A Hybrid BCO/HS Algorithm for Optimal Placement and Sizing of Static Var Compensators in Power Systems

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Abstract: In this paper, the bee colony optimization and harmony search algorithms are combined to form a hybrid algorithm for finding the optimal placement and sizing of static Var compensators (SVC) in transmission systems. A multi-criterion objective function considering both operational objectives and investment costs is considered. The results on the 57-bust test system showed that the hybrid algorithm give lower power loss and better voltage improvement compared to the other optimization methods in solving the SVC placement and sizing problem.

Key-Words: - SVC, Power Loss, Voltage Profile, Harmony Search Algorithm, Bee Colony Optimization

1 Introduction

The most widely used shunt FACTS devices within power networks is the static Var compensator (SVC) due to its low cost and good performance for system enhancement. It is a shunt-connected static Var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to provide voltage support and reduce power loss when installed at a proper location.

Many methods and approaches have been reported in the literature to determine optimal location of SVC in a power system using different techniques such as genetic algorithm (GA), simulated annealing (SA), artificial immune system (AIS) and particle swarm optimization (PSO) [1,2]. A solution algorithm based on SA is used to determine the location, types and sizes of Var sources at different loading conditions [3]. Here, the purchase cost, installation cost and total cost of energy loss over the life of the Var sources, are minimized considering operational constraints. In [4], GA is applied to determine the best location of only one SVC in a power system in which the objective function is defined for reducing power loss, voltage deviation and cost. An AIS technique is used to minimize the total loss and improve the voltage in a power system by determining the correct placement of SVC [5]. The well known PSO is explored in [6] to obtain optimal locations of SVCs in the IEEE 30 bus system.

Some of the recent heuristic optimization techniques are such as the harmony search (HS) algorithm and the bee colony optimization (BCO). The HS algorithm is a meta-heuristic optimization technique that is inspired by musicians in improvising their instrument pitches to find better harmony [7]. 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. An improved HS algorithm has been successfully applied to solve optimal placement of SVC devices to improve the voltage profile and reduce system power losses [8]. On the other hand, the BCO algorithm is a new member of swarm intelligence and it mimics the food foraging behavior of honey bees. This algorithm is simple, robust and capable of solving difficult optimization problems [9].

In this paper, to increase the accuracy of the new generated solutions, the BCO and HS algorithms are integrated to form a hybrid algorithm for finding optimal placement and sizing of static VAR compensators in transmission systems. For simplicity, this paper only addresses the optimal placement of only five SVC devices for voltage profile improvement and power loss reduction in the 57-bus test system. The obtained results are then compared with the PSO, Improved HS algorithm (IHSA) and BCO for validation.

2 Problem Formulation

In its simplest form, the SVC consists of a thyristor-controlled reactor in parallel with a bank of capacitors. From the operational point of view, the SVC behaves like a shunt connected variable reactance, which either generates or absorbs reactive power in order to regulate the voltage magnitude at
the point of connection to the power network. It is used extensively to provide fast reactive power and voltage regulation support. The thyristor’s firing angle control enables the SVC to have almost instantaneous speed in response. As an important component for voltage control, it is usually installed at the receiving node of the transmission lines.

In Fig.1, the SVC is modelled as a shunt element with a compensated reactive power, $Q_{SVC}$, set by available inductive and capacitive susceptances.

From Fig.1, the current drawn and reactive power injected by the SVC can be expressed as:

$$I_{SVC} = jB_{SVC} \times V$$

$$Q_{SVC} = -jB_{SVC} \times V^2$$

where $B_{SVC}$, $I_{SVC}$ and $Q_{SVC}$ are the susceptance, injected current and injected reactive power of SVC, respectively.

2.1. The objective function

A multi-objective function is considered in searching for a solution consisting of both the SVC location and size that minimizes the voltage deviation, active power loss and installation cost [4] described as follows:

**Minimize the active power loss:**

The total active power loss in an electric power system is given by,

$$P_{loss} = \sum_{i=1}^{b} R_i I_i^2 = \sum_{i=1}^{n} \sum_{j=1}^{l_{ij}} [V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j)]Y_{ij} \cos \phi_{ij} \tag{3}$$

where $b$ is the number of lines, $R_i$ is the resistance of line $l$, $I_i$ is the current through line $l$, $V_i$ and $\delta_i$ are the voltage magnitude and angle at node $i$ and $Y_{ij}$ and $\phi_{ij}$ are the magnitude and angle of the line admittance, respectively.

**Minimize the voltage deviation:**

The voltage improvement index for a power system is defined as the deviation of voltage magnitudes at each from unity. Thus, for a given system, the voltage improvement index is defined as,

$$L_v = \sum_{i=1}^{n} \left( \frac{V_{ref} - V_i}{V_{ref}} \right)^2 \tag{4}$$

where $n$ is the number of buses, $V_{ref}$ is the reference voltage at bus $i$ and $V_i$ is the actual voltage at bus $i$.

**Minimize the investment cost:**

The total SVC cost in US$/kVar is given as [4,8]:

$$C_{SVC} = \sum_{k=1}^{n} 0.0003Q_k^2 - 0.3051Q_k + 127.38 \tag{5}$$

where $Q_k$ is the reactive power capacity of $k^{th}$ installed SVC, in MVar.

2.2 Operational constraints

Since the objective of applying SVC is to control system variables such as line real and reactive power flows and bus voltages, the following constraints are considered.

**Power flow balance equations:**

The balance of active and reactive powers must be satisfied at each node. Power balance with respect to a bus can be formulated as:

$$P_{Gi} - P_{Li} = V_i \sum_{j=1}^{n} [V_j \cos(\delta_i - \delta_j) + B_{ij}' \sin(\delta_i - \delta_j)] \tag{6}$$

$$Q_{Gi} - Q_{Li} = V_i \sum_{j=1}^{n} [V_j \sin(\delta_i - \delta_j) - G_{ij}' \sin(\delta_i - \delta_j)] \tag{7}$$

where $P_{Gi}$ and $Q_{Gi}$ are the generated active and reactive powers, and $P_{Li}$ and $Q_{Li}$ are the load active and reactive powers at node $i$. The conductance, $G_{ik}'$ and susceptance, $B_{ik}'$ represent the real and imaginary components of element $Y_{ij}'$ of the $[Y_{bb}]$ matrix, obtained by modifying the initial nodal admittances matrix when introducing the SVC.

**Power flow limit:**

The apparent power that is transmitted through a branch $l$ must not exceed a limiting value, $S_{l_{max}}$, which represents the thermal limit of the line or transformer in steady-state operation:

$$S_l \leq S_{l_{max}} \tag{8}$$
**Bus voltage limits:** Bus voltages must be maintained around the nominal value and it is given by:

\[ V_{i, min} \leq V_i \leq V_{i, max} \]  

(9)

In practice, the accepted deviations can reach up to 10% of the nominal values [4].

The objective function for solving the SVC optimal placement problem is computed using equations (3)-(5). Due to the fact that the three objectives are different, it would be impossible to incorporate all the constraints in the same mathematical function. An overall fitness function is considered such that each objective function is normalized in a comparative manner with the base case system without SVC. This fitness function is given by,

\[ f(x) = \alpha \frac{P_{loss}}{\sum_{i} \Delta L_{loss}^{base}} + \beta \frac{L_v}{\sum_{i} \Delta V_{base}} + \eta \frac{C_{SVC}}{C_{max}} \]  

(10)

where \( P_{loss}, L_v \) and \( C_{SVC} \) are total active power loss, voltage deviation index and total SVC cost, respectively. \( \alpha, \beta \) and \( \eta \) are the corresponding coefficients the corresponding objective functions; cost factor, \( \sum_{i} \Delta L_{loss}^{base} \) is the total base case active power loss in the network, \( \sum_{i} \Delta V_{base} \) is the total base case voltage deviation and \( C_{max} \) is the maximum investment cost.

Taking into consideration the fact that the cost objective function is less important than the power loss reduction and voltage profile improvement, the corresponding coefficients for each objective are defined as \( \alpha = 40\%, \beta = 40\% \) and \( \eta = 20\% \).

### 3 Theoretical Background

The background theory of the HS algorithm, BCO algorithm and the hybrid HS/BCO algorithm is described briefly in this section.

#### 3.1 Harmony Search Algorithm

Harmony search algorithm is a meta-heuristic optimization algorithm inspired by the operation of orchestra music to find the best harmony between components which are involved in the operation process, for optimal solution [7]. 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 are described as follows [8]:

**Step 1: Initialization of the Optimization Problem**

Consider an optimization problem which is described as,

Minimize \( F(x) \) subject to \( x_i \in X_i, i=1,2,3,....N \).  

(11)

where \( F(x) \) is the objective function, \( x \) is the set of each design variable (\( x_i \)), \( X_i \) is the set of the possible range of values for each design variable (\( L_x < X_i < U_x \)) and \( N \) is the number of design variables.

The HS algorithm parameters are specified as 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.

**Step 2: Initialization of the Harmony Memory**

The harmony memory (HM) matrix shown in Eq.12 is filled with as many randomly generated solution vectors as HMS and sorted by the values of the objective function, \( f(x) \).

\[
HM = \begin{bmatrix}
x_1^{HM-1} & x_2^{HM-1} & ... & x_{N-1}^{HM-1} & x_N^{HM-1} \\
x_1^{HM} & x_2^{HM} & ... & x_{N-1}^{HM} & x_N^{HM} \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
x_1 & x_2 & ... & x_{N-1} & x_N \\
\end{bmatrix} \Rightarrow f(x^{(1)}) \Rightarrow f(x^{(2)}) \\
\Rightarrow f(x^{(HM-1)}) \Rightarrow f(x^{(HM)})
\]  

(12)

**Step 3: 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. 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 \( x_i \) from the HM with a probability of HMCR since \( j \in \{1, 2, ..., HMS\} \).

\[
x_i' \left\{ \begin{array}{l}
x_i' \in \begin{cases} x_1^{HM-1}, x_2^{HM-1}, ..., x_N^{HM-1} \\ x_1^{HM-1}, x_2^{HM-1}, ..., x_N^{HM-1} \end{cases} \\
\text{with probability } HMCR \\
x_i' \in X_i \\
\text{with probability } (1-HMCR)
\end{array} \right.
\]  

(13)

**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 neighbouring 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:
\[
x'_i \left\{ \begin{array}{ll}
Yes & \text{with probability } PAR \\
No & \text{with probability } (1 - PAR)
\end{array} \right.
\]

If the pitch adjustment decision for \( x'_i \) is yes, \( x'_i \) is replaced as follows:
\[
x'_i \leftarrow x'_i \pm bw
\]
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.

**Step 5: Checking stopping criterion**

If the stopping criterion which is based on the maximum number of improvisations is satisfied, computation is terminated. Otherwise, steps 3 and 4 are repeated.

### 3.2 Bee Colony Optimization Algorithm

The BCO algorithm is an optimization algorithm inspired by the natural foraging behaviour of honey bees to find the optimal solution. This algorithm is proposed by Karaboga for numerical optimization in 2005. A colony of honey bees can extend itself over long distances in multiple directions of more than 10 km. Flower patches with plentiful amounts of nectar that can be collected with less effort are visited by more bees, whereas patches with less nectar receive fewer bees. Scout bees search randomly from one patch to another. The bees who return to the hive, evaluate the different patches depending on certain quality threshold measured as a combination of some elements, such as sugar content. These bees deposit their nectar and go to the “dance floor” to perform a “waggle dance”. Bees communicate through this waggle dance which contains the following information: i) The direction of flower patches (angle between the sun and the patch); ii) The distance from the hive (duration of the dance) and iii) The quality rating (fitness or frequency of the dance). This information helps the colony to send its bees precisely. Follower bees go after the dancer bee to the patch to gather food efficiently and quickly. The same patch will be advertised in the waggle dance again when returning to the hive is still good enough as a food source and more bees will be recruited to that source. More bees visit flower patches with plentiful amounts of nectar.

In the BCO algorithm, the colony of bees consists of two groups, scout and employed bees. The scout bees seek a new food source and the employed bees look for a food source within the neighbourhood of the food source in their memories. Both scout and employed bees share their information with other bees within the hive [9]. Fig.2. shows the pseudo code of the algorithm in its simplest form.

- Generate randomly \( n_s \) scout bees.
- Calculate the nectar amount of each site visited by the scout bee.
- Sort the visited sites in descending order according to their nectar amounts.
- Select the best \( m \) visited sites out of \( n_s \) visited sites.
- While (stopping criterion not met):
  - Generate \( n_s \) neighbourhood search for each selected site.
  - Calculate the nectar amount of each neighbourhood search site.
  - Sort the \((n_s \times m)\) sites in descending order according to their nectar amounts.
  - Select the best \( m \) visited sites out of \((n_s \times m)\) visited sites.
- End While

Fig.2. Pseudo code of the BCO algorithm

The algorithm starts with \( n_s \) scout bees randomly distributed in the search space. The nectar amounts of sites visited by ns scout bees are calculated. Sites \((m)\) that have the highest nectar amounts are chosen for neighbourhood search. Recruit \( n_s \) bees for each selected site to explore neighbourhood search. The nectar amount of all \((n_s \times m)\) sites are calculated. Select \( m \) sites which have the highest nectar amount from \((n_s \times m)\) sites to form the next bee population [9].

### 3.3 Hybrid BCO/HS Algorithm

One of the most important problems in the BCO algorithm is the neighbourhood calculation. The HS algorithm in the step of improvisation presents a suitable solution for generating new solution vectors. As it is observable in Eq.(13), in the memory consideration of HS algorithm, the value of new \( x'_i \) with probability of \((1-HMCR)\) is selected among the whole values in possible range. If these values are selected among the sorted solution vectors according to their fitness values or their nectar amounts, the next generated solution vectors would be more accurate. Thus, to increase the accuracy of the new generated solutions, the BCO
and HS algorithms are combined. The procedures of the hybrid algorithm are described as follows:

i. Generate randomly \( n \) solution vectors.

ii. Calculate the fitness value of each site visited by each solution vector.

iii. Sort the visited sites in descending order according to their fitness values.

iv. Select the best \( m \) visited sites out of \( n \) visited sites and form the HM matrix.

v. Select the \((m+1)\)th to \((2m)\)th visited sites out of sorted visited sites and form the second HM (HM2) matrix.

vi. Improvise new harmony from the HM set using random selection, memory consideration and pitch adjustment rules. Note that in the memory consideration, the value of new \( x'_i \) with probability of \((1-HMCR)\) is selected from the HM2.

vii. If the new harmony gives less fitness value than the worst harmony in the HM, the worst harmony is replaced with the new harmony in the HM and the worst harmony in HM2 is replaced with the worst harmony in the HM. Otherwise, go to step (vi).

viii. Determine the best solution vectors.

### 4 Application of Hybrid Algorithm for Optimal Placement of SVC

The optimal placement of SVC at the buses is found by using the hybrid algorithm in which the optimal SVC set \( \{Q_{svc1}^{m}, ..., Q_{svcN}^{m}\} \) leads to a maximum power loss reduction, minimum voltage deviation and cost saving. Here, the Newton-Raphson power flow is applied for computing the power loss. The procedures for implementing the proposed method for optimal placement of SVC are described as follows:

i. Input system parameters such as buses, branches and generators data.

ii. Generate randomly \( n \) sets of SVC and add them for reactive power compensation at allowed buses. Each SVC set is considered as a solution vector. In this study, \( n \) is assumed to be 100.

iii. Calculate the total power loss, voltage deviation and total cost, respectively. Calculate the fitness value of each SVC set and sort in descending order according to their fitness values.

iv. Select the best 10 sets of SVC and form the HM matrix. 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, \( L_x \) and \( U_x \) are assumed to have minimum and maximum MVAR values of 0 MVAR and 20 MVAR, respectively. Thus, the HMS is assumed to be 10.

v. Select 11th to 20th SVC sets out of the sorted SVC sets and form the HM2 matrix.

vi. Improvise a new harmony using the three rules of random selection, memory consideration and pitch adjustment. Here, the optimal parameters are assumed as: \( HMCR = 90\% \), \( PAR=50\% \), \( bw=0.001 \) and \( NI = 5000 \). In the memory consideration, the value of new \( x'_i \) with probability of \((1-HMCR)\) is selected from the HM2.

vii. Run the power flow and calculate power loss, voltage deviation, total cost and fitness value.

viii. Check if the SVC set (new harmony) gives less fitness value than the worst harmony in the HM. If yes, the worst harmony is replaced with the new harmony in the HM and the worst harmony in HM2 is replaced with the worst harmony in the HM. Otherwise, go to step (vi).

ix. Determine the optimal SVC set (best harmony) which gives maximum power loss reduction, minimum voltage deviation and maximum cost saving.

### 5 Case Study and Results

The proposed method is tested on the 57-bus system shown in Fig.3. The system consists of 7 generators, of which one is the slack node, 50 load buses and 80 lines. The base case system load is 12.508 pu and the system power loss is 0.2841 pu. The power flow program is used to calculate the minimum power loss, \( P_{loss} \), when reactive power injection is varied in steps of 0.01 per unit independently at all the load buses. The reduction of the \( P_{loss} \) due to Q injection at the load bus is recorded together with the bus number.

For identification of optimal SVC placement, it is assumed that there are five SVCs in the 57-bus system. The proposed hybrid algorithm is implemented to determine the optimal placement and sizing of the 5 SVCs. The results obtained from the hybrid algorithm are compared with the results using the PSO, improved HS algorithm (IHS) and BCO algorithm as shown in Table 1. This study is performed with the restriction that the injected Q does not exceed 20 MVar. The results in Table 1 show that the optimal placement and sizing of the 5 SVCs are not the same for all the optimization methods.

For a more detailed analysis of the results, consider Table 2 which shows the total active power losses and total voltage deviations after installation of the SVC devices.
Fig. 3. Network configuration of the 57 bus power system

Table 1. SVC placement results using different optimization methods

<table>
<thead>
<tr>
<th>SVC on Bus</th>
<th>PSO</th>
<th>IHSA</th>
<th>BCO</th>
<th>BCO/HS</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>0</td>
<td>2.17</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>0</td>
<td>4.63</td>
<td>0</td>
</tr>
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<td>25</td>
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<td>26</td>
<td>0</td>
<td>3.46</td>
<td>3.61</td>
<td>2.89</td>
</tr>
<tr>
<td>30</td>
<td>5.99</td>
<td>4.03</td>
<td>3.43</td>
<td>4.19</td>
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<td>31</td>
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<td>3.62</td>
<td>2.86</td>
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<tr>
<td>32</td>
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<td>0</td>
<td>3.2</td>
<td>0</td>
</tr>
<tr>
<td>46</td>
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<td>0</td>
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</tr>
<tr>
<td>56</td>
<td>0</td>
<td>0</td>
<td>2.94</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2. Comparison of objective function components after installing SVC

<table>
<thead>
<tr>
<th>The objective function components</th>
<th>PSO</th>
<th>IHSA</th>
<th>BCO</th>
<th>BCO/HS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Power Losses (MW)</td>
<td>27.66</td>
<td>27.48</td>
<td>27.73</td>
<td>27.41</td>
</tr>
<tr>
<td>Total Voltage deviation (p.u)</td>
<td>0.457</td>
<td>0.453</td>
<td>0.462</td>
<td>0.446</td>
</tr>
<tr>
<td>SVC cost ($)</td>
<td>17205</td>
<td>13367</td>
<td>14622</td>
<td>12146</td>
</tr>
<tr>
<td>Fitness function value</td>
<td>0.583</td>
<td>0.578</td>
<td>0.589</td>
<td>0.5642</td>
</tr>
</tbody>
</table>

From Table 2, it is observable that the SVC placement by using hybrid BCO/HS algorithm lead to the lowest fitness function value, total power loss and SVC cost in comparison with the PSO, IHSA and BCO methods.

6 Conclusion

A hybrid BCO/HS algorithm for determining the optimal location and size of SVC devices in a transmission network has been presented. The proposed multi-objective hybrid algorithm has been validated on the 57-bus transmission network and the obtained results showed that the proposed algorithm gives greater reduction in total power loss and total SVC costs compared to PSO, IHSA and BCO methods.

References: