Self Adaptive Harmony Search Algorithm for Optimal Capacitor Placement on Radial Distribution Systems

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***Abstract*— Optimal capacitor placement is a complex combinatorial optimization process aimed at finding the location and size of capacitors on a radial distribution network that minimizes the system power and energy loss, deviation of node voltages and increases the available capacity of the feeders. A Harmony Search algorithm (HSA) is a recently developed algorithm which is conceptualized using the musical process of searching for a perfect state of harmony. It uses a stochastic search instead of a gradient search. In this paper, a Self Adaptive Harmony Search algorithm (SAHSA) is proposed to solve the optimal capacitor placement in order to minimize the power loss. Forward/Backward sweep power flow method is used to solve the radial distribution system. The proposed approach is tested on standard IEEE 33bus and IEEE 69-bus radial distribution systems. The results are compared with Particle Swarm Optimization (PSO) algorithm, and plant growth simulation algorithm (PGSA) and it is observed that the proposed method performed well in terms of the quality of solution.**

Keywords—harmony search, loss reduction, capacitor placement and loss sensitivity.

I. INTRODUCTION

Development and complexity of distribution system result in several problems such as increased losses and voltage drop. Studies have indicated that approximately 13% of generated power is consumed as loss at the distribution level [1]. Optimal capacitor placement is one of the most effective and useful method in reducing the power loss in distribution networks. Capacitors are installed in distribution systems for reactive power compensation. The capacitor placement problem is the process of determination of number of capacitors to be placed, location and size of the capacitors to be placed in a radial distribution system. The objective of the capacitor placement is to reduce the losses in the system and maintain voltage profile within the prescribed limits.

The optimal capacitor placement is a combinatorial optimization problem as it involves the optimization of location and size under minimization of power loss and improvement of voltage profile. Different optimization techniques and algorithms have been proposed over several years.

Optimal capacitor placement has been investigated over decades. Various methods have been investigated by the researchers in order to find capacitor location and size. It is found that meta heuristic techniques have given better results when compared to conventional optimization techniques. A fuzzy [2-3] based approach for the capacitor placement in radial distribution system is presented and the problem is formulated as fuzzy set optimization to minimize the real power loss and the system cost with voltage limiting constraints. Heuristic techniques [4-5] have been presented to obtain maximum cost of saving and loss reduction by assuming every node in system as candidate node. Some of the researchers applied genetic algorithm [6-11] and particle swarm optimization (PSO) [12-13] method for the capacitor sizing in order to reduce the real power losses. An improved music based algorithm [16] is applied to reduce the power loss by optimal placement and sizing of the capacitor. All these methods considered all buses as candidate buses as a result of which search space is more, thus the time of computation is more and chances of occurrences of local optima is more. Ant colony algorithm [14] and plant growth simulation algorithm (PGSA) [15] are applied to find the optimal capacitor location and size to reduce the power losses. In this paper the self adaptive harmony search algorithm is used to find the optimal size of the capacitor and a loss sensitivity methodology is used to find the location of the capacitors. The results are compared with PSO and PGSA.

II. PROBLEM FORMULATION

A. Objective functions:

The objective function of the optimal capacitor placement is to determine the location and size of the capacitor bank to be installed on the distribution system. Such a plan should reduce the real power loss.

1) Power loss reduction:

The power loss of a distribution system is calculated as:

$$P_{loss} = \sum_{i=1}^{nl} I_i^2 R_i \tag{1}$$

where 'I_i' *and* 'R_i' are the current and resistance of circuit branch 'i'; 'nl' is the number of circuit branches. A low P_{loss} value indicates economic operation of a network.

2) Operation constraints:

To provide quality electrical supply, the voltage magnitude at each bus after the placement of the capacitors must be within a permissible range and is expressed as

$$V_{min} \leq V \leq V_{max};$$

where V_{min} and V_{max} are the lower and upper limits of bus voltage.

B. Forward/Backward sweep power flow method:

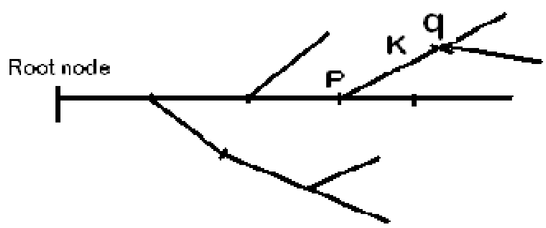

Figure.1: Radial distribution network.

Given the root node (0[th] node) voltage and assume the flat profile for initial voltages at all other nodes, the iterative solution algorithm consists of three steps[17].

1) Nodal Current Calculation:

At iteration j, the node current injection, I_i^j, at network node i is calculated as,

$$I_i^j = \left(\frac{S_i}{V_i^{j-1}} \right)^* - Y_i V_i^{j-1} \quad \text{i=1,2,……….,n} \qquad (2)$$

where V_i^{j-1} is the voltage at node i calculated during the (j-1)[th] iteration and S_i is the specified power injected at node i. Y_i is the sum of all the shunt elements at node i.

2) Backward Sweep:

At iteration j, starting from the branches in the last layer and moving towards the branches connected to the root node the current in the branch 'k', J_k is calculated by applying KCL at node q.

$$J_k^j = -I_q^j + \text{(sum of the currents in branches emanating from node q)} \quad \text{k=nb,nb-1,….1} \qquad (3)$$

where $I_{kp}^{(j)}$ is the current injection at node q.

3) Forward Sweep:

Nodal voltages are updated in a forward sweep starting from branches in the first layer to last layer. For each branch, 'k', the voltage at node q is calculated by applying KVL: using the updated voltage at node p and the branch current calculated in the backward sweep.

$$V_q^j = V_p^j - Z_k J_k^j \quad \text{k=1,2,…..,nb} \qquad (4)$$

Where Z_k is the series impedance of branch 'k'.

Repeat these three steps until the convergence is achieved.

Convergence Criterion:

The maximum real and reactive power mismatches at network nodes are used as convergence criterion.

The power injection for node i at j[th] iteration, $S_i^{(j)}$, is calculated as:

$$S_i^j = V_i^j (I_i^j)^* - Y_i \left| V_i^j \right|^2 \quad \text{i=1,2,…..,n} \qquad (5)$$

The real and reactive power mismatches at bus I are then calculated as

$$\Delta P_i^j = Re[S_i^j - S_i]$$
$$\Delta Q_i^j = Im[S_i^j - S_i] \quad \text{i=1,2,….n} \qquad (6)$$

C. Self Adaptive Harmony Search Algorithm (SAHSA)

SAHSA employs a novel method for generating new solution vectors that enhances accuracy and convergence rate of Harmony Search algorithm (HSA). A brief overview of the HSA and its modified procedure algorithm is presented herewith.

1) Harmony Search (HS) algorithm:

A HS algorithm was developed as an analogy with music improvisation process where music players improvise the pitches of their instruments to obtain better harmony [18]. The steps in the procedure of Harmony Search (HS) are:

Step 1: Initialize the problem and algorithm parameters.
Step 2: Initialize the harmony memory.
Step 3: Improvise a new harmony.
Step 4: Update the harmony memory.
Step 5: Check the stopping criterion.

Step1: Initialize the problem and algorithm parameters

Consider an optimization problem which is described as:

Minimize,

$$F(x) \text{ subject to } x_i \in X_i,\ i=1,2,3,.....N. \qquad (7)$$

where *F(x)* is objective function, '*x*' is a set of each design variable (x_i), 'X_i' is set of the possible range of values for each design variable ($Lx_i < X_i < Ux_i$), and '*N*' is the number of design variables.

The HS parameters are specified in this step. These are Harmony Memory Size (HMS), or number of solution vectors in the harmony memory; Harmony Memory Considering Rate (HMCR); Pitch Adjusting Rate (PAR); and Number of Improvisations (NI) or stopping criterion. The Harmony Memory (HM) is a memory location where all the solution vectors (sets of decision variables) are stored. The parameters *HMCR* and *PAR* are used to improve the solution vector and these are defined in step 3.

Step2: Initialize the harmony memory

In this step, the HM matrix is filled with as many randomly generated solution vectors as the HMS:

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \begin{matrix} \Rightarrow f(x^{(1)}) \\ \Rightarrow f(x^{(2)}) \\ \vdots \\ \Rightarrow f(x^{(HMS-1)}) \\ \Rightarrow f(x^{(HMS)}) \end{matrix} \qquad (8)$$

Step3: Improvise a 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 HSA determines the value x_i', it randomly picks any value $x_i^{\,j}$ from the HM with a probability of HMCR since $j = \{1,2,\ldots, \text{HMS}\}$.

$$x'_i \leftarrow \begin{cases} x'_i \in \{x_i^1, x_i^2, \ldots\ldots, x_i^{HMS}\} & \text{with probability } HMCR \\ x'_i \in X_i & \text{with probability } (1 - HMCR) \end{cases} \quad (9)$$

- *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 given as follows:

$$x'_i \leftarrow \begin{cases} Yes & \text{with probability } PAR \\ No & \text{with probability } (1 - PAR) \end{cases} \quad (10)$$

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:

$$x'_i \leftarrow x'_i \pm bw \quad (11)$$

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.

Step 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 [18].

Step 5: Checking stopping criterion

Computation is terminated upon satisfying the maximum number of improvisations or maximum number of iterations or maximum number of un-improvisations, which is the stopping criterion. Otherwise, steps 3 and 4 are repeated.

2) Self Adaptive Harmony Search Algorithm

Population diversity is the key problem in evolutionary algorithms, it decreases gradually from the early generation to the last, and the final generation has the same chromosomes. Traditional harmony search algorithm loses its ability to search in state space, because of creating New Harmony from similar harmonies. Therefore, increasing the generation will not have a significant effect on the final result [20]. The creation of similar harmonies in the final iterations is effected through the selection of appropriate values of the parameters. An increase in PAR and a decrease in HMCR certainly cause harmony variation in the final iterations and lower the convergence rate and accuracy. With great decrease in PAR and an increase in HMCR decrease the harmony diversity in the last generation. Thus, the probability of reaching an optimum solution is reduced. Hadi sarvariel.al.[20], Proposed to add a local search to the harmony search algorithm.

The steps in the procedure of Self Adaptive Harmony Search Algorithm (SAHSA) are:

Step 1: Initialize the problem and algorithm parameters.
Step 2: Initialize the harmony memory.
Step 3: Improvise a new harmony.
Step 4: Improvise a new harmony from best harmony (local Search).
Step 5: Update the harmony memory.
Step 6: Check the stopping criterion.

Adding step 4 reduces the defect of initial parameters across different problems. It also increases the convergence rate and accuracy. With the addition of a local search step, two new harmony vectors are created with each repetition of the algorithm. The first harmony vector obtained according to the traditional harmony search algorithm and depends on initial parameters. But the second harmony vector attempts to improve the best harmony randomly to each repetition, regardless of the initial parameters values. This factor also leads to harmony variations at each iteration and increases the rate at which an optimal solution is reached. The pseudo code for steps3,4 and 5 for self adaptive harmony search algorithm are shown in Table I.

TABLE:I PSEUDO CODE FOR STEPS 3,4 AND 5 OF SELF ADAPTIVE HARMONY SEARCH ALGORITHM

```
Step3:    for i=1 to Maximp
            for j=1 to HMS
              if(rand()<HMCR) then
                x_j^new=x_j^a where x_j^a ϵ{1,2,….,HMS}
                  if(rand()<PAR)
                      x_j^new= x_j^new±(rand()*bw)        where ran()ϵ (0.1)
                  endif
              else
                  x_j^new= x_j^l ± (rand()*(x_j^u- x_j^l))
             endif
Step4:       x_j^new1= x_j^best±(rand()*bw1(j))
                  where  bw1(j)=|max(x_j)-min(x_j)|
Step5:       if  x^new< x^worst
                x^worst= x^new
             endif
             if  x^new1< x^worst
                x^worst= x^new1
             endif
           endfor
          endfor
```

III. METHODOLOGY

In general, capacitors installed on feeders are pole-top banks with necessary group fusing. The fusing applications restrict the size of the bank that can be used. Therefore, the maximum sizes used are about 1800kvar at 15kV and 3600kvar at higher voltages. The capacitor allowable range is from 150kVAr to 1800kVAr with step of 1kVAr.

A methodology is used to determine the candidate nodes for the placement of capacitors using Loss Sensitivity Factors. The estimation of these candidate nodes basically helps in reduction of the search space for the optimization procedure.

A. Loss Sensitivity Factors:

Consider a distribution line connected between 'p' and 'q' buses as shown in figure 2.

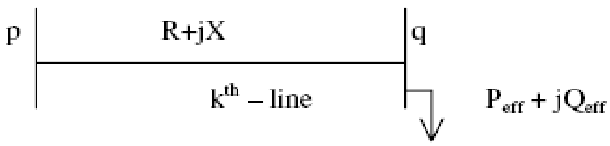

Figure 2: Feeder

Active power loss in the kth line is given by $I_k^2 * R_k$, which can be expressed as,

$$P_{lineloss}[q] = \frac{(P_{eff}^2[q] + Q_{eff}^2[q])R_k}{V^2[q]} \quad (15)$$

Peff[q] is the total effective active power supplied beyond the node 'q'.
Qeff [q] is the total effective reactive power supplied beyond the node 'q'.
The Loss Sensitivity Factors can be obtained as:

$$\frac{\partial P_{lineloss}[q]}{\partial Q_{eff}} = \frac{2 \times Q_{eff}[q] \times R_k}{V^2[q]} \quad (16)$$

B. Node Selection Using Loss Sensitivity Factors:

- Loss Sensitivity Factors are calculated by using base case load flows
- The descending order of elements vector will decide the sequence in which the buses are to be considered for compensation.
- At these buses, normalized voltage magnitudes are calculated by considering the base case voltage magnitudes given by
  norm[i] = V[i]/0.95 i=1 to nb (17)
- Now for the buses whose norm[i] value is less than 1.01 are considered as the candidate buses requiring the Capacitor Placement.
- It is worth note that the 'Loss Sensitivity factors' decide the sequence in which buses are to be considered for Compensation placement and the 'norm[i]' decide whether the buses need Q-Compensation or not.
- These candidate buses sequence is stored in 'rank bus' vector.

Once the candidate buses are identified, capacitor sizes to be placed at candidate buses are computed by using IMBHS algorithm. The solution consists of the capacitor sizes chosen to place at candidate buses.

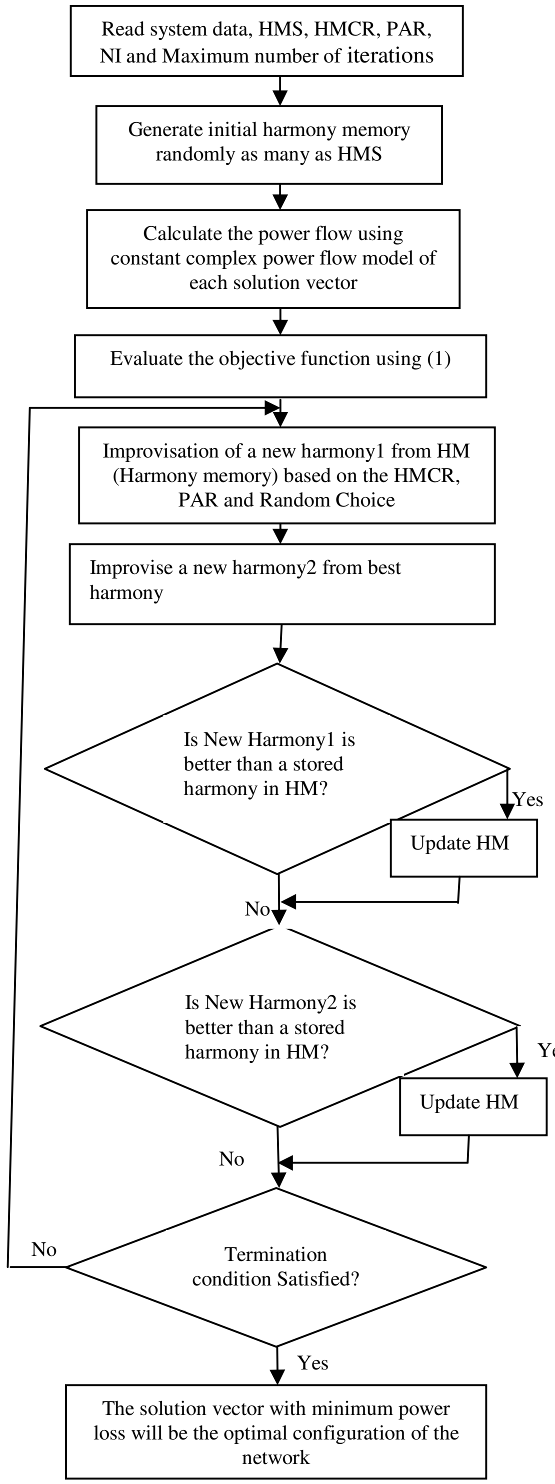

Figure 3: Flowchart of SAHS algorithm

Parameters of SAHS algorithm are given below.

TABLE I. PARAMETERS OF SAHSA

Harmony Memory Size (HMS)	10
Harmony Memory Consideration Rate (HMCR)	0.85
Pitch Adjusting Rate (PAR)	0.4
Band Width (BW)	1
Maximum Number of Improvisations (NI)	50
Maximum number of un improvements (NUI)	25
Maximum Number of iterations (ITERMAX)	100

IV. RESULTS AND DISCUSSION

The proposed method is tested on IEEE 33bus radial distribution system and IEEE 69 bus radial distribution system and the results obtained to demonstrate the effectiveness of the IMBHS when used for loss minimization via optimal capacitor placement.

The algorithm was developed in MATLAB, and the simulations were done on a computer with Pentium Dual Core, 1.7GHz, 1GB RAM.

For the IEEE 33 bus radial distribution system the total real and reactive power loads on the system are 3715 kW and 2300 kVAr, respectively. The initial power loss of this system is 202.67 kW. The lowest bus bar voltage is 0.9131 p.u., occurs at node 18. The loss sensitivity factors and normalized voltages of 33 bus radial distribution system are given in the table II.

TABLE II. LOSS SENSITIVITY FACTOR AND NORMALIZED VOLTAGE OF IEEE 33 BUS RADIAL DISTRIBUTION SYSTEMS.

Bus No.	Loss Sensitivity Factor	Norm Voltages	Bus No.	Loss Sensitivity Factor	Norm Volatges
2	0.0027	1.0495	18	0.0004	0.9612
3	0.0132	1.0347	19	0.0003	1.0489
4	0.0076	1.0268	20	0.0023	1.0452
5	0.0077	1.0190	21	0.0004	1.0444
6	0.0168	0.9996	22	0.0004	1.0438
7	0.0013	0.9960	23	0.0026	1.0309
8	0.0041	0.9909	24	0.0047	1.0239
9	0.0046	0.9843	25	0.0024	1.0204
10	0.0044	0.9782	26	0.0027	0.9976
11	0.0008	0.9773	27	0.0037	0.9949
12	0.0013	0.9757	28	0.0136	0.9829
13	0.0044	0.9692	29	0.0103	0.9742
14	0.0014	0.9669	30	0.0060	0.9705
15	0.0008	0.9654	31	0.0030	0.9661
16	0.0009	0.9639	32	0.0006	0.9651
17	0.0012	0.9618	33	0.0002	0.9648

The rank bus vector of IEEE 33 bus radial distribution system is given as {6,28,29,30,9,13,10,8,27,31,26,14,7,12,17, 16,15,11,32,18,33}. In this paper number of capacitor locations are considered as '5'. So first five buses whose loss sensitivity factors and Norm Voltages are highlighted in table II, "6, 28, 29, 30 and 9" in the rank bus vector are considered for capacitor placement.

The results for IEEE 33bus radial distribution system are given in the table III.

TABLE III. RESULTS FOR IEEE 33 BUS RADIAL DISTRIBUTION SYSTEMS.

	PSO[13]	**PGSA [15]**	**SAHSA (proposed)**
Capacitor Locations	7,12,28, 29,30	6,28,29	6,9,28,29,30
Capacitor sizes(Kvar)	350,200,100 , 250,650	1200,760,20 0	373,363,214, 204,614
Total Kvar	1550	2160	1768
Power Loss(kW)	140.51	135.4	135.12
Reduction in Power Loss(%)	30.67	33.19	33.33
Minimum Voltage in p.u. at bus 18	0.9038	0.9340	0.9344

For IEEE 33 bus radial distribution system, after capacitor the power loss is reduced to 135.12kW which shows 33% reduction when compared to the power loss before capacitor placement. The voltage profile also improved after capacitor placement and the minimum voltage is 0.9344.

The voltage profile for IEEE 33 bus radial distribution system before and after capacitor placement is shown in figure 5.

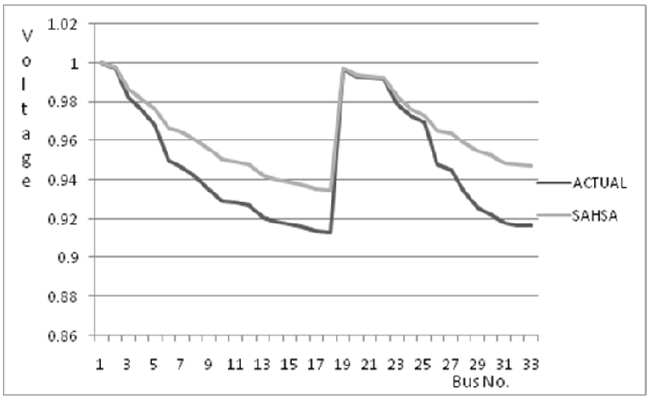

Fig 5: Voltage profile of IEEE 33 bus radial distribution system before and after capacitor placement

For the IEEE 69 bus radial distribution system the total real and reactive power loads on the system are 3802.19 kW and 2694.6kVAr, respectively. The initial power loss of this system is 225 kW. The lowest bus bar voltage is 0.9092 p.u., occurs at node 65. For this system also three buses are chosen for capacitor placement depends upon the loss sensitivity factor and normalized voltages. These buses are 57, 58 and 61. The results for IEEE 69 bus radial distribution system are given in the table IV.

TABLE IV. RESULTS FOR IEEE 69 BUS RADIAL DISTRIBUTION SYSTEMS.

	PSO[12]	PGSA [15]	SAHSA (proposed)
Capacitor Locations	46,47,50	57,58,61	57,58,61
Capacitor sizes(kVAr)	241,365, 1015	1200,274, 200	201,117, 1113
Total kVAr	1621	1674	1431
Power Loss(kW)	152.48	164.48	149.65
Reduction in Power Loss(%)	32.23	26.90	33.49
Minimum Voltage in p.u. at bus 65	-	0.9287	0.9309

For IEEE 69 bus radial distribution system 201kVAr, 117kVAr and 1113kVAr capacitors are placed at buses 57, 58 and 61 respectively. The power loss after capacitor placement is reduced by 33.49% and it is 151.53kW and the minimum voltage is increased from 0.9092 to 0.9309.

The voltage profile for IEEE 69 bus radial distribution system before and after capacitor placement is shown in figure 6.

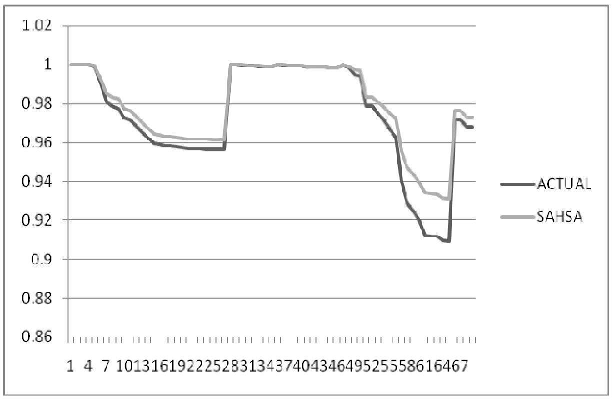

Fig 6: Voltage profile of IEEE 69 bus radial distribution system before and after capacitor placement

The results of the IEEE 33 and 69 bus radial distribution systems are compared with the results of PSO and PGSA and this method performance better when compared to PSO and PGSA.

V. CONCLUSION

An approach that employs loss sensitivity factors and self adaptive harmony search algorithm for optimal capacitor placement in radial distribution systems is proposed. Loss sensitivity factors are used for determination of location of the capacitors required for compensation which actually reduces the search space and computation time. SAHS algorithm is used to determine the capacitor sizes in order to reduce the power loss and improve the voltage profile. Usage of loss sensitivity factor determines the capacitor locations systematically and reduces the search space for optimal solution. The simulation results on IEEE 33 and 69 bus radial distribution systems performs well when compared to other stochastic methods available in literature like PSO and PGSA. This method places the capacitors at less number of locations with optimum size and offers higher saving in initial investment and annual maintenance.

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