Optimal Sizing of Capacitors Using Harmony Search Algorithm with Limited Search Space

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Abstract – **Capacitors in power systems are generally used to supply reactive power for the purpose of loss minimization and voltage profile improvement. The main objective of this study is to determine optimal sizing of capacitors so as to reduce the power loss and improve the voltage profile. Presently, the capacitor placement problem is widely solved by using heuristic optimization methods. In this study, the Harmony Search (HS) algorithm which is a meta-heuristic method is applied to solve the optimal capacitor sizing problem with limited search space. An effective and simple power flow method based on the backward/forward sweep power flow is also employed for the power flow simulations. The performance of the proposed HS with limited space algorithm is validated on the 10-bus and 34-bus radial distribution systems. The results are compared with Particle Swarm Optimization (PSO) method where Index Vector method is used for determining the optimal locations of capacitors.**

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Keywords: Capacitive Compensation, Distribution Systems, Harmony search algorithm

I. INTRODUCTION

Electric distribution systems are becoming large and complex leading to higher system losses and poor voltage regulation. Studies indicate that almost 13% of the total power generated is consumed as I^2R losses at the distribution level (Ng *et al.*, 2000). To reduce power losses and to maintain a voltage profile within acceptable limits, capacitors are used to provide reactive power compensation in distribution networks. Hence, shunt capacitors are widely used in distribution systems to reduce power losses, improve voltage profile and increase system capacity. However, the benefits of compensation depend greatly on the placement and size of the added capacitors. In general, the objective of the capacitor placement problem is to determine the optimal size and location of the installed capacitors by maximizing the reduction in active power losses.

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In the literature, many techniques have been reported for solving the optimal capacitor placement problem in distribution systems in which these techniques may be classified in the following categories: analytical, numerical programming, heuristic and artificial intelligence-based techniques [1]. Among these techniques, the heuristic based techniques have been widely applied in solving the optimal al capacitor placement problem [2-7] the immune based optimization technique is used for selecting proper locations and ratings of capacitor banks [6], [12] and the genetic algorithm is applied to find the optimum locations and sizes of fixed and switched capacitors at various load levels. The genetic algorithm is considered as one of the first meta-heuristic techniques used for solving optimal capacitor placement problem but it has some drawbacks such as divergence and local optima problems. Fuzzy logic has been applied to solve the capacitor placement problem[7], [13] in which the constraints are fuzzified and the alpha cuts are used to direct the search process to ensure that the objective function is improved at each iteration process. Other heuristic based techniques include the application of the ant colony algorithm for solving the capacitor placement and sizing problem. In the implementation of the ant colony optimization for the problem, capacitors should be in discrete values and not in continuous values which are usually more accurate. A disadvantage of the ant colony algorithm is that it has low speed because all paths must be reviewed by the ants. The Particle Swann Optimization (PSO) is then used in combination with the loss sensitivity indices to minimize real power losses and improve voltage profiles [3]. A discrete PSO algorithm is applied to optimally locate and size a fixed single-phase capacitor in a balanced radial distribution system. For this case, the problem is considered as a nonlinear integer optimization problem with both capacitor location and size having discrete values and the Newton-Raphson power flow method is used to calculate the cost function. Recently, the plant growth simulation algorithm is applied to solve the optimal capacitor placement problem in a distribution system [6].

This study presents a relatively new heuristic technique using harmony search algorithm for finding optimal placement and size of shunt capacitors in a radial distribution system. The harmony search algorithm is a meta-heuristic optimization method that is inspired by musicians in improvising their instrument pitches to find better harmony and it has several advantages in which it does not require initial value settings for the decision variables and it can handle both discrete and continuous variables. Since, algorithms already used in the field of optimization are based on naturally occurring processes, harmony search can be conceptualized from a musical performance process involving searching for a better harmony. This algorithm has been successfully applied to solve optimal placement of FACTS devices to improve power system security. In this study, the harmony search algorithm is used together with the backward/forward sweep power flow method[5] for determining the optimal placement and sizing of capacitors in a radial distribution network. This power flow method is considered fast in terms of computing speed as compared to the time consuming Newton-Raphson method. The proposed harmony search algorithm with limited search space is implemented on the 10-bus and 34-bus test systems.

II. PROBLEM FORMULATION

The problem is to determine the best shunt capacitor size and location in a radial distribution system by reducing the active power losses. The objective function for the minimization of power loss is described as

$$\text{Minimize } f=\min.(P_{T\,Loss})$$

$$\text{Subjected to } \; V_{min} \leq V \leq V_{max}$$

To solve the optimal capacitor placement and sizing problem for radial distribution networks, a suitable power flow method called as the backward/forward sweep power flow (Teng, 2000) is used for computing the power loss. In this power flow method, the relationship between the bus current injections and the branch currents is represented by the matrix [BIBC] which is given as:

$$[B] = [BIBC]\,[I] \qquad (1)$$

where [I] is the bus current injection vector and [B] is the branch current vector.

The relationship between the branch currents, [B] and bus voltages, [ΔV] is represented by the matrix [BCBV]. The matrices [BIBC] and [BCBV] are then multiplied to obtain the relationship between the voltage deviation, [AV] and the bus current injections [I], which is represented by the matrix [DLF] and given as:

$$[\Delta V] = [BCBV]\,[B] = [BCBV]\,[BIBC]\,[I] = [DLF]\,[I] \quad (2)$$

[DLF] is also known as the voltage drop to bus current injection matrix.

The backward/forward sweep power flow method at the k iteration considers the following equations

$$I_i^k = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \qquad (3)$$

$$[\Delta V^{k+1}] = [D\,L\,F]\,[I^k] \qquad (4)$$

III. HARMONY SEARCH ALGORITHM

Recently, a meta-heuristic optimization algorithm inspired by playing music has been developed and it is called as the Harmony Search (HS) algorithm. It is based on meta-heuristic which combine rules and randomness to imitate natural phenomena. HS algorithm is inspired by the operation of orchestra music to find the best harmony between components which are involved in the operation process, for optimal solution. As musical instruments can be played with some discrete musical notes based on player experience or based on random processes in improvisation, optimization design variables can be considered certain discrete values based on computational intelligence and random processes. Music players improve their. experience based on aesthetics standards while design variables in computer memory can be improved based on objective function.

The performance of music seeks a best state or excellent harmony determined by aesthetic estimation, as the optimization process seeks a best state determined by objective function evaluations. The combination of pitches in the ensemble provides aesthetic estimation. Evaluation of the objective function is performed by comparing the values produced by decision variables, which corresponds to harmony which can be improved via repetition. In this analogy, the objective function values can be improved iteration by iteration. As the optimization process looks for finding a global solution that is determined by the objective function, musical performances follow to find pleasing harmony which is determined by the aesthetic standard.

In music improvisation, each musician plays within possible pitches to make a harmony vector. If all the pitches create good harmony, the musician saved them in memory and increases good or better harmony for next time. Similarly, in the field of engineering optimization, at first each decision variable value is selected within the possible range and formed a solution vector. If all decision variable values lead to a good solution, each variable that has been experienced is saved in memory and it increases the possibility of good or better solutions for next time.

Among the advantages of the HS algorithm are that it can consider discontinuous functions as well as continuous functions because it does not require differential gradients; it does not require initial value setting for the variables; it is free from divergence and may escape local optima. The computational procedure of the HS algorithm which are implemented in steps are described as follows:

Step 1: Initialization of the optimization problem
Step 2: Initialization of the harmony memory (HM)
Step 3: Improvisation a New Harmony from the HM set
Step 4: Updating HM
Step 5: Repeat steps 3 and 4 until the end criterion is satisfied

1 Initialization of the optimization problem

Consider an optimization problem which is described as:

$$\text{Minimize } F(x) \text{ subject to } x_i \in X_i, \qquad i = 1, 2 \dots N$$

where
F(x) : Objective function

x : Set of each design variable (x_i)

X_i : Set of the possible range of values for each design variable ($Lx_i < X < Ux_i$)

N : Number of design variables

Here, the HS algorithm parameters are also specified in which the parameters are the Harmony Memory Size (HMS) or the number of solution vectors in the harmony memory, Harmony Memory Considering Rate (HMCR), Pitch Adjusting Rate (PAR), number of decision variables (N), Number of Improvisations (NI) and the stopping criterion.

2 Initialization of the harmony memory

The Harmony Memory (HM) matrix, shown in Eq. 5, is filled with as many randomly generated solution vectors as HMS and sorted by the values of the objective function,

$$HM = \left[\begin{array}{ccccc} x_1^1 & x_2^1 & \dots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \dots & x_{N-1}^2 & x_N^2 \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ x_1^{HMS-1} & x_2^{HMS-1} & \dots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \dots & x_{N-1}^{HMS} & x_N^{HMS} \end{array}\right] \begin{array}{l} \Rightarrow f(x^{(1)}) \\ \Rightarrow f(x^{(2)}) \\ . \\ . \\ . \\ \Rightarrow f(x^{(HMS-1)}) \\ \Rightarrow f(x^{(HMS)}) \end{array} \qquad (5)$$

3 Improvisation of new harmony from the HM set

A new harmony vector, x = (x_1', x_2',……x_n'), is generated based on three rules, namely, random selection, memory consideration and pitch adjustment. These rules are described as follows:

Random selection: When HS determines the value x_i' for the new harmony x = (x_1', x_2',……x_n'), it randomly picks any value from the total value range with a probability of (1-HMCR). Random selection is also used for previous memory initialization.

Memory consideration: When HS determines the value x_i', it randomly picks any value x_j' from the HM with a probability of HMCR since j = {1, 2,... , HMS}

$$x'_i \leftarrow \begin{cases} x'_i \in \{x_i^1, x_i^2, \dots, x_i^{HMS}\} & \text{with probablityHMCR} \\ x'_i \in X_i & \text{with probablity } (1-\text{HMCR}) \end{cases} \qquad (6)$$

Pitch adjustment: Every component of the new harmony vector x' = (x_1', x_2,….x_n') is examined to determine whether it should be pitch-adjusted.

After the value x_i' is randomly picked from HM in the above memory consideration process, it can be further adjusted into neighboring values by adding certain amount to the value, with probability of PAR. This operation uses the PAR parameter, which is the rate of pitch adjustment as follows:

$$x'_i \leftarrow \begin{cases} \text{Yes} & \text{with probablityPAR} \\ \text{No} & \text{with probablity } (1-\text{PAR}) \end{cases} \qquad (7)$$

The value of (1-PAR) sets the rate of doing nothing. If the pitch adjustment decision for x_i' is yes, x_i' is replaced as follows:

$$X'_i \leftarrow X'_i \pm bw \qquad (8)$$

where, bw is the arbitrary distance bandwidth for a continuous design variable.

In this step, pitch adjustment or random selection is applied to each variable of the new harmony vector in turns.

4 Updating HM:

If the new harmony vector x = (x_1', x_2',…x_n') is better than the worst harmony in the HM, from the viewpoint of the objective function value, the new harmony is entered in the HM and the existing worst harmony is omitted from the HM.

Checking stopping criterion: If the stopping criterion which is based on the maximum number of improvisations is satisfied, computation is terminated. Otherwise, steps C and D are repeated.

IV. PROPOSED OPTIMAL CAPACITOR PLACEMENT METHOD

In the proposed optimal sizing of capacitors, the HS algorithm is applied as an optimization technique to determine the optimal size of the capacitors at the buses and the backward/forward sweep power flow is applied for computing the power loss. The procedure for implementing the proposed optimal capacitor sizing is described as follows:

Step 1: Input system parameters such as line and load data
Step 2: Built the BIBC and BCBV matrices and compute the DLF matrix
Step 3: Randomly add the capacitors for reactive power compensation at the buses
Step 4: Calculate the total power loss. Each capacitor set is considered as the harmony vectors. Initialize the arrays of HM as in Eq. 5, randomly. The number of columns in the HM is equal to number of buses in the test system.
Step 5: Improvise a new harmony using the three rules of random selection, memory consideration and pitch adjustment.
Step 6: Calculate bus current injections and bus voltages using Eq. 3 and 4.
Step7: Calculate the total power loss using the backward/forward sweep power flow method.
Step 8: Check if the capacitor set (New Harmony) gives les power loss than the worst harmony in the HM If Yes, the worst harmony is replaced with the new harmony in the

HM Otherwise, go to step 5
Step 9: Determine the optimal capacitor set (best harmony) which gives maximum power loss reduction

Figure 1 describes the procedures involved in solving the optimal capacitor placement problem using the HS algorithm and the backward/forward sweep power flow method in terms of a flowchart.

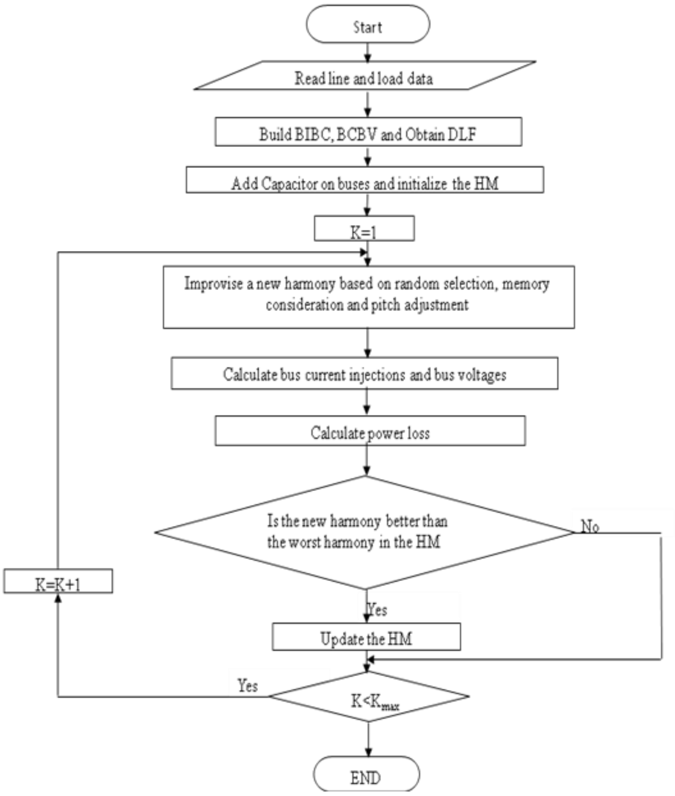

Fig. 1 Flow Chart for Harmony Search Algorithm

V. INDEX VECTOR METHOD

Index Vector is formulated by running the base case load flow on a given radial distribution network, and calculating reactive component of current in the branches and reactive power load concentration at each node. Based on the elements of the Index Vector, this method identifies a sequence of nodes to be compensated. The sequence of priority of the nodes is mainly determined by the Index-Vector.

$$Index\,[n] = \left[\frac{1}{V_n^2} + \frac{I_q[k]}{I_p[k]} + \frac{Q_{eff}[n]}{totalQ}\right]$$

where
Index[n] = “Index” for nth bus
V[n] = Voltage at nth bus
$I_q[k]$ = Imaginary component of current in kth branch
$I_p[k]$ = Real component of current in kth branch
Qeff[n] = Effective load at nth bus
TotalQ = Total reactive load of the given Distribution system

After finding the index values at all the buses using the above formula the index values are multiplied with reactive loads at the corresponding buses. That gives the actual index values used for determining the optimal locations.

VI. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a meta heuristic parallel search technique used for optimization of continues non linear problems. The method was discovered through simulation of a simplified social model. PSO has roots in two main component methodologies perhaps more obvious are ties to artificial life in general, and to bird flocking, fish schooling and swarming theory in particular. It is also related, however to evolutionary computation and has ties to both genetic algorithms and evolutionary programming. It requires only primitive mathematical operators, and is computationally inexpensive in terms of both memory requirements and speed. It conducts searches using a population of particles, corresponding to individuals. Each particle represents a Candidate solution to the capacitor sizing problem. In a PSO system, particles change their positions by flying around a multi dimensional search space until a relatively unchanged position has been encountered, or until computational limits are exceeded. In social science context, a PSO system combines a social and cognition models. The general elements of the PSO are briefly explained as follows:

Particle X(t): It is a k-dimensional real valued vector which represents the candidate solution. For an i_{th} particle at a time t, the particle is described as $X_i(t)=\{X_{i,1}(t), X_{i,2}(t),\ldots X_{i,k}(t)\}$.

Population: It is a set of ‘n’ number of particles at a time t described as $\{X_1(t), X_2(t)\ldots X_n(t)\}$.

Swarm: It is an apparently disorganized population of moving
particles that tend to cluster together while each particle seems to be moving in random direction.

Particle Velocity V(t): It is the velocity of the moving particle represented by a k-dimensional real valued vector $V_i(t)= \{v_{i,1}(t), v_{i,2}(t)\ldots\ldots v_{i,k}(t)\}$.

Inertia weight W(t): It is a control parameter that is used to control the impact of the previous velocity on the current velocity.

Particle Best (pbest): Conceptually pbest resembles autobiographical memory, as each particle remembers its own experience. When a particle moves through the search space, it compares its fitness value at the current position to the best value it has ever attained at any time up to the current time. The best position that is associated with the best fitness arrived so far is termed as individual best or Particle best. For each Particle in the swarm its pbest can be determined and updated during the search.

Global Best (gbest): It is the best position among all the individual pbest of the particles achieved so far.

Velocity Updation: Using the global best and individual best, the i_{th} particle velocity in k_{th} dimension is updated according to the following equation.

V[i][j]=K*(w*v[i][j]+c1*rand1*(pbestX[i][j]-X[i][j])+c2*rand2*(gbestX[j]-X[i][j])).

where,
K constriction factor
c1, c2 weight factors
w Inertia weight parameter
i particle number
j control variable
rand1, rand2 random numbers between 0 and 1

Stopping criteria: This is the condition to terminate the search process. It can be achieved either of the two following methods:
i. The number of the iterations since the last change of the best solution is greater than a pre-specified number.
ii. The number of iterations reaches a prespecified maximum value.

VII. CASE STUDIES AND RESULTS

In this paper, Harmony Search Algorithm (HSA) is applied to solve the optimal sizing of capacitors. The performance of the Harmony Search algorithm is validated on 10-Bus and 34-Bus radial distribution systems. To check the effectiveness of the Harmony Search algorithm the results are compared with Particle Swarm Optimization method. The optimal locations of capacitors are given by Index Vector method.

1 Results for 10-Bus radial distribution system

Fig.2 shows the single line diagram of 10-bus system. Data for the 10-Bus System is given in the table 1.

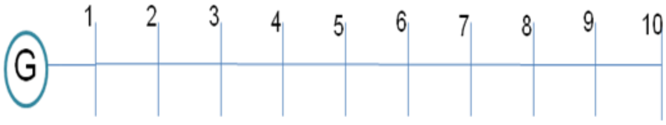

Fig. 2 Single line diagram of 10-Bus System

TABLE I:
IEEE 10-BUS SYSTEM DATA

Line No.	From Bus, i	To Bus, i+1	R Ω	X Ω	PL kW	QL kVAR
1	0	1	0.1233	0.4127	1840	460
2	1	2	0.014	0.6057	980	340
3	2	3	0.7463	1.205	1790	446
4	3	4	0.6984	0.6084	1598	1840
5	4	5	1.9831	1.7276	1610	600
6	5	6	0.9053	0.7886	780	110
7	6	7	2.0552	1.164	1150	60
8	7	8	4.7953	2.716	980	130
9	8	9	5.3434	3.0264	1640	200

2 Sizing of Capacitors using HAS considering all the load buses as potential locations

For 10-bus system Capacitor values and voltages obtained by Harmony Search Algorithm are shown in Table 2 and Table 3 respectively.

TABLE II
CAPACITOR COMPENSATION BY HARMONY SEARCH ALGORITHM

Bus No.	**Capacitor Values in kVAR**
2	574
3	3856
4	914
5	2304
6	242
7	714
8	217
9	388
10	362

The active power loss obtained after placement of capacitors by Harmony Search Algorithm is 649.83kW.

TABLE III:
VOLTAGES BEFORE AND AFTER CAPACITOR PLACEMENT

Bus No.	**Voltages Before Capacitor Placement**	**Voltages After Capacitor Placement**
1	1	1
2	0.9879	0.9894
3	0.9831	0.9868
4	0.9637	0.9707
5	0.9387	0.9574
6	0.9133	0.9393
7	0.901	0.9298
8	0.8914	0.9154
9	0.8886	0.9096
10	0.8753	0.9027

The index values for 10-bus system are shown in table IV

TABLE IV:
INDEX VALUES FOR 10-BUS SYSTEM

Bus Number	Index values
2	1453.4
3	705.47
4	835.90
5	2214.61
6	1830.48
7	640.67
8	871.37
9	1840.48
10	1939.42

By Index-Vector method the suitable locations for Capacitors are **5, 6, 9, 10** buses.

3 Capacitor sizes using PSO and HAS with limited locations

The capacitor sizes obtained using Particle Swarm Optimization and Harmony Search Algorithm are shown in the table 5.

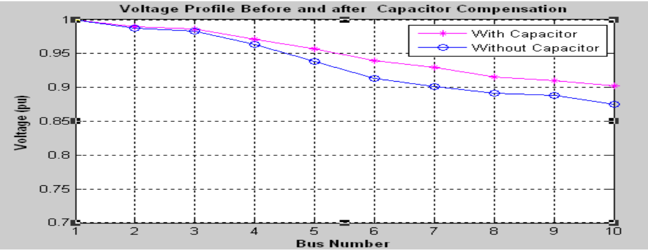

Fig. 3 Voltage Profile Before and After Capacitor Placement

In previous works, HAS is used for sizing of the capacitors where all load buses were taken as optimal locations. Where as in this work, limited locations were considered even for HSA. To compare the relative merits and demerits of HAS, it is compared with the performance of Particle Swarm Optimization. PSO is used only to find the optimal sizes of capacitors like HSA. The optimal locations were obtained by Index Vector method for both the sizing algorithms of HAS and PSO.

TABLE V:
CAPACITOR COMPENSATION BY PSO AND HAS IN LIMITTED NUMBER OF BUSES

Bus No.	**Capacitor Values using PSO (kVAR)**	**Capacitor Values using HSA (kVAR)**
5	3367	3709
6	1340	1284
9	2745	1379
10	941	1017
TOTAL	**8,393 kVAR**	**7,389 kVAR**
P_{loss}	**673.47 kW**	**669.51 kW**

4 Comparison of PSO and HSA

Power loss without compensation obtained is 783.03 kW.

TABLE VI:
COMPARISON OF LOSSES FOR 10-BUS SYSTEM

	PSO	**HSA**
Real Power Loss (kW)	673.47	669.51
Total real power loss reduction (kW)	109.56	113.52
% reduction in loss	13.99	14.45

TABLE VII:
COMPARISON OF VOLTAGE MAGNITUDES FOR 10-BUS SYSTEM

Bus No.	**Voltages obtained by PSO compensation**	**Voltages obtained by HAS compensation**
1	1	1
2	0.9890	0.9893
3	0.9861	0.9864
4	0.9698	0.9703
5	0.9562	0.9568
6	0.9378	0.9383
7	0.9291	0.9298
8	0.9136	0.9144
9	0.9076	0.9088
10	0.9012	0.9021

5. Results for 34-Bus radial distribution system

Fig.4 shows the single line diagram of 34-bus system. Data for the 34-bus system is given in the table 8.

For 34-Bus System, base voltage is given as 11kV and base kVA is given as 100kVA. In 34-Bus system first bus is slack bus and it has four laterals. There are 29 buses with loads. The data of IEEE 34 Bus System is given in the table 8.

TABLE VIII:
IEEE 34 BUS SYSTEM DATA

Line	From	To	R (Ω)	X (Ω)	Pload	Qload
1	1	2	0.117	0.048	230	142.5
2	2	3	0.1073	0.044	0	0
3	3	4	0.1645	0.0457	230	142.5
4	4	5	0.1495	0.0415	230	142.5
5	5	6	0.1495	0.0415	0	0
6	6	7	0.3144	0.054	0	0
7	7	8	0.2096	0.036	230	142.5
8	8	9	0.3144	0.054	230	142.5
9	9	10	0.2096	0.036	0	0
10	10	11	0.131	0.0225	230	142.5
11	11	12	0.1048	0.018	137	84
12	3	13	0.1572	0.027	72	45
13	13	14	0.2096	0.036	72	45
14	14	15	0.1048	0.018	72	45
15	15	16	0.9525	0.009	13.5	7.5
16	6	17	0.1794	0.498	230	142.5

17	17	18	0.1645	0.0457	230	142.5
18	18	19	0.2079	0.0473	230	142.5
19	19	20	0.189	0.043	230	142.5
20	20	21	0.189	0.043	230	142.5
21	21	22	0.262	0.045	230	142.5
22	22	23	0.262	0.045	230	142.5
23	23	24	0.3144	0.054	230	142.5
24	24	25	0.2096	0.036	230	142.5
25	25	26	0.131	0.0225	230	142.5
26	26	27	0.1048	0.018	137	85
27	7	28	0.1572	0.027	75	48
28	28	29	0.1572	0.027	75	48
29	29	30	0.1572	0.027	75	48
30	10	31	0.1572	0.027	57	34.5
31	31	32	0.2096	0.036	57	34.5
32	32	33	0.1572	0.027	57	34.5
33	33	34	0.1048	0.018	57	34.5

Size of Capacitors using Harmony Search Algorithm:
For 34-bus system the Capacitor values obtained by Harmony Search Algorithm are given in Table 9.

TABLE IX:
CAPACITOR COMPENSATION FOR 34-BUS SYSTEM
BY HAS CONSIDERING ALL LOCATIONS

Bus Number	Capacitor Values in kVAR
2	75
4	147
5	83
8	83
9	77
11	10
12	96
13	111
14	78
15	109
16	02
17	132
18	130
19	124
20	95
21	81
22	132
23	126
24	118
25	145
26	139
27	137
28	02
29	83
30	19
31	124
32	09
33	78
34	91

- The active power loss obtained using Harmony Search Algorithm is **159.66kW.**

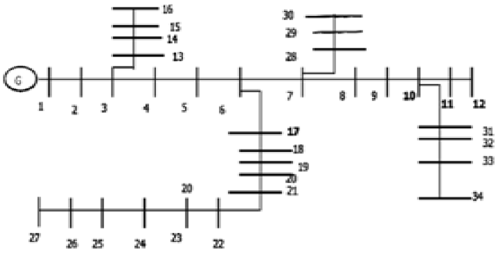

Fig. 4: Single Line Diagram of the 34 Bus System

- The voltages and voltage profile before and after capacitor placement are shown in Table 10 and Fig. 5 respectively.

TABLE X:
VOLTAGES BEFORE AND AFTER CAPACITOR PLACEMENT

Bus Number	Voltages Before Capacitor Placement	Voltages After Capacitor Placement
1	1.0	1.0
2	0.9940	0.9950
3	0.9888	0.9906
4	0.9816	0.9844
5	0.9754	0.9792
6	0.9695	0.9742
7	0.9654	0.9707
8	0.9631	0.9688
9	0.9605	0.9666
10	0.9592	0.9656
11	0.9587	0.9651
12	0.9586	0.9650
13	0.9885	0.9903
14	0.9882	0.9901
15	0.9881	0.9900
16	0.988	0.9900
17	0.9599	0.9663
18	0.9562	0.9632
19	0.9521	0.9596
20	0.9489	0.9568

21	0.9459	0.9543
22	0.9425	0.9514
23	0.9397	0.9489
24	0.9371	0.9467
25	0.9358	0.9455
26	0.9354	0.9451
27	0.9352	0.9450
28	0.9650	0.9704
29	0.9648	0.9702
30	0.9646	0.9701
31	0.9588	0.9653
32	0.9585	0.9653
33	0.9583	0.9648
34	0.9582	0.9647

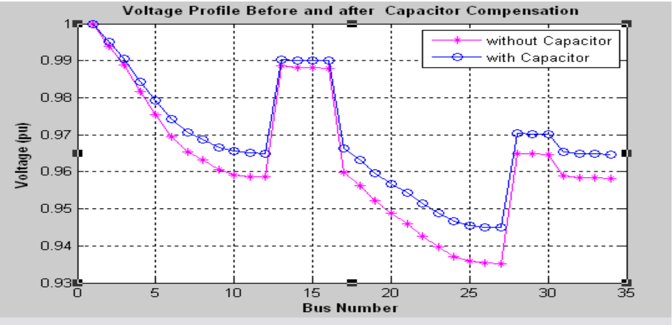

Fig. 5 Voltage Profile Before and After Capacitor Placement

Index values using Index Vector Method:

The index values for 34-bus system are shown in table XI.

TABLE XI
INDEX VALUES FOR 34-BUS SYSTEM

Bus No.	**Index**
2	280.3307
3	0
4	353.7759
5	346.574
6	0
7	0
8	**410.8431**
9	**396.367**
10	0
11	332.1208
12	120.2086
13	143.8615
14	132.6281
15	90.6022
16	37.5943
17	**421.983**
18	333.4674
19	366.8769
20	351.5466
21	355.1363
22	**399.7113**
23	**389.2408**
24	**377.1454**
25	361.6973
26	319.5172
27	113.6358
28	134.7084
29	124.7303
30	71.6884
31	95.9312
32	92.9978
33	86.3616
34	48.7969

By Index-Vector method the suitable locations for Capacitors are **17, 8, 22, 9, 23, 24** buses.

Capacitor sizes using Particle Swarm Optimization and Harmony Search Algorithm:

The capacitor sizes obtained using Particle Swarm Optimization and Harmony Search Algorithm are shown in the table 12.

TABLE XII
CAPACITOR COMPENSATION BY PSO AND HSA FOR 34-BUS SYSTEM AT LIMITED NUMBER OF BUSES.

Bus No.	**Capacitor values using PSO (kVAR)**	**Capacitor values using HSA (kVAR)**
8	818	118
9	199	633
17	378	632
22	452	408
23	653	234
24	211	508
TOTAL	**2,717 kVAR**	**2,533 kVAR**
P_{loss}	**162.25 kW**	**160.80kW**

Comparison of PSO and Harmony Search Algorithm

- Power loss without compensation obtained is **223.56 kw**.

TABLE XIII
COMPARISON OF LOSSES FOR 34-BUS SYSTEM

	PSO	**HSA**
Real Power Loss(kW)	162.25	160.80

Total real power loss reduction(kW)	61.31	62.76
% reduction in loss	27.424	28.073

VIII. Conclusions

In this paper, Harmony Search Algorithm (HSA) is implemented with limited search space, that is with limited number of buses as potential locations for solving the problem of optimal placement of capacitors. A simple load flow method using matrices BIBC and BCBV is implemented for power flow solutions. The HSA has been implemented on 10-Bus and 34-Bus radial distribution systems. A considerable reduction in active power loss and improvement in voltage profile are observed after compensation. The results of Harmony Search Algorithm are compared with Particle Swarm Optimization method. Index Vector method is used to determine the optimal locations of capacitors. From the results it is observed that maximum reduction in active power loss and improvement in voltage profile are better in Harmony Search Algorithm compared to Particle Swarm Optimization

TABLE XIV
COMPARISON OF VOLTAGE MAGNITUDES
FOR 34-BUS SYSTEM

Bus Number	Voltages obtained by PSO	Voltages obtained by HSA
1	1.0	1.0
2	0.9949	0.9950
3	0.9905	0.9906
4	0.9843	0.9845
5	0.9789	0.9792
6	0.9737	0.9743
7	0.9701	0.9708
8	0.9680	0.9689
9	0.9657	0.9667
10	0.9647	0.9656
11	0.9644	0.9651
12	0.9642	0.9650
13	0.9902	0.9902
14	0.9899	0.9899
15	0.9898	0.9898
16	0.9897	0.9897
17	0.9652	0.9654
18	0.9619	0.9622
19	0.9584	0.9587
20	0.9556	0.9560
21	0.9531	0.9536
22	0.9503	0.9509
23	0.9479	0.9486
24	0.9455	0.9464
25	0.9444	0.9451
26	0.9439	0.9447
27	0.9438	0.9445
28	0.9698	0.9705
29	0.9696	0.9703
30	0.9695	0.9701
31	0.9645	0.9652
32	0.9642	0.9649
33	0.9640	0.9647
34	0.9640	0.9647

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