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# Optimal Capacitor Placement in a Radial Distribution System using Harmony Search Algorithm

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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 appropriate placement of capacitors is also important so as to ensure that system power loss and total capacitor costs can be reduced. The main objective of this study is to determine optimal placement 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 relatively new meta-heuristic method is applied to solve the optimal capacitor placement problem. 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 algorithm is validated on the 9 and 34-bus radial distribution systems and the obtained capacitor placement results using HS are compared with other optimization methods.

**Key words:** Radial distribution system, capacitor placement, harmony search algorithm, backward/forward sweep load flow

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## 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 (Ibrik and Mahmoud, 2002; Al-Omari and Abdallah, 2008). 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 saving due to the loss reduction through the proper installation of shunt capacitors while minimizing shunt capacitor costs (Dura, 1968).

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 (Ng *et al*., 2000). Among these techniques, the heuristic based techniques have been widely applied in solving the optimal capacitor placement problem (Huang, 2000; Das, 2002; Masoum *et al*., 2004; Annaluru *et al*., 2004; Prakash and Sydulu, 2007; Al-Hajri *et al*., 2007; Srinivasa and Narasimham, 2008) or instance, the immune based optimization technique is used for selecting proper locations and ratings of capacitor banks (Huang, 2000) and the genetic algorithm is applied to find the optimum locations and sizes of fixed and switched capacitors at various load levels (Das, 2002). 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 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 (Masoum *et al*., 2004). Other heuristic based techniques include the application of the ant colony algorithm for solving the capacitor placement and sizing problem (Annaluru *et al*., 2004). 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

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ant colony algorithm is that it has low speed because all paths must be reviewed by the ants. The Particle Swarm Optimization (PSO) is then used in combination with the loss sensitivity indices to minimize real power losses and improve voltage profiles (Prakash and Sydulu, 2007). A discrete PSO algorithm is applied to optimally locate and size a fixed single-phase capacitor in a balanced radial distribution system (Al-Hajri *et al*., 2007). 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 radial distribution system (Srinivasa and Narasimham, 2008).

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 (Geem *et al*., 2001) 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 (Geem *et al*., 2001). This algorithm has been successfully applied to solve optimal placement of FACTS devices to improve power system security (Kazemi *et al*., 2009). In this study, the harmony search algorithm is used together with the backward/forward sweep power flow method (Teng, 2000) 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 is implemented on the 9-bus and 34-bus test systems.

## PROBLEM FORMULATION

The problem is to determine the best shunt capacitor size and location in a radial distribution system by minimizing the costs incurred by power loss and capacitor installation. To solve the optimal capacitor placement and sizing problem, the following objective function, F is considered.

$$F = \text{Minimize } \{\text{Yearly power loss cost} + \text{Yearly capacitor cost}\} \quad (1)$$

Subject to:

$$\text{Cost of yearly power loss} = K_P . P_{loss} \quad (2)$$

$$\text{Cost of yearly capacitor cost} = \sum_{i=1}^{n} K_i^c Q_i^c \quad (3)$$

$$0.9 \le V_i \le 1.1$$

$$0 \le Q_i^c \le 4050 (\text{kVar})$$

where, $P_{loss}$ is total power loss, n is number of candidate locations for capacitor placement, $K_P$ is the equivalent annual cost per unit of power loss in \$/(kW-year), $K_i^c$ is the annual capacitor installation cost and i = 1, 2,..., n are the indices of the buses selected for compensation.

To solve the optimal capacitor placement and sizing problem for radial distribution networks, a simpler 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:

$$[B] = [BIBC]\,[I] \quad (4)$$

where, [I] is the bus current injection vector and [B] is the branch current vector as shown in a simple radial distribution network of Fig. 1.

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, [ΔV] and the bus current injections [I], which is represented by the matrix [DLF] and given as:

$$[\Delta V] = [BCBV]\,[B] = [BCBV]\,[BIBC]\,[I] = [DLF]\,[I] \quad (5)$$

[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:

$$I_i^k = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \quad (6)$$

$$\left[\Delta V^{k+1}\right] = [DLF]\left[I^k\right] \quad (7)$$

The total power loss is given by:

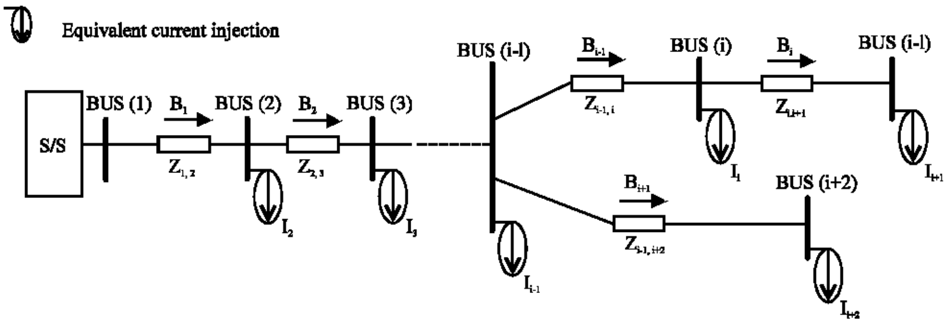

Fig. 1: Simple radial distribution network

$$P_{loss} = \sum_{i=1}^{n} \frac{R_i.\left(P^2_{\Sigma,i} + Q^2_{\Sigma,i}\right)}{\left|V_i^2\right|} \quad (8)$$

where, $R_i$ is the resistance of branch i; $P_{\Sigma i}$ and $Q_{\Sigma i}$ are the total real and reactive powers at bus i, respectively and $V_i$ is the voltage at bus i.

## 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 (Lee and Geem, 2005). 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.

Figure 2 shows a comparison of information between musical improvisation and engineering optimization. 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 (Lee and Geem, 2005).

In the HS algorithm, it looks for Vector or the path of X which can reduce the computational function cost or shorten the path. The computational procedures of the HS algorithm which are implemented in steps are described as follows (Lee and Geem, 2005):

**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

**A. Initialization of the optimization problem:** Consider an optimization problem which is described as:

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

Where:
F(x): Objective function
x : Set of each design variable ($x_i$)

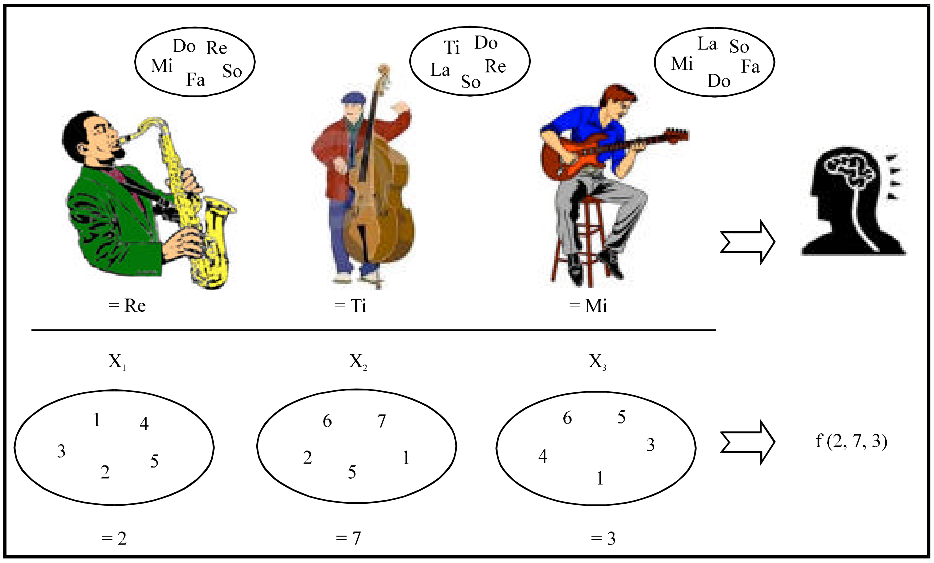

Fig. 2: Comparison between music improvisation and engineering optimization

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

**B. Initialization of the harmony memory:** The Harmony Memory (HM) matrix, shown in Eq. 9, is filled with as many randomly generated solution vectors as HMS and sorted by the values of the objective function, f (x ).

$$HM = \left[\begin{array}{ccccc|cc} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 & \Rightarrow & f(x^{(1)}) \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 & \Rightarrow & f(x^{(2)}) \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} & \Rightarrow & f(x^{(HMS-1)}) \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} & \Rightarrow & f(x^{HMS)}) \end{array}\right] \quad (9)$$

**C. Improvisation 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 (Lee and Geem, 2005). 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 $x_i^j$ from the HM with a probability of HMCR since j = {1, 2,…, HMS}.

$$x'_i \leftarrow \left\{\begin{array}{ll} x'_i \in \{x_i^1, x_i^2, \ldots, x_i^{HMS}\} & \text{with probablityHMCR} \\ x'_i \in X_i & \text{with probablity } (1-HMCR) \end{array}\right\} \quad (10)$$

**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:

$$x'_i \leftarrow \left\{\begin{array}{ll} \text{Yes} & \text{with probablityPAR} \\ \text{No} & \text{with probablity } (1-PAR) \end{array}\right\} \quad (11)$$

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:

$$x'_i \leftarrow x'_i \pm bw \quad (12)$$

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.

**D. 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 (Kazemi *et al*., 2009).

**E. 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.

## PROPOSED OPTIMAL CAPACITOR PLACEMENT METHOD

In the proposed optimal capacitor placement method, the HS algorithm is applied as an optimization technique to determine the optimal location of the capacitors at the buses and the backward/forward sweep power flow is applied for computing the power loss. The objective function of the optimization problem takes into account the savings due to the reduction of both power loss and capacitor installation costs. Thus, the optimal capacitor set $\{Q^c_{1,...,}\ Q^c_{i,...,}\ Q^c_N\}$ leads to a maximum power loss reduction and cost saving.

The procedures for implementing the proposed optimal capacitor placement method are 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 and total cost of each capacitor set using Eq. 1 and 8, respectively. Each capacitor set is considered as the harmony vectors. Initialize the arrays of HM as in Eq. 9, randomly. The number of columns in the HM is equal to number of buses in the test system. In this case, the optimal parameters of the test system example are assumed as follows:
- $Lx_i = 0$ kVar
- $Ux_i = 4050$ kVar (as in Table 2)
- HMS = 10

**Step 5:** Improvise a new harmony using the three rules of random selection, memory consideration and pitch adjustment. In this step, the optimal parameters are assumed as follows:
- HMCR = 90%
- PAR = 40%

**Step 6:** Calculate bus current injections and bus voltages using Eq. 4 and 5
**Step 7:** Calculate the total power loss and total cost saving using the backward/forward sweep power flow method
**Step 8:** Check if the capacitor set (New Harmony) gives more cost saving 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 and maximum cost saving

Figure 3 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.

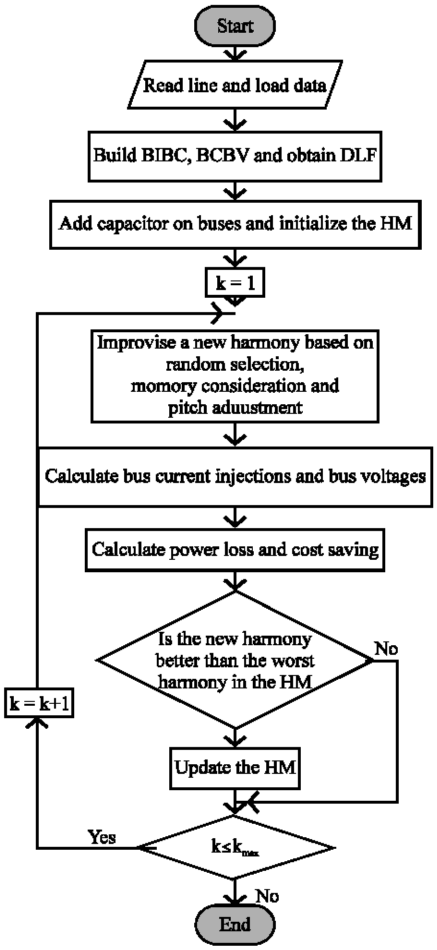

Fig. 3: The HS solution procedure for solving the capacitor placement problem

## RESULTS

The HS algorithm for solving the capacitor placement problem is applied on the 9 and 34 bus radial distribution systems shown in Fig. 4 and 5, respectively. The load and feeder data for the 9 bus system are as shown in Table 1. The details of the sizes and costs of the capacitors are tabulated as shown in Table 2. Here, the capacitor values are assumed continuous. For the 34 bus test system, the load and line data are shown in Table 3.

**A. Results of the 9- bus test system:** Results of the 9 bus test system in terms of capacitor sizes, capacitor locations, power loss and total costs using the HS algorithm are compared with other optimization techniques using Particle Swarm Optimization (PSO) (Prakash and Sydulu, 2007), plant growth simulation algorithm (Srinivasa and Narasimham, 2008), fuzzy logic (Mekhamer *et al*., 2003), fuzzy reasoning (Su and Tsai, 1996) and the concept of ensuring losses reduction (Hamada *et al*., 2008), as shown in Table 4. From the optimal capacitor placement results identified by the HS algorithm, it is shown that the HS algorithm is better than the other optimization techniques in which the power loss and total cost is greatly reduced as compared to the other techniques. Figure 6 shows the bus voltage profile before and after capacitor placement using the HS algorithm. From the figure, it is shown that the bus voltages are improved after placing the capacitors of various sizes at all the buses using the HS algorithm.

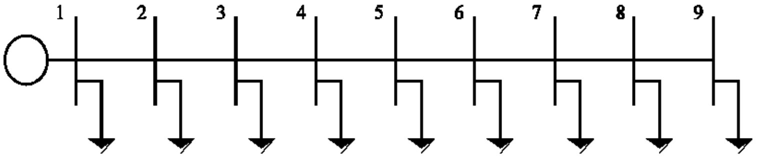

Fig. 4: The 9 bus test system

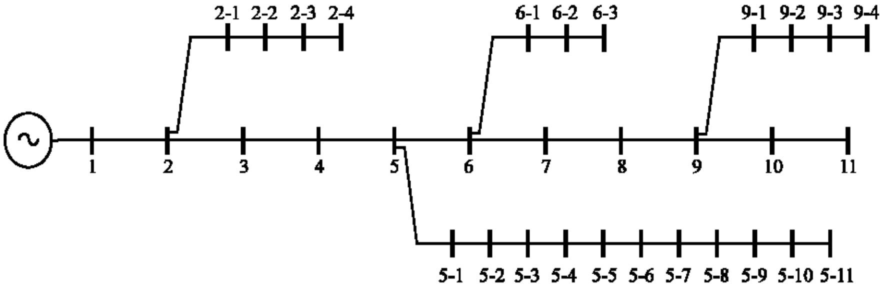

Fig. 5: The 34 bus test system

Table 1: Load and feeder data of the 9 bus test system

| | Bus No. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Data | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| **Load** | | | | | | | | | |
| P (kW) | 1840 | 980 | 1790 | 1598 | 1610 | 780 | 1150 | 980 | 1640 |
| Q (kvar) | 460 | 340 | 446 | 1840 | 600 | 110 | 60 | 130 | 200 |
| **Line** | | | | | | | | | |
| From | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| To | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| R (Ω) | 0.1233 | 0.014 | 0.7463 | 0.6984 | 1.9831 | 0.9053 | 2.0552 | 4.7953 | 5.3434 |
| X (Ω) | 0.4127 | 0.605 | 1.205 | 0.6084 | 1.7276 | 0.7886 | 1.164 | 2.716 | 3.0264 |

Table 2: Yearly costs of fixed capacitors

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Capacitor size (kvar) | 150 | 300 | 450 | 600 | 750 | 900 | 1050 | 1200 | 1350 |
| Capacitor cost ($/kvar) | 0.5 | 0.35 | 0.253 | 0.22 | 0.276 | 0.183 | 0.228 | 0.17 | 0.207 |
| Capacitor size (kvar) | 1500 | 1650 | 1800 | 1950 | 2100 | 2250 | 2400 | 2550 | 2700 |
| Capacitor cost ($/kvar) | 0.2 | 0.19 | 0.187 | 0.21 | 0.176 | 0.197 | 0.17 | 0.19 | 0.187 |
| Capacitor size (kvar) | 2850 | 3000 | 3150 | 3300 | 3450 | 3600 | 3750 | 3900 | 4050 |
| Capacitor cost ($/kvar) | 0.18 | 0.18 | 0.195 | 0.17 | 0.188 | 0.17 | 0.183 | 0.18 | 0.179 |

Table 3: Load and line data of the 34 bus system

| | | | Sectional parameters | | | | |
|---|---|---|---|---|---|---|---|
| | Load | | Bus No. | | Impedance ($\Omega$ km$^{-1}$) | | |
| Bus No. | P (kW) | Q (kvar) | From | To | R | X | Length (km) |
| 1 | 230 | 142.5 | 0 | 1 | 0.195 | 0.08 | 0.6 |
| 2 | 0 | 0 | 1 | 2 | 0.195 | 0.08 | 0.55 |
| 3 | 230 | 142.5 | 2 | 3 | 0.299 | 0.083 | 0.55 |
| 4 | 230 | 142.5 | 3 | 4 | 0.299 | 0.083 | 0.55 |
| 5 | 0 | 0 | 4 | 5 | 0.299 | 0.083 | 0.5 |
| 6 | 0 | 0 | 5 | 6 | 0.524 | 0.09 | 0.6 |
| 7 | 230 | 142.5 | 6 | 7 | 0.524 | 0.09 | 0.4 |
| 8 | 230 | 142.5 | 7 | 8 | 0.524 | 0.09 | 0.6 |
| 9 | 0 | 0 | 8 | 9 | 0.524 | 0.09 | 0.4 |
| 10 | 230 | 142.5 | 9 | 10 | 0.524 | 0.09 | 0.25 |
| 11 | 137 | 84 | 10 | 11 | 0.524 | 0.09 | 0.2 |
| 2-1 | 72 | 45 | 2 | 2-1 | 0.524 | 0.09 | 0.3 |
| 2-2 | 72 | 45 | 2-1 | 2-2 | 0.524 | 0.09 | 0.4 |
| 2-3 | 72 | 45 | 2-2 | 2-3 | 0.524 | 0.09 | 20 |
| 2-4 | 13.5 | 7.5 | 2-3 | 2-4 | 0.524 | 0.09 | 0.1 |
| 5-1 | 230 | 142.5 | 5 | 5-1 | 0.299 | 0.083 | 0.6 |
| 5-2 | 230 | 142.5 | 5-1 | 5-2 | 0.299 | 0.083 | 0.55 |
| 5-3 | 230 | 142.5 | 5-2 | 5-3 | 0.378 | 0.086 | 0.55 |
| 5-4 | 230 | 142.5 | 5-3 | 5-4 | 0.378 | 0.086 | 0.5 |
| 5-5 | 230 | 142.5 | 5-4 | 5-5 | 0.378 | 0.086 | 0.5 |
| 5-6 | 230 | 142.5 | 5-5 | 5-6 | 0.524 | 0.09 | 0.5 |
| 5-7 | 230 | 142.5 | 5-6 | 5-7 | 0.524 | 0.09 | 0.5 |
| 5-8 | 230 | 142.5 | 5-7 | 5-8 | 0.524 | 0.09 | 0.6 |
| 5-9 | 230 | 142.5 | 5-8 | 5-9 | 0.524 | 0.09 | 0.4 |
| 5-10 | 230 | 142.5 | 5-9 | 5-10 | 0.524 | 0.09 | 0.25 |
| 5-11 | 137.5 | 85 | 5-10 | 5-11 | 0.524 | 0.09 | 0.2 |
| 6-1 | 75 | 48 | 6 | 6-1 | 0.524 | 0.09 | 0.3 |
| 6-2 | 75 | 48 | 6-1 | 6-2 | 0.524 | 0.09 | 0.3 |
| 6-3 | 75 | 48 | 6-2 | 9 | 0.524 | 0.09 | 0.3 |
| 9-1 | 57 | 34.5 | 9 | 9-1 | 0.524 | 0.09 | 0.3 |
| 9-2 | 57 | 34.5 | 9-1 | 9-2 | 0.524 | 0.09 | 0.4 |
| 9-3 | 57 | 34.5 | 9-2 | 9-3 | 0.524 | 0.09 | 0.3 |
| 9-4 | 57 | 34.5 | 9-3 | 9-4 | 0.524 | 0.09 | 0.2 |

Table 4: Comparison of capacitor placement results of the 9 bus system

| | Reactive power of added capacitors in kVar | | | | | | |
|---|---|---|---|---|---|---|---|
| Bus No. | Before capacitor placement | Concept of ensuring losses reduction | PSO | Fuzzy logic | Fuzzy reasoning | Plant growth simulation | Harmony search algorithm |
| 1 | --- | 0 | 0 | 0 | 0 | 0 | 679 |
| 2 | --- | 300 | 0 | 3600 | 0 | 0 | 4042 |
| 3 | --- | 0 | 0 | 0 | 1050 | 0 | 680 |
| 4 | --- | 2850 | 1174 | 4050 | 1050 | 1200 | 2157 |
| 5 | --- | 1200 | 1182 | 1650 | 1950 | 1200 | 764 |
| 6 | --- | 300 | 0 | 0 | 0 | 0 | 522 |
| 7 | --- | 150 | 0 | 0 | 0 | 0 | 268 |
| 8 | --- | 150 | 264 | 600 | 0 | 200 | 236 |
| 9 | --- | 450 | 566 | 0 | 900 | 407 | 314 |
| Power loss (kW) | 783.8 | 684 | 696.21 | 686 | 704.26 | 694.93 | 649.1 |
| Capacitor cost ($/year) | --- | 1149.1 | 1309.1 | 1152.5 | 1191.1 | 1591.8 | 2095.2 |
| Total cost ($/year) | 131,675 | 116,111 | 118,582 | 117,035 | 119,508 | 118,340 | 109,2825 |

**B. Results of the 34- bus test system:** Accordingly, Table 5 shows a comparison of the optimal capacitor placement results of the 34 bus system in which the results of the HS algorithm are compared with other optimization techniques. Figure 7 shows the bus voltage profile before and after capacitor placement using the HS algorithm for the 34 bus system. The results in Table 5 show that the proposed HS algorithm give the greatest reduction in terms of power loss and total costs as compared to other optimization methods. It is also shown that almost all of the buses have been selected for capacitor placement in the HS optimization method

Table 5: Comparison of capacitor placement results of the 34 bus system

| Capacitor size at the respective bus in kVar | Before capacitor placement | PSO | Fuzzy reasoning | Plant growth simulation | Harmony search algorithm |
|---|---|---|---|---|---|
| $Q_1^c$ | --- | 0 | 0 | 0 | 118 |
| $Q_2^c$ | --- | 0 | 0 | 0 | 0 |
| $Q_3^c$ | --- | 0 | 0 | 0 | 126 |
| $Q_4^c$ | --- | 0 | 250 | 0 | 125 |
| $Q_5^c$ | --- | 0 | 0 | 0 | 0 |
| $Q_6^c$ | --- | 0 | 0 | 0 | 0 |
| $Q_7^c$ | --- | 0 | 0 | 0 | 130 |
| $Q_8^c$ | --- | 0 | 0 | 0 | 134 |
| $Q_8^c$ | --- | 0 | 0 | 0 | 124 |
| $Q_9^c$ | --- | 0 | 0 | 0 | 0 |
| $Q_{10}^c$ | --- | 0 | 750 | 0 | 72 |
| $Q_{11}^c$ | --- | 0 | 0 | 0 | 42 |
| $Q^c_{2-1}$ | --- | 0 | 0 | 0 | 40 |
| $Q^c_{2-2}$ | --- | 0 | 0 | 0 | 37 |
| $Q^c_{2-3}$ | --- | 0 | 0 | 0 | 0 |
| $Q^c_{2-4}$ | --- | 0 | 0 | 0 | 128 |
| $Q^c_{5-1}$ | --- | 0 | 300 | 0 | 129 |
| $Q^c_{5-2}$ | --- | 0 | 0 | 0 | 130 |
| $Q^c_{5-3}$ | --- | 781 | 0 | 1200 | 130 |
| $Q^c_{5-4}$ | --- | 479 | 0 | 200 | 131 |
| $Q^c_{5-5}$ | --- | 0 | 0 | 0 | 133 |
| $Q^c_{5-6}$ | --- | 803 | 0 | 769 | 134 |
| $Q^c_{5-7}$ | --- | 0 | 0 | 0 | 135 |
| $Q^c_{5-8}$ | --- | 0 | 0 | 0 | 131 |
| $Q^c_{5-9}$ | --- | 0 | 0 | 0 | 127 |
| $Q^c_{5-10}$ | --- | 0 | 0 | 0 | 75 |
| $Q^c_{5-11}$ | --- | 0 | 1400 | 0 | 43 |
| $Q^c_{6-1}$ | --- | 0 | 0 | 0 | 41 |
| $Q^c_{6-2}$ | --- | 0 | 0 | 0 | 46 |
| $Q^c_{6-3}$ | --- | 0 | 0 | 0 | 32 |
| $Q^c_{9-1}$ | --- | 0 | 0 | 0 | 33 |
| $Q^c_{9-2}$ | --- | 0 | 0 | 0 | 33 |
| $Q^c_{9-3}$ | --- | 0 | 0 | 0 | 31 |
| $Q^c_{9-4}$ | --- | 0 | 0 | 0 | 26 |
| Power loss (kW) | 221.67 | 168.8 | 165.5 | 161.07 | 158.16 |
| Total KVar | --- | 2063 | 2700 | 2039 | 2616 |
| Capacitor cost ($/year) | --- | 446 | 1577.6 | 1424.24 | 997.32 |
| Total cost ($/year) | 37,241 | 29,936 | 28,250 | 28,484 | 27,568 |

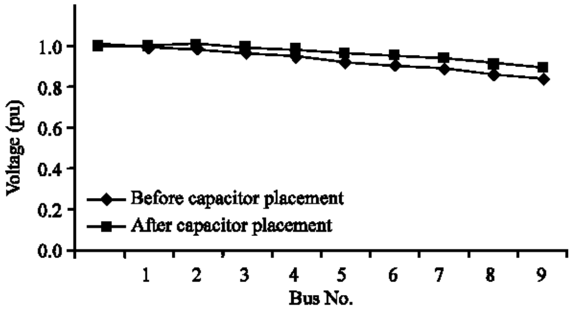

Fig. 6: Voltage profile improvement on the 9 bus system

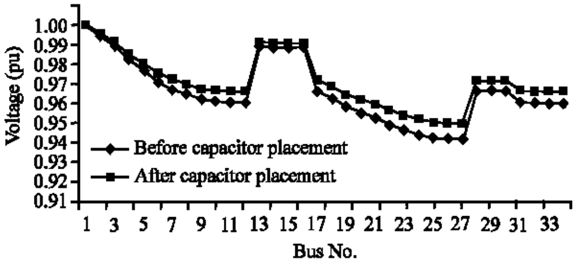

Fig. 7: Voltage profile improvement on the 34 bus system

whereas only few buses are selected for capacitor placement in the other optimization methods. In Fig. 7, it is shown that the voltage magnitudes of the 34 bus system are close to 1 p.u. after placing the capacitors of various sizes at almost all the buses using the HS algorithm.

## CONCLUSION

The application of HS algorithm as a new meta-heuristic optimization method for determining the optimal location and size of shunt capacitors in a distribution network has been presented. The backward/forward sweep power flow is also used to obtain faster power flow solutions. The proposed HS algorithm has been validated on the 9-bus and also 34-bus radial distribution systems and the obtained results showed that the HS optimization method gives greater reduction in power loss and total costs compared to the other optimization methods.

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