Optimal Reconfiguration of Power Distribution Network Using Hybrid Firefly and Particle Swarm Optimization Algorithm

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Abstract- Electrical energy has become the most essential requirement for working of today’s modern world. Power distribution networks (PDN) are required for providing power from distribution substations to consumers but are subjected to power loss and voltage drop problems. These problems greatly affect the operational cost and voltage stability level of a PDN. Network reconfiguration (NR) is a cost effective approach to optimize PDN for reduction of power loss and improvement of voltage profile (VP). This paper presents an effective meta-heuristic, population-based algorithm for finding optimal configuration of a PDN. In particular Hybrid Firefly and Particle Swarm Optimization (HFPSO) algorithm is used. The HFPSO algorithm has enhanced exploration and exploitation strategies, and fast convergence rate. MATLAB software is used to implement the algorithm and IEEE 33-bus radial distribution system (RDS) is considered for NR. The results obtained show that active power loss is reduced by 46.35% from original value of power loss and minimum voltage is improved to 0.9572p.u. The comparison of obtained results with literature show that HFPSO algorithm has efficiently reduced active power loss and improved VP of the network.

Index Terms-- Hybrid firefly and particle swarm optimization, Network reconfiguration, Power distribution network, Voltage profile.

I. INTRODUCTION

PDN is an essential component of electrical power system which provides power from substations to final consumers [1]. There are several problems associated with these networks, such as power loss and voltage drop. The main reason for these problems are the resistance and reactance current present in feeders which are greatly affected by configuration of PDN [2]. Therefore, configuration of PDN is very important for optimal planning of power system. Poor configuration results in high power loss, poor VP and low power factor [3]. These problems leads to extra charges for power distribution companies. To reduce these losses, various methods are used, such as incorporating distributed generation (DG), installation of capacitor banks, network voltage raising and distribution system network reconfiguration [4]. Among these techniques, NR requires least investment as it utilizes the resources already available in the distribution network [5].

The NR is processed by changing the status (close/open) of tie-lines and sectionalizers present in PDN [5] while meeting the network constraints which includes limits of bus voltages, and line currents [6]. Sectionalizers are normally closed and tie-lines are normally open. Objective function determines the configuration of these lines [7]. Hence, to employ an efficient algorithm for NR is necessary. The main aim of NR is reduction of active power loss (APL) to improve system performance [7, 8]. Other objectives includes improving VP, reducing equipment overload and balancing the load between feeders. However, minimizing losses will lead to achievement of other objectives as well.

Merlin and Back proposed the first NR problem in 1975 and determined the optimal solution for minimum power loss [9]. In last two decades, through the advancement in computer sciences, researchers have developed several techniques for optimization of PDNs through NR which can be categorized to analytical, meta-heuristic and artificial intelligence (AI) techniques [10]. The analytical techniques have high computational efficiency but they cannot deal with multi-objectives. Analytical techniques are usually applied for NR having unique switching approaches such as interchance switch strategy [11]; close-all switch strategy [12], open-all switch strategy [13]; and sensitivities computation method [14]. Meta-heuristic and AI techniques have less computational efficiency than analytical techniques [15]. These are population based stochastic methods that do not require objective function to be continuous and convex and thus can efficiently handle the constrained optimization problems [16]. Various meta-heuristic techniques for NR namely Genetic algorithm (GA) considering power loss [17-19], harmony search algorithm (HSA) [20], cuckoo search algorithm (CSA) [21], self-adaptive differential evolutionary algorithm (SADE) [22], stochastic fractal search algorithm (SFSA) [23], fireworks algorithm (FWA) [24], grey wolf optimization [25], particle swarm optimization (PSO) [26-28], firefly algorithm (FA) [29], and improved adaptive imperialist
competitive algorithm (IAICA) [30], evolutionary algorithm [31] are present in literature. So far, these have been the most popular and effective techniques to solve the problems related to optimization of power distribution systems generally and NR problem particularly. However, these approaches are more likely to converge on local optima. As a result, main goal of researchers is to solve the problem of local convergence of meta-heuristic approaches. For global optimization, some of these methods do not generate effective results. Such population-based algorithms are useful for local optimal solution. However the trajectory techniques are good at finding global optimal solution. So, advantages of both techniques can be utilized by combining these methods [32]. The main goals of hybridization of PSO algorithm are to balance the exploitation and exploration rates [33]. In comparison with PSO, FA does not have local best variable and thus it is free from problem of local convergence [34]. Furthermore, FA does not have velocity vector, so it is also free from the problems of velocity variations [35]. Hybrid Firefly and Particle Swarm Optimization (HFPSO) algorithm is one of the most recent hybrid meta-heuristic technique [36], which have been used to solve some engineering problems and the results showed that HFPSO algorithm has the ability to produce successful results that were never seen earlier [36].

The application of HFPSO algorithm to NR problem has never been studied previously and using a powerful optimization algorithm can effectively solve NR problem. This paper presents HFPSO to solve NR problem in the field of Electrical Power Engineering. Following are the main contributions of this paper:

1) HFPSO algorithm is used in this paper to solve the problem of NR.
2) The algorithm is applied for reducing power loss and improving VP of standard IEEE 33-bus RDS.
3) Comparison between the findings and results of other simulations using different algorithms found in literature.
4) It is noted from statistical analysis that reliability of HFPSO algorithm is very high for solving NR problem.

The structure of the paper is as follows: Mathematical problem formulation is presented in section 2. A brief overview of FA, PSO and HFPSO algorithms, respectively is presented in section 3. Section 4 describes the implementation of HFPSO to NR problem. Results and comparison of different algorithms are explained in Section 5. Section 6 briefly concludes the article.

II. PROBLEM FORMULATION

The main objective is to find the optimal configuration of RDS. Since many switching combinations are possible, finding the optimal combination is a complex constrained optimization problem. To minimize active power loss (APL), reactive power loss (RPL) and deviation of voltage from the standard value 1 p.u. are the three main objectives considered. So if these objective functions with their individual weight factors are considered, then mathematical expression of multi-objective function (MOF) is given by (1).

\[
FF = MOF = \min(FF_1, FF_2, FF_3)
\]  

Therefore

\[
FF = \min(W_0 \cdot P_L, W_0 \cdot Q_L, W_0 \cdot CVD)
\]

where:

\[
FF = \text{fitness function},
\]

\[
P_L = \text{function of APL},
\]

\[
Q_L = \text{function of RPL},
\]

\[
CVD = \text{function of cumulative voltage deviation}.
\]

The CVD is equal to sum of voltage deviation from desired value (1 p.u.) at every bus as given in (3).

\[
CVD = \sum_{i=1}^{nb} |1 - V_i|
\]

where: 

\[
nb = \text{total number of buses},
\]

\[
V_i = \text{ith bus voltage}.
\]

In FF, \( W_L, W_x, W_v \) are weight factors with respect to \( P_L, Q_L \) and CVD, respectively. Generally, the sum of absolute value of weight factors is 1 as given in (4).

\[
|W_L| + |W_x| + |W_v| = 1
\]

In a PDN, the losses are always in the form of \( P_L, Q_L \), and CVD for problems like NR. These losses can be calculated using the weight factors. Each loss is assigned a weight factor according to its significance and impact on system losses. Thus, we have considered these objective functions as their weighted sum, as shown in (2). The constraints are described as follows:

A. VOLTAGE LIMIT

The voltage of each bus \( V_i \) should be within permissible limits of minimum \( V_{min} \) and maximum \( V_{max} \) as given in (5).

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

where: \( i = 1, 2, 3 \ldots n \),

B. LINE LOADING

The apparent power of the lines \( S_k \) should be less than or equal to maximum allowable power \( S_{k}^{\text{max}} \) as given by (6).

\[
S_k \leq S_{k}^{\text{max}}
\]

C. LOAD CONNECTIVITY

Every bus must be connected to the substation.

D. RADIAL STRUCTURE

The PDN should be radially connected such that the number of lines should be less than the number of buses by one.

III. HYBRID FIREFLY AND PARTICLE SWARM OPTIMIZATION (HFPSO)

A. FIREFLY OPTIMIZATION ALGORITHM

It is a bio-inspired algorithm on the basis of flashing patterns and behaviors of fireflies at night. For the sake of survival, these fireflies emit a distinct flashing light [34, 37]. The method depends on the absorption of medium and intensity of flashing light. Light intensity from a light source decreases with increase in distance as defined by inverse square law. Furthermore, the light is also absorbed by the medium through which it passes. Its
position (X) and velocity (V) are mathematically expressed as the following equations [38],

$$X_i(t + 1) = X_iB_0e^{n^2i} - (X) i - g_{best}t + ae \quad (7)$$

$$V_i(t + 1) = X_i(t + 1) + X_{temp} \quad (8)$$

B. PARTICLE SWARM OPTIMIZATION (PSO) ALGORITHM

In 1995, Kennedy and Eberhart created PSO algorithm and it is a meta-heuristic method [39]. Living organism’s behavior such as a flock of birds or swarm of fish is the base of this method. The advantages of this algorithm includes easy implementation, fast convergence and less calculating variables but this method offers slow convergence when populations are close to one another and get stuck in local optima [40]. Its position (X) and velocity (V) vectors are mathematically expressed as given below [39]:

$$V_i(t + 1) = wV_i(t) + c_1r_1 \left(P_{best}i(t) - X_i(t)\right) + c_2r_2 \left(g_{best}i(t) - X_i(t)\right) \quad (9)$$

$$X_i(t + 1) = X_i + V_i(t + 1) \quad (10)$$

where w is inertia weight, acceleration coefficients are $c_1$ and $c_2$, two random numbers are $r_1$ and $r_2$ in the range [1, 0]. Based on the number of iterations, inertia weight is estimated in a linearly decreasing sequence. The following is a mathematical formula for calculating inertia weight [41, 42]:

$$w = w^{max} - \frac{(w^{max} - w^{min}) \times \text{iteration}}{\text{Max-iteration}} \quad (11)$$

C. HYBRID FIREFLY AND PARTICLE SWARM OPTIMIZATION (HFPSO) ALGORITHM

In [36], Ibrahim Berkan Aydilek developed HFPSO algorithm. Objective functions including continuous and discrete functions can be minimized or maximized with optimization algorithms with numerous constraints to get most practicable solution for an optimization problem. In order to get benefits of both algorithms (FA and PSO), there is a need to maintain equilibrium between exploitation and exploration [43, 44]. In FA, terms of personal best ($P_{best}$) and velocity (V) are not included. Fast convergence is offered by PSO method in terms of local optimal solution for global search whereas in region of local search, FA is more beneficial. Fine global optimal solution is offered by it.

IV. IMPLEMENTATION OF HFPSO TO NR PROBLEM

For finding optimal configuration, the load flow analysis technique is used. HFPSO is used for power loss reduction and to place lines in an appropriate condition. The first step of simulation is to input data of distribution system (Data of buses, Data of lines, Data of loads). Then randomly initialize initial configuration by predefining sectionalizers and tie-line switches. Iteratively change the sectionalizers and tie-line switches. Then run the load flow program for RDS. Calculate branch currents, power loss and voltage profile. Check the criteria for feeder reconfiguration. If yes print the results shown on output window otherwise go to step 3. Fig. 1 shows flowchart of HFPSO algorithm.

IEEE 33-bus RDS data and load flow analysis method is used to calculate system losses. HFPSO algorithm is used to reduce system losses by applying a selection to the current population to create an intermediate distribution population. In the beginning, input parameters are entered. Both population-based techniques then utilize these parameters in a step-by-step fashion. After that, constant swarm vectors in ranges of velocity and space of search are initiated. Allocation of individual best ($P_{best}$) and global best ($g_{best}$) swarms is mathematically done. In final iteration, comparison of calculated values is performed. Furthermore, record the current location, and determine location and new velocity afterwards [36].

![Flowchart of HFPSO algorithm for NR problem](image_url)
V. RESULTS AND DISCUSSION
The code of this algorithm is executed in MATLAB environment in an Intel core i7 Laptop with CPU of 2.6 GHz and RAM of 16 GB. Initially, the lines 33, 34, 35, 36, and 37 are considered as tie-lines (normally open).

A. RESULTS BEFORE RECONFIGURATION
From load flow analysis of the base network presented in Fig. 2, the VP of each bus, APL and RPL were computed. The VP before reconfiguration is shown in Fig. 4, and 0.9108p.u. is the minimum voltage level.

B. RESULTS AFTER RECONFIGURATION
The results show that APL after NR is 109.69 kW as compared with base value of 204.46 kW. This tells that 94.766 kW of active power can be saved. The APL percentage reduction is 46.35%. NR using HFPSO algorithm caused closing of four tie-lines, namely: 33, 34, 35, and 36, while opening of sectionalizes namely: 7, 9, 14, and 32 as shown in Fig. 3. Results are summarized in table 1. The voltages before and after NR of each bus are given in Table 2 and plotted in Fig. 4. The value of minimum voltage after NR is 0.9572 p.u.

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Voltage Before Reconfiguration</th>
<th>Voltage After Reconfiguration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.0014</td>
</tr>
<tr>
<td>2</td>
<td>0.9970</td>
<td>0.9985</td>
</tr>
<tr>
<td>3</td>
<td>0.9829</td>
<td>0.9884</td>
</tr>
<tr>
<td>4</td>
<td>0.9755</td>
<td>0.9839</td>
</tr>
<tr>
<td>5</td>
<td>0.9681</td>
<td>0.9796</td>
</tr>
<tr>
<td>6</td>
<td>0.9561</td>
<td>0.9731</td>
</tr>
<tr>
<td>7</td>
<td>0.9526</td>
<td>0.9725</td>
</tr>
<tr>
<td>8</td>
<td>0.9390</td>
<td>0.9641</td>
</tr>
<tr>
<td>9</td>
<td>0.9328</td>
<td>0.9639</td>
</tr>
<tr>
<td>10</td>
<td>0.927</td>
<td>0.9675</td>
</tr>
<tr>
<td>11</td>
<td>0.9261</td>
<td>0.9676</td>
</tr>
<tr>
<td>12</td>
<td>0.9246</td>
<td>0.9679</td>
</tr>
<tr>
<td>13</td>
<td>0.9185</td>
<td>0.9653</td>
</tr>
<tr>
<td>14</td>
<td>0.9162</td>
<td>0.9645</td>
</tr>
<tr>
<td>15</td>
<td>0.9148</td>
<td>0.9613</td>
</tr>
<tr>
<td>16</td>
<td>0.9134</td>
<td>0.9609</td>
</tr>
<tr>
<td>17</td>
<td>0.9114</td>
<td>0.9588</td>
</tr>
<tr>
<td>18</td>
<td>0.9108</td>
<td>0.9575</td>
</tr>
<tr>
<td>19</td>
<td>0.9065</td>
<td>0.9599</td>
</tr>
<tr>
<td>20</td>
<td>0.9029</td>
<td>0.9830</td>
</tr>
<tr>
<td>21</td>
<td>0.9022</td>
<td>0.9784</td>
</tr>
<tr>
<td>22</td>
<td>0.9016</td>
<td>0.9749</td>
</tr>
<tr>
<td>23</td>
<td>0.9094</td>
<td>0.9821</td>
</tr>
<tr>
<td>24</td>
<td>0.9027</td>
<td>0.9816</td>
</tr>
<tr>
<td>25</td>
<td>0.9074</td>
<td>0.9753</td>
</tr>
<tr>
<td>26</td>
<td>0.9542</td>
<td>0.9747</td>
</tr>
<tr>
<td>27</td>
<td>0.9516</td>
<td>0.9724</td>
</tr>
<tr>
<td>28</td>
<td>0.9403</td>
<td>0.9713</td>
</tr>
<tr>
<td>29</td>
<td>0.9321</td>
<td>0.9638</td>
</tr>
<tr>
<td>30</td>
<td>0.9286</td>
<td>0.9606</td>
</tr>
<tr>
<td>31</td>
<td>0.9245</td>
<td>0.9572</td>
</tr>
<tr>
<td>32</td>
<td>0.9236</td>
<td>0.9579</td>
</tr>
<tr>
<td>33</td>
<td>0.9233</td>
<td>0.9614</td>
</tr>
</tbody>
</table>

![Figure 2. IEEE 33-bus RDS before NR](image)

![Figure 3. IEEE 33-bus RDS after NR](image)

![Figure 4. Before and after NR voltage profile](image)
C. COMPARISON OF RESULTS WITH OTHER TECHNIQUES

Table 3 presents the comparison of HPSO algorithm with other techniques which used IEEE 33 bus RDS for NR. It is proved by the overall results that the algorithm of HPSPSO gave optimal results as compared to other existing algorithms for NR.

<table>
<thead>
<tr>
<th>Method</th>
<th>APL (kw)</th>
<th>APL reduction (kw)</th>
<th>Min. Voltage</th>
<th>Opened Switches</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPSO</td>
<td>109.69</td>
<td>94.76</td>
<td>0.9572</td>
<td>7,9,14,32,37</td>
</tr>
<tr>
<td>HSA[20]</td>
<td>142.68</td>
<td>60.01</td>
<td>0.9342</td>
<td>7,10,14,36,37</td>
</tr>
<tr>
<td>SPSO[26]</td>
<td>139.79</td>
<td>63.01</td>
<td>-</td>
<td>7,9,14,32,37</td>
</tr>
<tr>
<td>SFA[29]</td>
<td>139.55</td>
<td>63.13</td>
<td>0.9378</td>
<td>7,9,14,32,37</td>
</tr>
<tr>
<td>IAIACA[30]</td>
<td>139.6</td>
<td>63.19</td>
<td>0.9380</td>
<td>7,9,14,32,37</td>
</tr>
<tr>
<td>FWA[24]</td>
<td>139.98</td>
<td>62.70</td>
<td>0.9412</td>
<td>7,9,14,28,32</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

This paper solved NR problem using HPSO algorithm for reducing power loss and improving VP of PDN. A constrained multi-objective function was considered. Load flow analysis technique and HPSO algorithm has been used for analysis. The results achieved present that reduction in the value of APL is of 94.76 kW (46.35%) from the original value of 204.46kw and improvement in the value of minimum voltage is 0.0464p.u and exact value is 0.9572p.u. The comparison of results with various other optimization techniques revealed that optimizing PDN using HPSO algorithm contributed significantly in improving the bus voltages, and power loss.

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