Optimal location of capacitors and capacitor sizing in a radial distribution system using Stud krill herd Algorithm

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Abstract: This paper presents a new meta-heuristic technique, Stud Krill Herd Algorithm (SKHA) for solving capacitor placement problem in radial distribution system (RDS). The algorithm predicted the optimal size of the capacitors and should be placed at the proper location for loss minimization and hence improvement in voltage. The Stud krill herd algorithm is established along the biological herding behavior of krills along with genetic operators namely Stud selection and Crossover operator. The method is implemented in 69 IEEE RDS test system 94 bus Portugal system and the results are compared with other algorithms from the literature. The outcomes reveal the potency of the algorithm. The simulation is taken away on the MATLAB environment.

Keywords: Capacitor placement, Power loss minimization, Radial distribution system (RDS), Stud Krill herd algorithm (SKHA)

I. Introduction

In the radial distribution system, capacitors are primarily used for reactive power compensation. From the studies, 10 – 20% of total power generated is wasted in the form of ohmic losses at the distribution level. Reactive currents flowing in the network are the main source for these losses and are minimized by the usage of shunt capacitors. From [1], Capacitors are used for the minimization of power/energy losses, improvement of power factor, system security and maintenance of better voltage regulation. The main steps of this capacitor problem are (i) selection of number of capacitor units (ii) optimal location of capacitor units and (iii) sizing of capacitor units. Hence, getting the optimal position and size of capacitors plays a significant part in the planning and operation of an electrical system.

The authors [2] presented the overview of optimum shunt capacitor placement in distribution system based upon different methods and compared the results with Particle Swarm Optimization (PSO). The authors [3] gave a brief introduction and discussed various works done on the Shunt Capacitor Problem (SCP) till 2014. Also, they used two methods, namely sensitivity analysis for searching suitable locality of capacitors and Gravitational Search Algorithm (GSA) for selecting the size of capacitors. The authors [4] utilized the teaching – learning based optimization for selection of capacitor size and placement to minimize power loss and cost.

The authors [5] proposed an integrated approach of loss sensitivity factor and voltage stability index for finding the optimal location of capacitor banks and Bacterial Foraging Optimization Algorithm (BFOA) for finding the optimal size of SC banks. In this paper [6], the location and size of capacitors are found by two bio – inspired algorithms bat algorithm and cuckoo search algorithm. In [7], the authors proposed loss sensitivity factor for selection of capacitor location and bat algorithm to select the size of capacitor. The authors [8] used power loss index for selecting the location and flower pollination algorithm to select the size of capacitor banks. Furthermore numerous solution techniques namely Ant colony optimization (ACO) [9], Shuffled frog leap algorithm (SFLA) [10], Modified monkey search algorithm [11], Whale optimization [12], Shark smell optimization [13], Hybrid PSO with Quasi Newton algorithm [14], Improved harmony Algorithm [15], Cuckoo search algorithm [16], Combined harmony search and particle artificial bee colony algorithm [17], Particle swarm optimization combined with Gravitational search algorithm [18] and Analytical approach [19] are developed for solving OCP problem.

This paper presents one of the new bio – inspired algorithm, namely Stud Krill herd algorithm is used for solving the capacitor optimization problem. RDS active power loss minimization is taken as an objective function subjected to various constraints namely voltage limit, reactive power limit and capacitor location and an optimum solution is obtained using SKH algorithm. The paper is organized as follows: (I) Introduction (II) Problem Formulation (III) Overview of Stud Krill herd algorithm (IV) Test system and Result analysis (V) Conclusion and finally References.

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In 2012, Gandomi and Alavi [20], proposed a biologically inspired swarm intelligence algorithm. This method is based on the simulation of herding behavior of the large number of individual krills. Later in 2014, the same authors along with Wang [21], added updated genetic operators to KH method.

The main drawbacks in all the above methods are poor convergence speed and obtaining near optimal solutions. This paper is aimed to overcome all the above drawbacks by implementing one of the new bio-inspired, heuristic technique, Krill herd algorithm with stud operators namely Stud krill herd algorithm. In [22], the authors applied Stud krill herd algorithm for solving DG placement problem to achieve power loss minimization.

In this proposed approach, the following assumptions are taken:

- Harmonics effect is neglected.
- The system is within the acceptable balance tolerance.
- Bus 1 is always considered as slack/swing bus.

II. Problem Formulation

2.1 Power flow equation

2.1.1 Power loss equation

The forward – backward sweep algorithm based on Kirchhoff’s laws is applied to find the power flow in the radial distribution system [23]. The real and reactive power loss equation is given by

\[ P_L = P_{inj} - \sum_{a=1}^{n} P_a \]  

where, \( P_{inj} \) – injected real power at bus 1; \( P_{inj} = P_{Slack} \)

\[ Q_L = Q_{inj} - \sum_{a=2}^{n} Q_a \]  

where, \( Q_{inj} \) – injected reactive power at bus 1; \( Q_{inj} = Q_{Slack} \)

2.1.2 Power loss after capacitor installation

Capacitors at optimal location reduce the system power loss, improve voltage stability and reliability. Total system power loss after capacitor installation is given by

\[ Q_{LCap} = Q_{Slack} + \sum_{a=2}^{n} Q_{Cap} - \sum_{a=1}^{n} Q_a \]  

where, \( n \) - number of buses, \( n_{cap} \) – number of capacitor units connected

2.2 Objective function and Constraints

The objective function \( F \) of the radial distribution system comprises of minimization of power loss subject to various constraints.

\[ F = \min (P_L) \]  

2.2.1 Constraints

Voltage limit

The voltage magnitude should be within the minimum and maximum limits.

\[ V_{a_{min}} < V_a < V_{a_{max}} \]  

where, \( V_{a_{min}} \) – Minimum voltage limit (0.95 p.u.) and \( V_{a_{max}} \) – Maximum voltage limit (1.05 p.u.)

Reactive power limit

\( Q_{cap_{min}} \) is the reactive power delivered from the capacitor and it should be within minimum and maximum limits.

\[ Q_{cap_{min}} \leq Q_{cap} \leq Q_{cap_{max}} \]  

where, \( Q_{cap_{min}} \), \( Q_{cap_{max}} \) – minimum and maximum permissible limit of reactive power delivered from capacitor

Capacitor location

Capacitors should be placed within the total number of nodes.

\[ 1 < Cap_{loc} < n; n = \text{number of nodes} \]  

2.3 Load model

Different load models are obtained by varying the factors \( \alpha \) and \( \beta \) in the mathematical representation of the relationship between bus voltage and real and reactive power at bus a and is given by

\[ P_a = \rho P_D V_a^\alpha \]  

\[ Q_a = \rho Q_D V_a^\beta \]
where, \( \rho \) - Load factor is varied by which the power demand is increased or decreased, \( \alpha \) and \( \beta \) are load coefficients. The above factors are varied, in order to verify the usefulness of the algorithm in the practical execution. The values are as followed in Table (1):

<table>
<thead>
<tr>
<th>Type of Load</th>
<th>( \rho )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Power (CP) - Light</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Constant Power (CP) - Nominal</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Constant Power (CP) - Heavy</td>
<td>1.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Constant Current (CC)</td>
<td>1.0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Constant Impedance (CI)</td>
<td>1.0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Industrial</td>
<td>1.0</td>
<td>0.18</td>
<td>6</td>
</tr>
<tr>
<td>Residential</td>
<td>1.0</td>
<td>0.92</td>
<td>4.04</td>
</tr>
<tr>
<td>Commercial</td>
<td>1.0</td>
<td>1.51</td>
<td>3.4</td>
</tr>
</tbody>
</table>

### III. Overview Of Stud Krill Herd Algorithm

Stud krill herd algorithm is a heuristic technique developed by Gandomi et al. They first introduced Krill Herd Algorithm (KHA) [20] which is based on the herding behavior of krills. The objective function used in KHA is determined by the distance between krill and food and the density of krills. In 2014, the same authors along with Wang introduced genetic reproductive schemes namely Stud selection and Crossover operator into KHA [21]. The aim of SKH is to accelerate convergence speed. The SSC operator is employed only to take the newly generating better solutions for each krill individual and to fine-tune the selected solution in order to improve its stability and robustness for global optimization. The proposed SKH approach can search the whole space widely by basic KH method and take out useful information by SSC operator. The flowchart for Stud krill herd algorithm application to capacitor problem is shown in Fig. (1) and the algorithm steps are as follows:

#### 3.1 Stud krill herd algorithm steps

Begin

**Step 1:** Define the population size \( N \) and maximum iteration count \( I_{\text{max}} \).

**Initialization:** Set The iteration Count \( I = 1 \); initialize the population \( X_i \) of \( N \) krill individuals; set the foraging speed \( V_f \), the maximum diffusion speed \( D_{\text{max}} \), and the maximum induced speed \( N_{\text{max}} \); a probability of crossover \( p_c \).

**Step 2:** Evaluating population. Evaluate the krill population based on its position.

**Step 3:** While \( I < I_{\text{max}} \) do

Perform the three motions.

1. **Movement induced by other krill individuals**

For each krill individual the movement is given by,

\[
N^\text{new}_i = \left[ N_{\text{max}} \right] \left\{ \sum_{j=1}^{NN} \left( K_i - K_j \right) - \left( X_i - X_j \right) \right\} \left\{ 2 \left( \frac{r}{I_{\text{max}}} \right) R_{t,\text{best}} \hat{X}_{t,\text{best}} \right\}^2 + \omega_n N^\text{old}_i \tag{10}
\]

where,

- \( K_i \) - fitness value of the \( i^{th} \) krill individual (\( i = 1 \) to \( N_k \))
- \( K_j \) - fitness value of the neighbor (\( j = 1 \) to \( NN \))
- \( K_{worst}, K_{best} \) - worst and best fitness value of the krill individual
- \( X \) - related position of the krill individual
- \( \varepsilon \) - small positive number
- \( N_{\text{max}} \) - maximum induced speed in \( \text{ms}^{-1} \)
- \( I \) - actual iteration count
- \( I_{\text{max}} \) - maximum iteration count
- \( R_{t,\text{best}} \) - best fitness value of \( i^{th} \) krill
- \( \hat{X}_{t,\text{best}} \) - position corresponds to \( R_{t,\text{best}} \) of \( i^{th} \) krill
- \( \omega_n \) - inertia weight of the motion induced, in the range of (0,1)
- \( N^\text{old}_i \) - last motion induced
- \( r \) - random number between 0 and 1

2. **Foraging activity**

The foraging motion depends on food location and previous experience about food location.

\[
F_t = V_f \left\{ 2 \left( 1 - \frac{r}{I_{\text{max}}} \right) \hat{X}_{t,\text{food}} + \frac{R_{t,\text{best}} \hat{X}_{t,\text{best}}}{\left\| \hat{X}_{t,\text{best}} \right\|} \right\} + \omega_f F^{\text{old}}_t \tag{11}
\]

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Sensing distance is given by the equation

\[ d_{s,i} = \frac{1}{5N} \sum_{j=1}^{N} ||X_i - X_j|| \]

If the distance between the krill individuals is less than the defined sensing distance, then they are neighbors.

where, 
- \( N \) – number of krill individuals
- \( V_i \) – foraging speed, ms\(^{-1}\)
- \( \omega_f \) – inertia weight of the foraging motion in the range (0, 1)
- \( F_i^{old} \) – last foraging motion

3. Physical diffusion

The physical diffusion of the krill individual is a random process.

\[ D_i = D_{max} \left( 1 - \frac{i}{i_{max}} \right) \delta \]

where, 
- \( D_{max} \) – maximum diffusion speed, \( D_{max} \in [0.01, 0.02] \) ms\(^{-1}\)
- \( \delta \) – random directional vector \([-1 & 1]\)

Apply mutation operator

\[ X_{i,m} = \begin{cases} 
X_{gbest,m} + \mu(X_{p,m} - X_{q,m}) & \text{rand}_{i,m} < Mu \ \\
X_{i,m} & \text{else}
\end{cases} \] (13)

Update position for krill \( i \) by SSC operator as following

Perform selection operator

Choose the best krill (the Stud) for mating.

Implement crossover operator

\[ X_{i,m} = \begin{cases} 
X_{r,m} & \text{rand}_{i,m} < C_r \\
X_{i,m} & \text{else}
\end{cases} \] (14)

Generate new krill \( X_i' \) by crossover.

- Evaluate its quality/fitness \( K_i' \).
- if \( K_i' < K_i \) then do
  - Accept the new generated solution \( X_i' \) as \( X_{i+1} \)
else
  - Update the krill as \( X_{i+1} \)

The position vector is given by

\[ X_i(t + \Delta t) = X_i(t) + \Delta t \frac{dx_{i,t}}{dt} \]

where \( \Delta t = C_t \sum_{j=1}^{NV} (UB_j - LB_j) \)

\[ \frac{dx_{i,t}}{dt} = N_i + F_i + D_i \]

where, 
- \( N_i \) – movement induced by other krill individuals
- \( F_i \) – foraging activity
- \( D_i \) – random diffusion

\( i = 1 \) to \( nk \) \( nk \) – number of krill individuals

\( NV \) – total number of variables

\( C_t \) – constant between [0, 2]

\( UB, LB \) – upper and lower bound of the variables

If the related fitness value of each of the above mentioned effective vector \( (K_i, K_{i,\text{best}}, K_{i,\text{food}}) \) is better than the fitness of the \( i^{th} \) krill it has an attractive effect else repulsive effect.

end if

Check the limits and evaluate each krill based on its new position \( X_{i+1} \).

end for i

Sort all the krill and find the current best.

I = I + 1;

Step 4: end while

Step 5: Output the best solutions.

End
3.2 Flowchart for the Stud Krill herd Algorithm application to OCP problem

![Flowchart](image)

**Fig. (1)** Flowchart for the SKHA application to OCP problem

IV. Test System And Result Analysis

In order to verify the effectiveness of the proposed algorithm, it is implemented on the 69 bus IEEE radial test system and 94 bus Portuguese radial distribution systems. The software program is developed in MATLAB 2009a environment and executed on Intel Core processor i3 – 2120 CPU with 3.30GHz. The various control parameters applied for SKHA are given in Table (2) and are common for all the test systems. For all the test systems, bus 1 is taken as slack bus. The load is varied as light (0.5), nominal (1.0) and peak (1.6) at full load condition and results are tabulated for all the test systems.

<table>
<thead>
<tr>
<th>Control Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of krill individuals ( n_k )</td>
<td>10</td>
</tr>
<tr>
<td>Maximum number of iterations ( I_{\text{max}} )</td>
<td>100</td>
</tr>
<tr>
<td>Maximum induced speed ( N_{\text{max}} )</td>
<td>0.01</td>
</tr>
<tr>
<td>Inertia weight of motion induced ( \omega_n )</td>
<td>0.9</td>
</tr>
<tr>
<td>Foraging speed ( V_f )</td>
<td>0.02</td>
</tr>
<tr>
<td>Inertia weight of foraging motion ( \omega_f )</td>
<td>0.9</td>
</tr>
<tr>
<td>Constant ( C_t )</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4.1 Case 1: 69 – bus System

For the 69 bus RDS test system the base voltage is 12.66kV and the total load is \((3.80 + j 2.69)\) MVA and the single line diagram is shown in Fig. (2). The proposed method is employed on 69 bus system and the power loss of the system without Capacitors is 220.534 kW. The proposed SKHA is used to find the optimal capacitor locations and sizes at different load levels; the acquired results are structured in Table (3). The graphical representation of network real power losses and voltage profile with multiple capacitors at different load levels are given in Fig (3) and Fig (4). After capacitor placement at nominal load condition (CP), the real power loss is reduced to 142.7028 kW and the minimum voltage is 0.932 at bus 65. The total kVAR capacity of the capacitor units is 3661kVAR. The results are compared with other methods which show the effectiveness of SKHA in the improvement of results and tabulated in Table (4).

![Diagram](image)

**Fig (2)** Single line diagram of 69 bus system
**Table (3)** Summary of results of 69 bus system with load variation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>69 bus system</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Load flow results</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{nom}$ (kW)</td>
<td>50.6496</td>
<td>220.534</td>
<td>638.0838</td>
<td>156.5804</td>
<td>185.4969</td>
</tr>
<tr>
<td>$Q_{nom}$ (kVAR)</td>
<td>23.6004</td>
<td>100.0283</td>
<td>251.4235</td>
<td>72.6461</td>
<td>85.8430</td>
</tr>
<tr>
<td>$V_{min}$</td>
<td>0.9572/1.0/2.6</td>
<td>1.0/2.2/3.2</td>
<td>0.9966/0.9590/0.9960/0.9572</td>
<td>1.0/2.2/3.2</td>
<td>1.0/2.2/3.2</td>
</tr>
<tr>
<td>Capacitor location</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size in kVAR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power loss, kW</td>
<td>51.620/1/2/3</td>
<td>16.387</td>
<td>49.579</td>
<td>12.284</td>
<td>16.144</td>
</tr>
<tr>
<td>Qloss, kVAR</td>
<td>12.36/1/2/3</td>
<td>32.183</td>
<td>41.460</td>
<td>62.583</td>
<td>11.279</td>
</tr>
<tr>
<td>$V_{min}$, busno</td>
<td>0.9572/1.0/2.6</td>
<td>1.0/2.2/3.2</td>
<td>0.9966/0.9590/0.9960/0.9572</td>
<td>1.0/2.2/3.2</td>
<td>1.0/2.2/3.2</td>
</tr>
</tbody>
</table>

**Fig. (3)** Power loss reduction with Capacitors

**Table (4)** Comparison of results with other methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Power loss after capacitor installation, kW</th>
<th>% Reduction</th>
<th>$V_{max}$, pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSA [3]</td>
<td>145.9</td>
<td>35.16</td>
<td>0.9511</td>
</tr>
<tr>
<td>TLBO [4]</td>
<td>146.35</td>
<td>34.96</td>
<td>0.9313</td>
</tr>
<tr>
<td>FPOA [8]</td>
<td>145.777</td>
<td>35.2</td>
<td>0.9323</td>
</tr>
<tr>
<td>Fuzzy+SFLA [10]</td>
<td>152.3945</td>
<td>32.2703</td>
<td>NA</td>
</tr>
<tr>
<td>PSOGSA [18]</td>
<td>145.60945</td>
<td>35.2166</td>
<td>0.9330</td>
</tr>
<tr>
<td>Analytical approach [19]</td>
<td>147</td>
<td>34.66</td>
<td>0.931</td>
</tr>
<tr>
<td>Proposed SKHA</td>
<td>142.7028</td>
<td>35.2922</td>
<td>0.932</td>
</tr>
</tbody>
</table>

**Fig. (4)** Voltage profile improvement with Capacitors
4.2 Case 2: 94–bus System

The base voltage of 94 bus Portuguese RDS test system is 15kV with a total load (4.797+j2.324) MVA and the single line diagram is shown in Fig. (5). The power loss of the system without capacitors is 362.8578 kW. The proposed SKHA is employed to find the optimal capacitor locations and sizes; the acquired results are structured in Table (5). The graphical representation of network real power losses and voltage profile with multiple capacitors are given in Fig (6) and Fig (7). After capacitor placement the real power loss is reduced to 267.0254kW and the minimum voltage is 0.9106 at bus 92. The total kVAR capacity of capacitor unit compensation is 2431kVAR. At different load levels the performance of the system is also given in Table (5).

Fig (5) Single line diagram of 94 bus system

Table (5) Summary of results of 94 bus system with load variation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>94 bus system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load flow results</td>
<td></td>
</tr>
<tr>
<td>$P_{loss}$ (kW)</td>
<td>79.6936</td>
</tr>
<tr>
<td>$Q_{loss}$ (kVAR)</td>
<td>110.9393</td>
</tr>
<tr>
<td>$V_{min}$</td>
<td>0.9295</td>
</tr>
<tr>
<td>$V_{max}$</td>
<td>0.9977/2</td>
</tr>
</tbody>
</table>

Table (5) Summary of results of 94 bus system with load variation

<table>
<thead>
<tr>
<th>Load flow results</th>
<th>94 bus system</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{loss}$ (kW)</td>
<td>79.6936</td>
</tr>
<tr>
<td>$Q_{loss}$ (kVAR)</td>
<td>110.9393</td>
</tr>
<tr>
<td>$V_{min}$</td>
<td>0.9295</td>
</tr>
<tr>
<td>$V_{max}$</td>
<td>0.9977/2</td>
</tr>
</tbody>
</table>

Fig. (6) Power loss reduction with Capacitors

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Fig. (7) Voltage profile improvement with Capacitors

V. Conclusion

This paper has presented Stud krill herd algorithm for capacitor placement and sizing problem in radial distribution system. From the results it is revealed that the algorithm gives the optimal solution when compared to other methods from literature. Real power losses of the system and reactive power losses at all the load levels have reduced noticeably. The results illustrate that including capacitors improve the voltage magnitude at all the buses. Based on the quality of outcome, it is concluded that Stud krill herd algorithm can be the hopeful technique for solving the optimal capacitor placement problem in radial distribution system.

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References


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