Distribution Network Reconfiguration Using Grey Wolf Optimizer (GWO) algorithm

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Abstract— The present paper describes the application of the Grey Wolf Optimizer (GWO) to determine the optimal reconfiguration in radial distribution networks. The main objectives are to minimize the active power loss. A detailed performance analysis is applied on 33, 69, 84, and 118 bus networks to illustrate the effectiveness of the proposed methodology.

Index Terms— reconfiguration, power losses, grey wolf optimizer, radial distribution networks.

I. INTRODUCTION

Distribution networks are usually designed to be radial, to have only one path between each customer and the substation. Radial networks possess some advantages over meshed networks, including lower short circuit currents and simpler switching and protecting equipment. However, the radial structure provides lower overall reliability. Therefore, to use the benefits of the radial structure and, at the same time, to overcome the difficulties, distribution systems are planned and built as weakly meshed networks but operated as radial networks.

Two types of switches are generally found in the distribution networks for both protection and configuration management. These are sectionalizing switches (normally closed switches) and tie switches (normally opened switches [1]). Reconfiguration is defined as altering the topological structure of distribution networks by changing the open/close status of sectionalizing and tie-switches in order to optimize network operation parameters.

A survey of early works is provided in Ref. [2]. A non-exhaustive list of successive references illustrating the various methods are included in Refs. [3-13].

In this paper, a Grey Wolf Optimizer (GWO) algorithm is used on the reconfiguration problem of the radial distribution networks to minimize real power loss. The organization of this paper is as follows. In Section II, the mathematical formulation for the problem of optimal reconfiguration is presented. Section III brieﬁes the GWO algorithm. Section IV provides the complete details of the proposed GWO reconfiguration algorithm. The simulation test resulting in two typical radial distribution networks are presented and discussed in Section V. Section VI concludes the paper.

II. PROBLEM FORMULATION

A. Objective Function

The reason why power losses are selected as an objective function is that the losses are one of vital quantities in distribution systems and it is critical to keep power losses low for a better usage of network resources. The system total power loss is formulated as:

\[
P_{\text{loss}} = \sum_{i=1}^{N} \sum_{j=1}^{N} \left( A_i \left( P_i P_j + Q_i Q_j \right) + B_i \left( Q_i P_j - P_i Q_j \right) \right)_{i \neq j}
\]

\[
A_i = \frac{R_i \cos(\delta_i - \delta_j)}{V_i V_j} \quad B_i = \frac{R_i \sin(\delta_i - \delta_j)}{V_i V_j}
\]

where \( P_i, Q_i, P_j, Q_j \) are the net real and reactive power injection at buses \( i \) and \( j \), respectively; \( R_i \) is the line resistance between buses \( i \) and \( j \), \( V_i, \angle \delta_i, V_j, \angle \delta_j \) are the voltage magnitude and angle at buses \( i \) and \( j \), respectively; and \( N \) is the total number of buses.

B. Constraints

1. Equality Constraints

At each bus of the network, power flow equations should be satisfied as follows:

\[
P_i - P_L = \sum_{j=1}^{N_{\text{bus}}} Y_{ij} \left[ G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right]
\]

\[
 Q_i - Q_L = \sum_{j=1}^{N_{\text{bus}}} Y_{ij} \left[ G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) \right],
\]

\[
 i = 1, 2, \ldots, N_{\text{bus}}
\]

where \( Y_{ij} = G_{ij} + jB_{ij} \) is the element of the bus admittance matrix corresponding to buses \( i \) and \( j \).

2. Inequality Constraints

a. Bus voltage limitation

In distribution system, the voltage must be kept within the standard limits of each bus and it may mathematically be expressed as:
The电压在第i个节点的范围为：

\[ V_i \text{ min} \leq V_i \leq V_i \text{ max} , \quad i = 2, 3, \ldots, N_{\text{bus}} \] (3)

where \( V_i \text{ min} \) and \( V_i \text{ max} \) are the minimum (resp. maximum) voltages of the \( i \)th bus.

b. Line Thermal Limit

The rating of each branch is constrained by its permissible power as:

\[ \left| S_{ij} \right| \leq S_{ij} \text{ max} , \quad i, j = 2, 3, \ldots, N_{\text{bus}} \] (4)

where \( S_{ij} \) is the apparent power flow at distribution system lines between bus \( i \) and \( j \); \( S_{ij} \text{ max} \) is the permitted rating of branch \( ij \).

3. Radiality constraint

It is vital to keep the network radial after reconﬁguration due to some technical reasons such as protection coordination. In this paper, bus incidence matrix \( \hat{A} \) is proposed for checking the radiality of candidate solutions [14]. Matrix \( \hat{A} \) has one row for each branch and one column for each node with an entry \( a_{ij} \) in row \( i \) and column \( j \) according to the following rules:

\[ a_{ij} = \begin{cases} 1 & \text{if branch starts at node } i \\ -1 & \text{if branch starts at node } j \\ 0 & \text{otherwise} \end{cases} \] (5)

The square matrix \( A \) can be obtained from the matrix \( \hat{A} \) by deleting the column corresponding to the reference node. If the determinant of \( \hat{A} \) is equal to 1 or -1, then the system is radial. Else if that is equal to zero, this means that either the system is not radial, or groups of loads are disconnected from the service.

C. Constraints- Handling Mechanism

The constraints are handled as follows:

1. Equality Constraints

In the distribution feeders, the system Jacobian matrix is usually ill-conditioned because of high R/X ratio in line segments. Thus, traditional methods, such as Gauss-Seidel and Newton-Raphson, are not appropriate for solving the load flow problem in most cases and may often fail to converge. Based on this matter, for solving the load flow of distribution networks, the known backward-forward technique [15] has been adopted in this work.

2. Inequality Constraints

The inequality constraints (10) and (11) are handled by introducing penalty functions. Those functions indicate that a violated inequality constraint will be punished and then augmented to the objective functions (2) and (8).

\[ F_{\text{Penduced}} = F + \sum_{i=1}^{N_{\text{br}}} K_i \left( V_i - V_i^{\text{lim}} \right)^2 + \sum_{i=1}^{N_{\text{br}}} K_i \left( S_{Li} - S_{Li}^{\text{lim}} \right)^2 \] (6)

where \( F \) is the objective function value, \( V_i^{\text{lim}} \) and \( S_{Li}^{\text{lim}} \) are described as

\[ V_i^{\text{lim}} = \begin{cases} V_i & \text{if } V_i > V_i^{\text{max}} \\ V_i^{\text{min}} & \text{if } V_i < V_i^{\text{min}} \\ V_i^{\text{min}} & \text{if } V_i^{\text{min}} \leq V_i \leq V_i^{\text{max}} \end{cases} \] (7)

\[ S_{Li}^{\text{lim}} = \begin{cases} S_{Li} & \text{if } S_{Li} > S_{Li}^{\text{max}} \\ S_{Li}^{\text{min}} & \text{if } S_{Li} < S_{Li}^{\text{min}} \\ S_{Li}^{\text{min}} & \text{if } S_{Li}^{\text{min}} \leq S_{Li} \leq S_{Li}^{\text{max}} \end{cases} \] (8)

where \( K_i \) and \( K_i \) are the penalty factors. In this paper, the values of penalty factors have been considered 10,000.

III. GREY WOLF OPTIMIZER (GWO) ALGORITHM

In 2014, Syedali Mirjalili et al. [16], proposed a new population based meta-heuristic optimization algorithm entitled “Grey Wolf Optimizer” (GWO). The social leadership and hunting technique of grey wolves were the main inspiration of this algorithm. Similarly to other meta-heuristics, it initializes the optimization process by generation a set of random candidate solutions (wolves). During every iteration, the ﬁrst three best wolves are considered as alpha (\( \alpha \)), beta (\( \beta \)), and delta (\( \delta \)), who lead other wolves (\( \omega \)) toward promising zones of the search space.

Grey wolves tend to encircle the prey when the hunt. To model encircling behavior, the equation is deﬁned as follows:

\[ \overline{X}(t + 1) = \overline{X}(t) - \bar{A} \left( \overline{C} \overline{X}(t) - \overline{X} \right) \] (9)

\[ \bar{A} = 2 \bar{a} \cdot \text{rand} - \bar{a} \] (10)

\[ \bar{C} = 2 \cdot \text{rand} \] (11)

where \( t \) is the iteration number, \( \bar{A} \) and \( \bar{C} \) are coefﬁcient vectors, \( \overline{X} \) is the position vectors of prey, \( \overline{X}_\bar{r} \) indicates the position vector of a grey wolf. \( \text{rand} \) are random vectors in \([0, 1]\) and the variable \( \bar{a} \) decreases linearly from 2 to 0 with the iteration steps:

\[ \bar{a} = 2 - t / t_{\max} \] (12)
It should be noted that each mega wolf is required to update its position with respect to alpha, beta, and delta simultaneously as follows

\[
D_a = \overrightarrow{C_1X_a(t)} - \overrightarrow{X}
\]

\[
D_\beta = \overrightarrow{C_2X_\beta(t)} - \overrightarrow{X}
\]

\[
D_\delta = \overrightarrow{C_3X_\delta(t)} - \overrightarrow{X}
\]

\[
\overrightarrow{X}_1 = \overrightarrow{X}_a - \overrightarrow{A}_1 \cdot \overrightarrow{D_a}
\]

\[
\overrightarrow{X}_2 = \overrightarrow{X}_\beta - \overrightarrow{A}_2 \cdot \overrightarrow{D_\beta}
\]

\[
\overrightarrow{X}_3 = \overrightarrow{X}_\delta - \overrightarrow{A}_3 \cdot \overrightarrow{D_\delta}
\]

\[
\overrightarrow{X}(t + 1) = \left(\overrightarrow{X}_1 + \overrightarrow{X}_2 + \overrightarrow{X}_3\right)/3
\]  

IV. APPLICATION OF THE GWO TO THE PROPOSED PROBLEM

1. Decision variables

Because of the design of the network, the fundamental loops are numbered from 1 to BL, respectively. Then, one switch from every BL loops is opened to keep the network radial with considering constraints of system. This helps to reduce the generation of infeasible configuration during each stage of the optimization algorithm.

\[
X = [Sw_1, Sw_2, \ldots, Sw_{BL}]
\]

where \(X\) represents the state variables (solution) and \(SW_i\) represents the open switch number that is selected from the ith fundamental loop. Thus, the size of \(X\) is equal to the number of distribution system fundamental loops. The number of network fundamental loops is equal to the number of tie switches. Therefore, the encoding of individuals is as shown in Figure 2, where each candidate switch is denoted by discrete integer is corresponding to the respective loop vector.

\[
Sw_1 \in FL_1 \quad Sw_2 \in FL_2 \quad \ldots \quad Sw_i \in FL_i \quad \ldots \quad Sw_{BL} \in FL_{BL}
\]

Figure 1. Encoding of individuals

2. The Proposed Method Steps

The steps of the GWO algorithm are given below.

**Step 1:** Define the input data including the system base configuration, line impedance and bus data (Load Power i.e., Real Power and Reactive Power) and status of switches.

**Step 2:** Initialize GWO parameters such as population size (PS), maximum number of iterations (iter) and the vectors \((\overrightarrow{A}, \overrightarrow{C}\) and \(\overrightarrow{a}\)).

**Step 3:** Perform the distribution load flow analysis using a backward/forward sweep approach for each control variables vector. According to the results of the distribution load flow, the objective function value \(F_{obj}(X)\) (eq. 1), equality and inequality constraints are evaluated and then the augment objective function \(F(X)\) is calculated by using the values of objective function, constraints, and penalty factors (eq. 6).

**Step 4:** Update leader wolves \(X_{a}, X_{\beta}\) and \(X_{\delta}\) (first three best search agents).

**Step 5:** Use eq.10, eq.11 and eq.12 to calculate the coefficient vectors \((\overrightarrow{A}, \overrightarrow{C}\) and \(\overrightarrow{a}\)).

**Step 6:** Update the wolves’ position using eq. 9.

Repeat the procedure from step 3 to 6 until the maximum number of iteration is reached. The last \(X_{a}\) is the solution of the problem.

V. SIMULATIONS AND RESULTS

In this section, the proposed algorithm is tested on 33-bus [17], 69-bus [18], 84-bus [19] and 118-bus [20] radial distribution networks. Table 1 shows the effectiveness of the proposed algorithm on system performance in comparison with base case (before reconfiguration). The proposed GWO methodology is programmed in MATLAB 7.1. The test environment is set up on a computer with Intel Core i7-2630QM CPU, 3.30 GHz, 12GB RAM, running on Windows 10.

As can be seen from the comparison of columns (2) and (5) in Table 1, the total active power losses of all test systems are reduced significantly after reconfiguration.

The voltage profiles of all test systems are depicted in Fig. 3. As it can be seen, the voltage levels at all nodes for the radial distribution systems are improved and placed in an acceptable margin.
TABLE 1. RESULT OF THE PROPOSED ALGORITHM

<table>
<thead>
<tr>
<th>Test System</th>
<th>Before Reconfiguration</th>
<th>After Reconfiguration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real Power Loss (kW)</td>
<td>Minimum node voltage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(p.u.)</td>
</tr>
<tr>
<td></td>
<td>Branches switched out</td>
<td>Real Power Loss (kW)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimum node voltage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(p.u.)</td>
</tr>
<tr>
<td></td>
<td>Loss reduction (%)</td>
<td></td>
</tr>
<tr>
<td>33-bus</td>
<td>202.66</td>
<td>0.9131</td>
</tr>
<tr>
<td>69-bus</td>
<td>224.78</td>
<td>0.9092</td>
</tr>
<tr>
<td>84-bus</td>
<td>531.81</td>
<td>0.9285</td>
</tr>
<tr>
<td>118-bus</td>
<td>1297.86</td>
<td>0.8688</td>
</tr>
<tr>
<td>7-14-9-32-37</td>
<td>139.51</td>
<td>0.9378</td>
</tr>
<tr>
<td>14-70-69-58-61</td>
<td>99.58</td>
<td>0.9427</td>
</tr>
<tr>
<td>55-7-86-72-88-90-83-92-39-34-40-62</td>
<td>470.32</td>
<td>0.9532</td>
</tr>
</tbody>
</table>

Fig. 3. Voltage profile before and after reconfiguration

TABLE 2. COMPARISONS OF AVERAGE WITH PREVIOUS METHOD

<table>
<thead>
<tr>
<th>Test system</th>
<th>Methods</th>
<th>Optimal configuration</th>
<th>Real power loss (kW)</th>
<th>Minimum node voltage (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33-bus</td>
<td>PSO</td>
<td>7-14-9-32-37</td>
<td>142.12</td>
<td>0.9336</td>
</tr>
<tr>
<td>69-bus</td>
<td>PSO</td>
<td>13-70-69-58-61</td>
<td>99.67</td>
<td>0.9427</td>
</tr>
<tr>
<td>84-bus</td>
<td>PSO</td>
<td>61-7-86-72-13-89-90-82-92-39-34-42-54</td>
<td>476.91</td>
<td>0.9503</td>
</tr>
<tr>
<td></td>
<td>Proposed GWO</td>
<td>14-70-69-58-61</td>
<td>99.58</td>
<td>0.9427</td>
</tr>
<tr>
<td></td>
<td>Proposed GWO</td>
<td>55-7-86-72-88-90-83-92-39-34-40-62</td>
<td>470.32</td>
<td>0.9532</td>
</tr>
</tbody>
</table>
The results obtained using GWO method is compared with Particle Swarm Optimization method (PSO) and the results are shown in Table 2.

VI. CONCLUSION

This paper has presented a GWO based approach for optimum reconfiguration of radial distribution networks, the objective function was the minimization of power losses while satisfying system constraints. The proposed algorithm was tested on 33-bus, 69-bus, 84-bus and 118-bus radial distribution test systems. The results have proved the efficiency of this method for reduction of active power losses and enhancement of voltage profile.

REFERENCES


