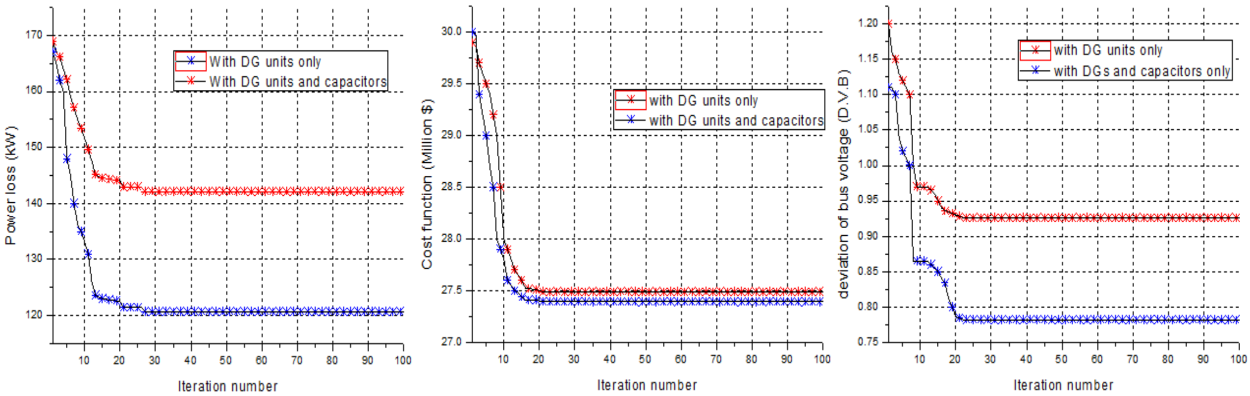

Fig.1. Convergence characteristics of MPSO for single objective functions of minimization of power loss, cost function and deviation of bus voltage for IEEE-33 bus system

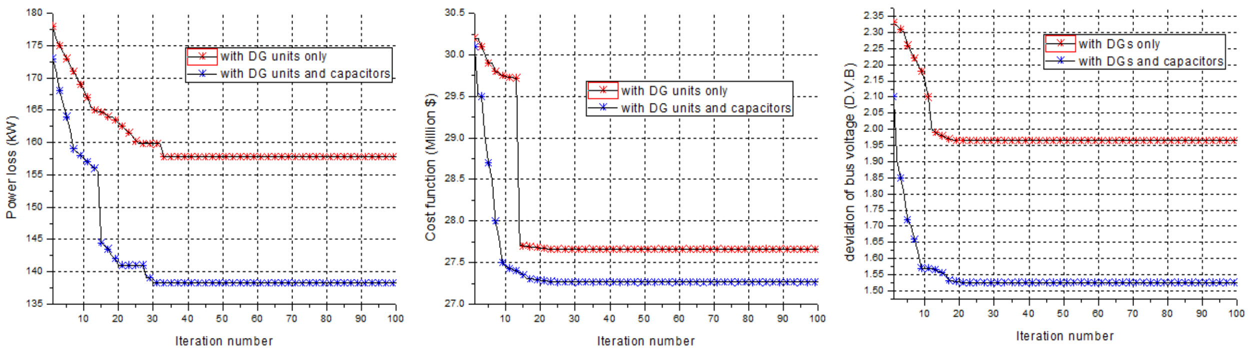

Fig.2. Convergence characteristics of MPSO for single objective functions of min. of power loss, cost function and D.V.B for IEEE-69 bus system

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TABLE 3: RESULTS OF IEEE-33 BUS SYSTEM FOR TWO OBJECTIVES FOR DIFFERENT WEIGHT FACTORS

Set No	Weighing factors		Combination-1				Combination-2				Combination-3			
	W 1	W 2	With DG units only		With DG units and Capacitors		With DG units only		With DG units and Capacitors		With DG units only		With DG units and Capacitors	
			T.P.L (kW)	Cost function (Million $)	T.P.L (kW)	Cost function (Million $)	Cost function (Million $)	D.B. V	Cost function (Million $)	D.B. V	T.P.L (kW)	D.B. V	T.P.L (kW)	D.B. V
1	0.1	0.9	170.11	27.4957	152.47	27.3921	27.8352	0.926	27.7244	0.783	171.47	0.925	156.31	0.781
2	0.2	0.8	170.11	27.4957	152.47	27.3921	27.8352	0.925	27.7241	0.791	167.28	0.927	151.26	0.789
3	0.3	0.7	166.46	27.6544	151.16	27.4155	27.7149	0.925	27.7241	0.791	167.28	0.927	151.26	0.789
4	0.4	0.6	164.36	27.6544	149.16	27.4265	27.7149	0.931	27.4272	0.806	163.11	0.934	147.98	0.802
5	0.5	0.5	164.36	27.6544	149.16	27.4265	27.5988	0.931	27.4272	0.806	163.11	0.934	147.98	0.802
6	0.6	0.4	158.49	27.7749	141.26	27.5664	27.5988	0.931	27.4272	0.806	159.27	0.938	141.21	0.804
7	0.7	0.3	158.49	27.7749	141.26	27.5664	27.4944	0.943	27.3838	0.813	159.27	0.938	141.21	0.804
8	0.8	0.2	149.76	27.8391	138.79	27.7172	27.4944	0.943	27.3838	0.813	151.22	0.942	137.68	0.812
9	0.9	0.1	149.76	27.8349	138.79	27.7172	27.4944	0.943	27.3838	0.813	151.22	0.942	137.68	0.812

TABLE 4: RESULTS OF IEEE-69 BUS SYSTEM FOR TWO OBJECTIVE FUNCTIONS FOR DIFFERENT WEIGHT FACTORS

Set No	Weighing factors		Combination-1				Combination-2				Combination-3			
	W1		With DG units only		With DG units and Capacitors		With DG units only		With DG units and Capacitors		With DG units only		With DG units and Capacitors	
			T.P.L (kW)	Cost function (Million $)	T.P.L (kW)	Cost function (Million $)	Cost function (Million $)	D.B.V	Cost function (Million $)	D.B.V	T.P.L (kW)	D.B.V	T.P.L (kW)	D.B.V
1	0.1	0.9	168.38	27.6678	143.24	27.2614	28.5411	1.964	27.2830	1.526	168.61	1.961	143.18	1.525
2	0.2	0.8	168.38	27.6678	143.24	27.2614	28.5411	1.964	27.2830	1.526	168.61	1.961	143.18	1.525
3	0.3	0.7	165.72	27.8741	141.87	27.2678	28.3245	1.972	27.2751	1.558	164.97	1.982	141.46	1.552
4	0.4	0.6	165.72	27.8741	141.87	27.2678	28.3245	1.972	27.2750	1.558	164.97	1.982	141.46	1.552
5	0.5	0.5	165.72	27.8741	141.87	27.2678	27.9543	1.986	27.2704	1.641	164.97	1.982	141.46	1.552
6	0.6	0.4	162.16	28.1187	140.71	27.2746	27.9543	1.986	27.2704	1.641	162.42	1.992	140.77	1.639
7	0.7	0.3	162.16	28.1187	140.71	27.2746	27.6571	1.994	27.2648	1.641	162.42	1.992	140.77	1.639
8	0.8	0.2	160.47	28.6747	139.22	27.2821	27.6571	1.994	27.2648	1.731	160.26	2.010	139.21	1.730
9	0.9	0.1	160.47	28.6747	139.22	27.2821	27.6587	2.011	27.2621	1.731	160.26	2.010	139.21	1.730

TABLE 5: RESULTS OF IEEE-33 BUS SYSTEM FOR THREE OBJECTIVE FUNCTIONS FOR DIFFERENT WEIGHT FACTORS

S. No.	Weighing Factors			Case-1 (With DG units only)			Case-2 (With DG units and capacitors)		
	W1	W2	W3	T.P.L (kW)	Cost function (Million $)	D.B.V	T.P.L (kW)	Cost function (Million $)	D.B.V
1	0.1	0.1	0.8	174.16	27.8417	0.9265	128.74	27.7255	0.7824
2	0.1	0.8	0.1	174.16	27.5111	0.9435	128.74	27.4021	0.8145
3	0.8	0.1	0.1	152.47	27.8417	0.9435	121.41	27.7255	0.8145
4	0.5	0.3	0.2	157.16	27.7047	0.9387	122.38	27.5112	0.8109
5	0.5	0.2	0.3	157.16	27.8244	0.9356	122.38	27.6458	0.8088
6	0.3	0.5	0.2	163.28	27.6246	0.9387	124.62	27.4946	0.8109
7	0.3	0.2	0.5	163.28	27.8244	0.9291	124.62	27.6458	0.7911
8	0.2	0.5	0.3	167.87	27.6246	0.9356	126.81	27.4951	0.8088
9	0.2	0.3	0.5	167.87	27.7047	0.9292	126.81	27.5112	0.7912

TABLE 6: RESULTS OF IEEE-69 BUS SYSTEM FOR THREE OBJECTIVE FUNCTIONS FOR DIFFERENT WEIGHT FACTORS

S. No.	Weighing Factors			Case-1 (With DG units only)			Case-2 (With DG units and capacitors)		
	W1	W2	W3	T.P.L (kW)	Cost function (Million $)	D.B.V	T.P.L (kW)	Cost function (Million $)	D.B.V
1	0.1	0.1	0.8	166.34	26.7742	1.964	142.54	27.2636	1.527

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2	0.1	0.8	0.1	166.34	28.7142	2.002	142.54	27.2811	1.731
3	0.8	0.1	0.1	158.27	28.7142	2.002	138.47	27.2811	1.731
4	0.5	0.3	0.2	160.76	28.2741	1.999	139.21	27.2785	1.687
5	0.5	0.2	0.3	160.76	28.4126	1.994	139.21	27.2701	1.649
6	0.3	0.5	0.2	162.19	27.8678	1.999	140.68	27.2785	1.687
7	0.3	0.2	0.5	162.19	28.4126	1.987	140.68	27.2686	1.611
8	0.2	0.5	0.3	164.44	27.8681	1.994	141.71	27.2701	1.649
9	0.2	0.3	0.5	164.44	28.2744	1.987	141.71	27.2686	1.611

The multi objective MPSO results of IEEE-33 bus system for two objective functions in three combinations and three objective functions for different weight factors are given table 3 and 5. Convergence characteristics of the MPSO for IEEE-33 bus system for single objective function are shown in fig.1. For an IEEE-69 bus system MPSO results for single objectives are given table 2 and MOMPSO results for two and three objectives are given in table 4 and 6. Convergence characteristics of the MPSO for IEEE-69 bus system for single objective function are shown in fig.2.

V. CONCLUSION

In this work an algorithm based on modified particle swarm optimization is tested by solving multi objective DG and capacitor sitting and sizing problem. Loss sensitive factors are used to identify the sensitive nodes to place the DG units and capacitor units and their size is obtained by modified particle swarm optimization (MPSO) by minimizing multiple objective functions subjected to a practical constraints. It is identified from results that the power loss, cost function and deviation of bus voltage are reduced after including the DG units and capacitors simultaneously.

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