OPTIMAL CONDUCTOR SELECTION IN RADIAL DISTRIBUTION SYSTEMS USING WHALE OPTIMIZATION ALGORITHM

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Abstract

Nowadays, electrical power system networks are driven harder, and they are required to deliver more energy. Electrical losses reduction is one of the most important ways to conserve the generated energy, especially in the distribution systems. In this regard, the optimal conductor selection can reduce the electrical power losses, while enhancing the voltage profile in a cost-effective manner. In this paper, a novel approach based on a recent meta-heuristic algorithm, known as whale optimization (WO) algorithm is proposed to solve the optimal conductor selection problem of radial distribution networks. An updated practical conductor’s library is introduced. Further, practical techno-economic aspects are considered such as load growth considerations and payback period calculations. The objective function is to minimize the combined cost of energy loss and conductors’ investment cost. The considered constraints are the bus voltage limits and the conductors’ current carrying capacities. The proposed approach is applied to two different systems; the first one is a 16-bus small-scale system and the second is a large-scale 85-bus system. The obtained results are compared with other results available in the literature, and showed the effectiveness of the proposed algorithm in reducing the network losses, maximizing the overall saving, while maintaining the specified constraints over almost a five-year period while taking into account high annual load growth rate.

Keywords: Optimal conductor selection; Whale optimization algorithm; Radial distribution networks.
1. Introduction

Due to the gap between the increasing electrical demand and the limited power generation resources, researchers focused on conserving the electric energy in line with increasing the generated power to cater for this continuous growth in electrical demands. Power loss reduction is considered as one of the most important ways of conserving the generated energy. The significant power losses in the overall power system networks are concentrated in the distribution systems because they are usually characterized by their reduced voltage levels, high lines’ currents, and low lines’ resistances [1, 2]. Researchers have explored many methodologies for power losses reduction in distribution networks such as shunt capacitors placement, network reconfiguration, distributed generation (DG) allocation, and optimal conductor selection. Optimal selection of the conductor sizes of a distribution network is a complicated problem as it should take into account many constraints such as the specified voltage limits for the different buses, current carrying capacity of the feeders, loading profile alteration, and load growth, as well as other economic considerations that concern with cost of losses and conductors, and interest and depreciation rates.


One can see that the methodologies presented in the literature for solving the optimal conductor selection problem can be categorized into two main approaches; the first one is based on conventional analytical algorithms [5-14] and the second is based on new intelligent meta-heuristic algorithms [15-20].


Mendoza et al. [15], on the other side, the intelligent optimization techniques have inspired many researchers to employ it for solving the optimal conductor selection problem, such as evolutionary strategy (ES), discrete particle swarm optimization (DPSO) [16], genetic (GA) [17], harmony search (HS) with a differential operator [18], analytic and GA [19], Grasshopper Optimization algorithm (GOA) [20], Crow search algorithm (CSA) [21] and sine-cosine optimization algorithm (SCA) [22]. The practical selection of the optimal conductors set should consider present loads in addition to the expected load growth for a certain time span [23-25].

Optimal conductor selection can allow additional penetration of DGs into distribution networks. Nowadays, the maximum amount of DG units that can be integrated into the distribution system, without violating the system operational performance limits, is called the hosting capacity (HC). One of the approaches used by network operators to face the challenges of continuous load growth and high DG penetrations is to reinforce the network. It is believed that network reinforcement and optimal conductor selection are considered as effective techniques for HC enhancement that will play a significant role in future power systems and smart grids [26, 27].

The WO algorithm is proposed in this work due to the intelligent behaviour of crows in storing their excess food, hiding their food place from others, and bringing their food back when they need [28]. The WO algorithm has multiple advantages such as having few parameters to be set, faster convergence capability and higher sensitivity when compared to the widely known meta-heuristic algorithms. Due to these advantages, it has been recently employed to solve many engineering problems in the literature [29, 30].

In this paper, a novel approach based on a recent meta-heuristic algorithm, whale optimization (WO) algorithm [28] is proposed to solve the optimal conductor selection problem of radial distribution networks. From the literature survey, it is clear that application of WO has not been discussed so far to solve the optimal conductor selection problem in radial distribution systems. This encourages utilizing this algorithm for the problem. A practical conductor’s library containing twenty conductor types is introduced based on actual manufacturer data that comply with the BS 50182 [31]. This rich library explores a wider search space and ensures finding the most optimal set of conductors that satisfy the economic objective functions while complying with the preset constraints. A constrained objective function is employed to minimize overall cost, and comply with the system voltage limits and the conductors’ current carrying capacities. Practical aspects are considered such as available market conductors utilization, load growth considerations, and payback period calculations. The proposed WO algorithm is applied on two different test systems, 16-bus system, and 85-bus system. The achieved results are compared with other methods available in the literature and showed the effectiveness of the proposed algorithm in reducing the network losses,
maximizing the overall saving, while maintaining the specified constraints over a five-
year period taking into account high annual load growth rate.

2. Problem formulation

2.1. Objective function

In optimal conductor selection problem, the goal is to select conductor size and type
from a set of available inventory such that the total cost is minimized while
satisfying nonlinear constraints on voltage limits of the buses and maximum
ampacities of the conductors. The cost consists of the annual cost of energy losses
and the capital investment cost of the conductor which is formulated as follows:

\[
\text{Cost}(j,c) = CL(j,c) + CC(j,c)
\]

\[
CL(j,c) = P_{loss}(j,c) \times \left[ k_p + (k_c \times LSF \times T) \right]
\]

The loss factor which is defined as the ratio of energy loss in the system during
a given time period to the energy loss that could result if the system peak loss had
persisted throughout that period. \( LSF \) is expressed in terms of the load factor, the
average load to the peak demand in a given time period, as follows [16, 18]:

\[
LSF = 0.2 (LF) + 0.8 (LF)^2
\]

Thus, the total annual cost of the energy loss can be expressed as follows:

\[
CL_{total} = \sum_{j} \sum_{c} P_{loss}(j,c) \times \left[ k_p + (k_c \times LSF \times T) \right]
\]

The capital investment cost of the conductor is defined in the terms of the annual
depreciation of the capital cost of the \( j \)th branch with the \( c \)th conductor, thus:

\[
CC(j,c) = IDF \times l(j) \times A(c) \times IC(c)
\]

so that,

\[
IDF = \frac{iiF}{i(i+1)^F - 1}
\]

The objective function (OF) for the optimal selection of types and sizes of the
conductors can be expressed as:

\[
\text{OF} = \min \left( CL_{total} + CC_{total} \right)
\]

2.2. Constraints

The considered constraints can be expressed, as follows:

**Bus voltage constraint**

\[
U_{min}(m) \leq |U_{(m,c)}| \leq U_{max}(m) \quad \forall \ (m \in k, c \in n)
\]

where \( U_{min}(m) \) and \( U_{max}(m) \) are considered as 0.9 p.u. and 1.1 p.u., respectively.

**Conductor current carrying capacity constraint**

\[
|I(j,c)| \leq I_{max}(c) \quad \forall \ (j \in b, c \in n)
\]
2.3. Additional techno-economic considerations

Load growth

Practically, optimal conductor sizes selection should consider the existing loads in addition to possible load growth for a certain planning period [10]. This period is usually determined by the feeder ability to accept load growth without violating the node voltage or the branch’s current constraints. During the ‘pre-determined’ planning period, the load growth can be considered as an annual growth rate in proportion to the connected loads in the base year (1st year). Mathematically, the active and reactive power loads at the Nth year is given by:

\[ P_L(N) = \begin{cases} P_L(1) \times (1 + g)^N & \text{for } N = 1, 2, 3, ..., M \\ P_L(1) \times (1 + g)^M & \text{for } N = M + 1, ..., F \end{cases} \]  

(10)

\[ Q_L(N) = \begin{cases} Q_L(1) \times (1 + g)^N & \text{for } N = 1, 2, 3, ..., M \\ Q_L(1) \times (1 + g)^M & \text{for } N = M + 1, ..., F \end{cases} \]  

(11)

Equations (8) and (9) of the proposed constraints shall be checked initially in the base year, and then the load growth shall be calculated according to Eqs. (10) and (11). Further, the loading pattern shall increase gradually till violation of any of the constraints occurs. In this condition, the breaking year ‘M’ is reached and the maximum duration that the feeder can handle the load growth without violating the preset constraints is determined. Beyond the breaking year, the optimally selected conductors can accept additional load growth until the end of their lifetime, but with the support of external compensators such as the shunt capacitors, DGs, and energy storage schemes. Additionally, Fig. 1 shows the load growth pattern during the conductor’s lifetime. Table 1 gives the numerical values of the parameters used in the formulation of the objective function and the constraints.

\[ \text{Load growth is possible with alternative solutions} \]

\[ \text{Feeder cannot accept load growth due to Constraint violation} \]

\[ \text{Feeder can accept load growth} \]

\[ \text{Load growth is possible with alternative solutions} \]

![Fig. 1. Load growth pattern during conductor lifetime.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_v ) (Rs/kW)</td>
<td>2500</td>
<td>( i ) (%)</td>
<td>8</td>
</tr>
<tr>
<td>( k_e ) (Rs/kWh)</td>
<td>0.5</td>
<td>( F ) (years)</td>
<td>25</td>
</tr>
<tr>
<td>( IC(c) ) (Rs/mm²/km)</td>
<td>500</td>
<td>( IDF )</td>
<td>0.1</td>
</tr>
<tr>
<td>( LF )</td>
<td>0.4</td>
<td>( g ) (%)</td>
<td>10</td>
</tr>
<tr>
<td>( LSF )</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Payback period

The optimal selection of distribution system conductors may result in purchasing of larger conductor sizes which means additional conductors’ cost. This additional cost should be justified to the planners of the distribution system (decision makers), as follows:

- Optimally selected conductors will result in reduced overall network losses, therefore allows for more rigid load growth plans.
- Reducing the network losses will result in enhanced system performance and will save annual energy consumption.
- The cumulative annual energy saving will equalize with the additional initial conductors cost in a certain period known as the payback period. After this period, the annual energy saving is purely gained by the network operators.

Considering that optimal conductors’ selection led to increasing the original system conductor size from the base case area say $A_x(j,c)$ to the optimized area $A_y(j,c)$. Accordingly, the procedure for calculating the payback period can be presented as follows:

The total cost of the original system conductors can be formulated as follows:

$$C_{\text{orig}} = \sum_{j} A_x(j,c) \times l(j) \times IC(c)$$  \hspace{1cm} (12)

The total cost of the optimized system conductors can be formulated as follows:

$$C_{\text{Opt}} = \sum_{j} A_y(j,c) \times l(j) \times IC(c)$$  \hspace{1cm} (13)

The total additional cost due to optimal conductor selection is:

$$\Delta C_{\text{total}} = C_{\text{Opt}} - C_{\text{orig}}$$  \hspace{1cm} (14)

The cost of annual energy saving due to optimal conductor selection for all network branches is:

$$C_{\text{as}} = (P_{\text{loss base}} - P_{\text{loss Opt}}) \times T \times K_e$$  \hspace{1cm} (15)

$$PP = \frac{\Delta C_{\text{total}}}{C_{\text{as}}}$$  \hspace{1cm} (16)

3. Whale Optimization Algorithm (WO)

Nature-inspired meta-heuristic algorithms have shown surprisingly efficient results to tackle difficult problems. Mirjalili and Lewis [28] developed this domain, the WO, which is a nature-inspired meta-heuristic optimization algorithm based on mimicking the hunting behaviour of humpback whales. Whales are considered as highly intelligent animals with emotions. Whales have common cells in their brains similar to those of human called spindle cells. These cells are responsible for judgment, emotions, and social behaviours in humans. The hunting technique of the humpback whales is called bubble-net feeding technique. Humpback whales prefer to hunt small fishes (preys) close to the surface. When the humpback whale detects its prey, it dives around 12 m down and then starts to create bubbles in a spiral shape around the prey. The prey fears to cross these bubbles that appear as a trap. At that moment, the whale swims up to the surface and collects his trapped prey as shown in Fig. 2.
3.1. Mathematical model

The bubble-net feeding technique of the humpback whales is mathematically modelled in three stages [28], as briefed below.

i. Encircling the prey
ii. Bubble-net hunting method (exploitation phase)
   a. Shrink mechanism
   b. Spiral update of the position
iii. Globalization of the search (exploration phase)

3.1.1. Encircling the prey

Humpback whales can recognize the location of prey and encircle them. Since the position of the optimal design in the search space is not known in advance, the WO algorithm assumes that the current search agent is the target prey or is close to the optimum one. After the best search agent is defined, the other search agents will try to update their positions towards the best search agent which is represented by the following equations:

\[ \vec{D} = |\vec{C} \cdot \vec{X}^* (t) - \vec{X}(t)| \]  
(17)
\[ \vec{X}(t+1) = \vec{X}^* (t) - \vec{A} \cdot \vec{D} \]  
(18)

The vectors \( \vec{A} \) and \( \vec{C} \) are calculated as follows:

\[ \vec{A} = 2\vec{a} - \vec{a} \]  
(19)
\[ \vec{C} = 2 \cdot \vec{r} \]  
(20)

3.1.2. Bubble-net hunting technique

a. Shrink mechanism

This behaviour is achieved by decreasing the value of \( a \) in Eq. (19) from 2 to 0. Accordingly, the value of \( \vec{A} \) is also decreased by a random value in the interval ["
Figure 3 shows the possible positions from the random whale’s position at \((X, Y)\) toward the prey position at \((X^*, Y^*)\) that is applied to \((0 \leq A \leq 1)\).

b. Spiral update of the position

In this stage, the attacking mechanism is executed and the distance between the whale located at \((X, Y)\) and the prey located at \((X^*, Y^*)\) is calculated. Then, a spiral equation is created between the position of the whale and prey to mimic the helix-shaped movement of the whales as shown in Fig. 4 and Eq. (21).

\[
\bar{X}(t+1) = \bar{D}^* \cdot e^{\pi A} \cdot \cos (2\pi A) + \bar{X}^*(t) \quad (21)
\]

\[
\bar{D} = |\bar{X}^*(t) - \bar{X}(t)| \quad (22)
\]

It is worth mentioning that humpback whales swim around the prey within a shrinking circle and along a spiral-shaped path simultaneously. To model these simultaneous movements; a 50% probability is assumed to choose between either the shrinking or updating the spiral movements to the whales’ position, as follows:

\[
\begin{align*}
\bar{X}(t+1) &= \bar{X}^*(t) - \bar{A} \cdot \bar{D} \quad \text{if } p < 0.5 \\
\bar{X}(t+1) &= \bar{D}^* \cdot e^{\pi A} \cdot \cos (2\pi A) + \bar{X}^*(t) \quad \text{if } p \geq 0.5
\end{align*}
\]

Fig. 3. Bubble-net search technique.

Fig. 4. Spiral updating of the position.
3.1.3. Globalization of the search

The position of the search agent is updated according to a randomly chosen search agent instead of the best search agent found so far. To consider this randomness, Eqs. (17) and (18) are updated after replacing $X^*$ with $X_{\text{rand}}$, as follows:

$$
\vec{D} = \vec{C} \cdot \vec{X}_{\text{rand}}(t) - \vec{X}(t) 
$$

$$
X(t+1) = X_{\text{rand}}(t) - \vec{A} \cdot \vec{D} 
$$

The WO algorithm includes two internal parameters to be adjusted ($A$ and $C$) depending on the selection of the vector $\vec{a}$. To sum up, the WO procedure is shown in Fig. 5.

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**Fig. 5. Flowchart for the WO algorithm.**
4. Results and Discussion

In this work, twenty conductor types are used. The numerical values of the used parameters are summarized in Table 1. Ismael et al. [22] and Leppert and Allen [23] described, that the load flow analysis is based on a forward-sweep algorithm is performed and the corresponding fitness function is calculated using the WO. In order to verify the effectiveness of the proposed WO algorithm; two radial distribution networks are examined in MATLAB platform, the first one is a small-scale network of 16-bus system, the second one is a large-scale network of 85-bus system.

4.1. 16-bus system

The 16-bus system configuration is shown in Fig. 6, the base voltage and apparent power of this system is 11 kV and 100 MVA respectively. The substation bus voltage (bus 1) is 1 p.u. and the line and load data for this system are obtained from [4]. Practical conductor’s library is introduced based on actual manufacturer data [33]. The available conductor types and their electrical specifications are presented in Table 2. According to Thenepalle [19], the conductors’ library is presented in Table 3 to be compared with the results obtained using the proposed algorithm. Other published results for the 16 bus are excluded from the comparison because of noncompliance with the considered constraints.

![Fig. 6. Configuration of 16-bus radial distribution network.](Image)

<table>
<thead>
<tr>
<th>Conductor type</th>
<th>$A$ ($\text{mm}^2$)</th>
<th>$R$ ($\Omega$/km)</th>
<th>$X$ ($\Omega$ /km)</th>
<th>$I_{\text{max}}$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.5</td>
<td>2.718</td>
<td>0.374</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>1.374</td>
<td>0.355</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>1.098</td>
<td>0.349</td>
<td>130</td>
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<tr>
<td>4</td>
<td>20</td>
<td>0.9116</td>
<td>0.345</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>0.6795</td>
<td>0.339</td>
<td>175</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>0.5449</td>
<td>0.335</td>
<td>200</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>0.4565</td>
<td>0.353</td>
<td>250</td>
</tr>
<tr>
<td>8</td>
<td>42</td>
<td>0.3977</td>
<td>0.327</td>
<td>270</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
<td>0.3841</td>
<td>0.327</td>
<td>257</td>
</tr>
<tr>
<td>10</td>
<td>48</td>
<td>0.3656</td>
<td>0.329</td>
<td>260</td>
</tr>
<tr>
<td>11</td>
<td>50</td>
<td>0.3434</td>
<td>0.328</td>
<td>270</td>
</tr>
<tr>
<td>12</td>
<td>55</td>
<td>0.3023</td>
<td>0.327</td>
<td>290</td>
</tr>
<tr>
<td>13</td>
<td>65</td>
<td>0.2745</td>
<td>0.315</td>
<td>305</td>
</tr>
<tr>
<td>14</td>
<td>80</td>
<td>0.2193</td>
<td>0.282</td>
<td>395</td>
</tr>
<tr>
<td>15</td>
<td>80</td>
<td>0.2214</td>
<td>0.268</td>
<td>380</td>
</tr>
<tr>
<td>16</td>
<td>80</td>
<td>0.2221</td>
<td>0.271</td>
<td>385</td>
</tr>
<tr>
<td>17</td>
<td>95</td>
<td>0.1844</td>
<td>0.266</td>
<td>425</td>
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<tr>
<td>18</td>
<td>110</td>
<td>0.1589</td>
<td>0.261</td>
<td>470</td>
</tr>
<tr>
<td>19</td>
<td>130</td>
<td>0.1375</td>
<td>0.256</td>
<td>510</td>
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<tr>
<td>20</td>
<td>140</td>
<td>0.1223</td>
<td>0.252</td>
<td>560</td>
</tr>
</tbody>
</table>
Table 3. Electrical specifications of the used ACSR conductors in [19].

<table>
<thead>
<tr>
<th>Conductor type</th>
<th>A (mm²)</th>
<th>R (Ω/km)</th>
<th>X (Ω/km)</th>
<th>I_{max} (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12.90</td>
<td>1.3760</td>
<td>0.3896</td>
<td>115</td>
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<tr>
<td>B</td>
<td>15.91</td>
<td>1.098</td>
<td>0.3100</td>
<td>138</td>
</tr>
<tr>
<td>C</td>
<td>19.55</td>
<td>0.9108</td>
<td>0.3797</td>
<td>150</td>
</tr>
<tr>
<td>D</td>
<td>25.87</td>
<td>0.6795</td>
<td>0.2980</td>
<td>180</td>
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<td>E</td>
<td>32.26</td>
<td>0.5441</td>
<td>0.3673</td>
<td>208</td>
</tr>
<tr>
<td>F</td>
<td>37.32</td>
<td>0.4565</td>
<td>0.2850</td>
<td>226</td>
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<tr>
<td>G</td>
<td>42.07</td>
<td>0.3841</td>
<td>0.2795</td>
<td>250</td>
</tr>
<tr>
<td>H</td>
<td>48.39</td>
<td>0.3657</td>
<td>0.3579</td>
<td>270</td>
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</tbody>
</table>

The used parameters of the proposed WO algorithm are presented in Table 4. The obtained WO results are compared to those obtained using EP [4] and HSDE [18] and the comparison is presented in Tables 5 and 6. It is noticed that the network active power loss optimized by the proposed algorithm is reduced to 26.0841 kW, which is less than other published results; this means the power loss is reduced by 51.275% compared to the original network loss. The optimal annual cost obtained by the proposed algorithm is 180,167.364 Rs./year, which will save about 22.34% of the original network cost with a payback period of 6.76 years. The bus voltage values of the original network and that optimized using the proposed algorithm are presented in Fig. 7. Figure 8 shows the current flow in branches compared to their maximum limits. The response of the WO algorithm is presented in Fig. 9. The load growth results are presented in Table 7. Voltage profile and branch current flows of the 16-bus system over a five-year span are presented in Figs. 10 and 11, respectively. From the presented figures, one can notice that the proposed optimal conductor selection algorithm succeeded in minimizing the overall system costs and keeping the bus voltages and branch currents within the prescribed limits not only for the current load profile but also for a five-year span with high annual load growth factor of 10%. As shown in Table 7, the voltage of bus 16 begins to exceed its allowable limit (0.9 p.u.). Therefore, other compensation techniques should be adopted to allow for more load growth without violating the system limits.

A sensitivity analysis has been performed for selecting the optimum WO algorithm parameters, mainly vector $\tilde{a}$ and $n$. A case study was examined to calculate the losses’ cost of the 16-bus system considering various WO parameters as presented in Table 8. Three independent values were assumed for each of $\tilde{a}$ and $n$. It is assumed that all other parameters are kept constant. It was concluded that the linear decrement of vector $\tilde{a}$ from 2 to 0 leads to improved results while other values give worse results because they de-emphasize exploitation and exploitation process. In addition, it was noticed that large number of search agents allow for better reach to the global optimum.

Table 4. Numerical values of the used parameters of the proposed WO algorithm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of search agents ($n$)</td>
<td>100</td>
</tr>
<tr>
<td>$\tilde{a}$</td>
<td>Linearly decreases from 2 to 0</td>
</tr>
<tr>
<td>Maximum number of iterations</td>
<td>500</td>
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</tbody>
</table>
Table 5. Comparison of conductor selection results for the 16-bus system.

<table>
<thead>
<tr>
<th></th>
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<td>17</td>
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<td>2</td>
<td>3</td>
<td>Racoon</td>
<td>H</td>
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Table 6. Comparison of final results for the 16-bus system.

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<tr>
<th>Variables</th>
<th>Original system</th>
<th>After optimal conductor selection</th>
</tr>
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<tbody>
<tr>
<td>$U_{\text{min}}$ at node 16</td>
<td>0.8867</td>
<td>0.9153</td>
</tr>
<tr>
<td>Power Loss (kW)</td>
<td>53.47</td>
<td>37.36</td>
</tr>
<tr>
<td>Loss reduction (%)</td>
<td>-</td>
<td>30.14</td>
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<tr>
<td>Optimal cost (Rs)</td>
<td>231,990</td>
<td>208,796</td>
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<tr>
<td>Net saving (%)</td>
<td>-</td>
<td>10</td>
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<tr>
<td>Payback period (years)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 7. Bus voltages of the original and optimized 16-bus network.
Optimal Conductor Selection in Radial Distribution Systems using Whale

Fig. 8. Branch currents compared to their maximum limits.

Fig. 9. The variation of fitness function for the 16-bus network.

Table 7. The load growth results obtained for 16-bus system.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total active power (kW)</th>
<th>Total power losses (kW)</th>
<th>$U_{\text{min}}$ at bus 16 (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>675.75</td>
<td>26.08</td>
<td>0.9300</td>
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<td>2</td>
<td>743.33</td>
<td>31.95</td>
<td>0.9225</td>
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<td>3</td>
<td>817.66</td>
<td>39.63</td>
<td>0.9141</td>
</tr>
<tr>
<td>4</td>
<td>899.42</td>
<td>48.15</td>
<td>0.9048</td>
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<td>5</td>
<td>989.37</td>
<td>59.28</td>
<td>0.8943</td>
</tr>
</tbody>
</table>

Fig. 10. Voltage profile over a five-year span for the 16-bus system.

Fig. 11. Branch currents over a five-year span with 10% load growth factor.

Table 8. Sensitivity analysis for the WO algorithm parameters.

<table>
<thead>
<tr>
<th>(n)</th>
<th>(\bar{a} = \text{from 1 to 0})</th>
<th>(\bar{a} = \text{from 2 to 0})</th>
<th>(\bar{a} = \text{from 4 to 0})</th>
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<tr>
<td>10</td>
<td>208,972.04</td>
<td>193,021.91</td>
<td>197,029.68</td>
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<td>40</td>
<td>195,963.53</td>
<td>185,919.58</td>
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<td>100</td>
<td>188,010.24</td>
<td>180,167.36</td>
<td>181,332.88</td>
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4.2. 85-bus system

The 85-bus system configuration is shown in Fig. 12, the base voltage and apparent power of this system is 11 kV and 100 MVA respectively. The substation bus voltage (bus 1) is 1 p.u. and the line and load data for this system are initiated [32] and developed [18]. The obtained WO results are compared to those obtained using BWM [13], HSDE [18], and CSA [21] and the comparison is presented in Tables 9 and 10. It is noticed that the network active power losses optimized by the proposed algorithm are reduced to 83.55 kW, which is less than other published results; this means the power loss is reduced by 73.55% compared to the original network loss. The optimal annual cost obtained by the proposed algorithm is 372,243.95 Rs./year, which will save about 66.36% of the original network cost with a payback period of 0.53 years. The bus voltage values of the original network and that optimized using the proposed algorithm are presented in Fig. 13. Figure 14 shows the current flow in branches compared to their maximum limits.

Fig. 12. Configuration of 85-bus radial distribution network.
Fig. 13. Bus voltages of the original and optimized 85-bus network.

Fig. 14. Branch currents compared to their capacities for the 85-bus system.

Voltage profile and branch current flows of the 85-bus system over a five-year span are presented in Figs. 15 and 16, respectively. From the presented figures, one can notice that the proposed optimal conductor selection algorithm succeeded in minimizing the overall system costs and keeping the bus voltages and branch currents within the prescribed limits not only for the current load profile but also for a five-year span with high annual load growth factor of 10%. After the 5th year, the voltage of bus 54 begins to reach its minimum allowable limit (0.9 p.u.). Therefore, other compensation techniques should be adopted to allow for more load growth without violating the system limits.
Table 9. Comparison of conductor selection results for the 85-bus system.

<table>
<thead>
<tr>
<th></th>
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Table 10. Comparison of final results for the 85-bus system.

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<tr>
<th>Variables</th>
<th>Original system</th>
<th>After optimal conductor selection</th>
<th>Proposed WO</th>
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<tbody>
<tr>
<td>$U_{\text{rms}}$ at node 54</td>
<td>0.8713</td>
<td>0.9458</td>
<td>0.8900</td>
</tr>
<tr>
<td>Power Loss (kW)</td>
<td>315.84</td>
<td>134.26</td>
<td>256.96</td>
</tr>
<tr>
<td>Loss reduction (%)</td>
<td>-</td>
<td>57.51</td>
<td>18.64</td>
</tr>
<tr>
<td>Optimal cost (Rs)</td>
<td>1,106,732</td>
<td>485,040</td>
<td>929,035</td>
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<tr>
<td>Net saving (%)</td>
<td>-</td>
<td>56.17</td>
<td>16.06</td>
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<tr>
<td>Payback period (years)</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</table>
5. Conclusions

In this work, the WO algorithm is proposed to solve the problem of optimal selection of conductors of radial distribution networks. The WO algorithm is applied on two different test systems, 16-bus system, and 85-bus system. The achieved results are compared with other methods available in the literature and showed the superiority of the proposed algorithm over the other published methods. One can notice that the proposed set of conductors explored a wider search space that succeeded in finding the most optimal set of conductors that satisfy the objective functions while complying with the pre-set constraints. Finally, the proposed WO algorithm succeeded reducing the network losses, maximizing the overall saving while maintaining compliance with the specified constraints over five years with a reasonable payback period, while taking into account high annual load growth rate. Following highlights are observed through simulation case studies:
The introduction of the proposed actual conductors library provided optimal techno-economic results for the problem of conductors selection in radial distribution networks.

The optimal conductor selection is considered as one of the important tools for reducing the network losses in a cost effective manner.

The WO algorithm proved its efficiency and suitability for solving small scale and large scale system applications.

Load growth considerations and payback period calculations are important techno-economic aspects for the distribution system planners.

Finally, our study was limited to the constant loading profile in balanced and sinusoidal electrical systems. Another factor that was beyond the framework of this study, but will be included in future studies, is the consideration of a real-time loading profile in unbalanced and non-sinusoidal distribution networks.

### Nomenclatures

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{A}, \hat{C} )</td>
<td>Coefficient vectors</td>
</tr>
<tr>
<td>( A(c) )</td>
<td>Cross section area of the ( c )th type conductor</td>
</tr>
<tr>
<td>( \hat{a} )</td>
<td>Linearly decreasing factor to represent the shrinking bubbles</td>
</tr>
<tr>
<td>( b )</td>
<td>Total number of branches in the system</td>
</tr>
<tr>
<td>( C_{\text{as}} )</td>
<td>Cost of annual energy saving due to optimal conductor selection</td>
</tr>
<tr>
<td>( CC )</td>
<td>Capital investment cost of the conductor</td>
</tr>
<tr>
<td>( CC^{\text{total}} )</td>
<td>Total capital investment cost of all branches</td>
</tr>
<tr>
<td>( CL )</td>
<td>Annual cost of energy losses</td>
</tr>
<tr>
<td>( CL^{\text{total}} )</td>
<td>Annual cost of the energy loss</td>
</tr>
<tr>
<td>( C^{\text{Opt}} )</td>
<td>Total cost of the optimized system conductors</td>
</tr>
<tr>
<td>( C^{\text{orig}} )</td>
<td>Total cost of the original system conductors</td>
</tr>
<tr>
<td>( c )</td>
<td>Branch type</td>
</tr>
<tr>
<td>( \hat{D}_i )</td>
<td>distance between the ( i )th whale to the prey</td>
</tr>
<tr>
<td>( F )</td>
<td>Planned lifetime of the feeder</td>
</tr>
<tr>
<td>( g )</td>
<td>Annual load growth rate</td>
</tr>
<tr>
<td>( IC(c) )</td>
<td>Investment cost of the ( c )th type conductor per unit area per unit length</td>
</tr>
<tr>
<td>( IDF )</td>
<td>Interest and depreciation factor</td>
</tr>
<tr>
<td>( I(j,c) )</td>
<td>Current flowing in conductor ( j ) of type ( c )</td>
</tr>
<tr>
<td>( I_{\text{max}}(c) )</td>
<td>Maximum current carrying capacity of the ( c )th type conductor</td>
</tr>
<tr>
<td>( i )</td>
<td>Interest rate value</td>
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<tr>
<td>( j )</td>
<td>Branch number</td>
</tr>
<tr>
<td>( k )</td>
<td>Total number of buses in the system</td>
</tr>
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<td>( k_p )</td>
<td>Cost of peak demand power loss</td>
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<tr>
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<td>Cost of energy losses</td>
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<tr>
<td>( l(j) )</td>
<td>Length of branch ( j )</td>
</tr>
<tr>
<td>( M )</td>
<td>Breaking year</td>
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<tr>
<td>( m )</td>
<td>Bus number</td>
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</table>
Optimal Conductor Selection in Radial Distribution Systems using Whale...  

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
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<td>n</td>
<td>Number of the available conductors’ types</td>
</tr>
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<td>Objective function</td>
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<td>$P_L(1)$</td>
<td>Active load power in the 1\textsuperscript{st} year</td>
</tr>
<tr>
<td>$P_L(N)$</td>
<td>Active load power in the N\textsuperscript{th} year</td>
</tr>
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<td>$P_{loss}(j,c)$</td>
<td>Active power loss of the $j$th branch with a $c$th conductor under peak load</td>
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<td>Network losses of the original network</td>
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<tr>
<td>$P_{Opt}$</td>
<td>Network losses of the optimized network</td>
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<td>$PP$</td>
<td>Payback period</td>
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<td>Random number in [0, 1]</td>
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<td>$Q_L(1)$</td>
<td>Reactive load power in the 1\textsuperscript{st} year</td>
</tr>
<tr>
<td>$Q_L(N)$</td>
<td>Reactive load power in the N\textsuperscript{th} year</td>
</tr>
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<td>$\vec{r}$</td>
<td>Random vector in [0, 1].</td>
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<td>s</td>
<td>Constant for defining the shape of the logarithmic spiral</td>
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<td>$T$</td>
<td>Number of hours per year (8760 hour)</td>
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<td>Index for the current iteration</td>
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<td>Maximum voltage at bus $m$</td>
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<tr>
<td>$U_{mid}(m)$</td>
<td>Minimum voltage at bus $m$</td>
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<td>Random position vector</td>
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<td>$X^*$</td>
<td>Position vector of the best solution obtained so far</td>
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<tr>
<td>$\vec{X}_{rand}$</td>
<td>Random position vector (a random whale)</td>
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<tr>
<td>z</td>
<td>Random number in $[-1, 1]$</td>
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<tr>
<td>$\Delta C_{total}$</td>
<td>Total additional cost due to optimal conductor selection</td>
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References


