Optimal power flow solution using HFSS Algorithm

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The optimal power flow is a pragmatic problem in a power system with complex behavior that includes many control parameters. Many metaheuristic algorithms with different search methodologies have been proposed for solving the OPF problem. However, existing algorithm faces challenges such as stagnation, premature convergence, and local optima trapping during the optimization process, which provide low-quality and misleading results for real-world problems. In this paper, a novel algorithm which is inspired by the natural foraging phenomenon of the flying squirrel named as Squirrel Search Algorithm is used and it is hybridized with arithmetic crossover operation to enhance its effectiveness and be used for solving the OPF problem. So, the proposed algorithm is named the Hybrid Flying Squirrel Search Algorithm (HFSSA). The capability and performance of the proposed algorithm are observed on benchmark test functions and on the IEEE-30 bus system. Generation fuel cost, emission, and transmission losses are considered objectives of an optimal power flow problem. We got optimal values by handling the control parameters; Generation fuel cost as 799.86 $/h, Emission as 0.20374 ton/h, and transmission loss as 3.1687 MW. The obtained results corroborate that the proposed algorithm outperforms the existing algorithms for solving the OPF problem.

Key words: Emission; Generation fuel cost; Hybrid Flying Squirrel Search Algorithm (HFSSA); Optimal Power Flow (OPF); Power Injection modeling (PIM); Transmission losses.

INTRODUCTION

In recent years, development is taking place at a good pace which has led to an increase in the demand for electricity at a rigorous rate. Establishing new plants to fulfill the demand is not a good alternative, thus there is a need to utilize the existing system to its level best. To identify the optimal control variables in the power system the proposed optimal control technique is used and it helps to automatically adjust to minimize instantaneous generation fuel cost, emission, transmission losses, or any other objectives, and at those control variables power system can be planned and operated (Hermann and Williams, 1968).

Basically, the OPF problem is solved by satisfying considered constraints such as equality, inequality, and device constraints. Lot of conventional and metaheuristic techniques has been proposed for solving OPF problems, in the literature. Xie and Song (2002), Javad et al. (2011), El-Hawary et al. (1999a), El-Hawary et al. (1999b) Alsac

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and Stott (1973) and Sun et al. (1984) described conventional methods such as interior point, linear programming, etc, but these methods are not suitable for big power system networks, and it takes a large time to reach optimal value. The results obtained using these methods sometimes mislead the results. In heuristic optimization techniques, many intelligent algorithms have developed that help to overcome the problem faced in classical approaches. Some algorithms are based on an evolutionary-inspired algorithm like enhanced self-adaptive differential evolution (Pulluri et al., 2017), enhanced genetic algorithm (Kumari and Maheswarapu, 2010), backtracking search optimization (Chaib et al., 2016), and genetic algorithm (Osman et al., 2004); some are human-inspired algorithms like biogeography-based optimization (Bhattacharya and Chattopadhyay, 2010), tabu search algorithm (Abido, 2002), gray wolf optimizer (El-Fergany and Hasanien, 2015) and some are nature inspired algorithms like particle swarm optimization (Abido, 2002), artificial bee colony algorithm (Jadon et al., 2014), the modified flower pollination (Barocio et al., 2016), hybrid cuckoo search algorithm (Balasubba, 2017), Nature-inspired algorithms have some features in common, firstly they emulate any natural occurring phenomenon, and secondly there is no need of gradient information and thirdly it implicit on random variables (Li et al., 2016). The performance of various metaheuristic techniques for single and multi-objective optimization with different facts devices are described (Mallala et al., 2022; Ahmed et al., 2014; Balasubbareddy et al., 2022; Balasubbareddy et al., 2022:1-9; Ahmed et al., 2022a; Balasubbareddy et al., 2015;1-17; Ijaz et al., 2014; Balasubbareddy et al., 2017:44-53; Balasubbareddy et al., 2022; Ahmed et al., 2022b; Balasubbareddy et al., 2012; Ahmed et al., 2022c; Dhiraj et al., 2020; Ahmed et al., 2022d; Balasubba, 2016).

In this paper, a nature-inspired algorithm is considered which is the squirrel search algorithm (SSA) (Mohit et al., 2019) inspired by the foraging process of flying squirrels (Thomas and Weigl, 1998), is hybridized with arithmetic crossover operation (Yalcinoz and Halis, 2005; Qun et al., 2014) and proposed a new algorithm named as hybrid flying squirrel search algorithm (HFSSA). This proposed algorithm is tested on benchmark test function and used for solving the single objective problems of OPF that is, generation fuel cost, emission, and transmission loss.

Mathematical problem formulation

The OPF problem formulation with subject to constraints is given mathematically as follows:

Minimize function \( F_i(a,b) \) \[ \forall i = 1,2,\ldots,t \]

Sub. to: \( m(a,b) = 0 \), \( n(a,b) \leq 0 \)

The dependent variables:

\[
a^T = [P_{G,1},V_{L,1},\ldots,V_{L,NLINE},Q_{G,1},\ldots,Q_{G,NGB},S_{L,1},\ldots,S_{L,NTL}]\]

Control variables:

\[
b^T = [P_{G,2},\ldots,P_{G,NGB},V_{G,1},\ldots,V_{G,NGB},Q_{SH,1},\ldots,Q_{SH,NC},T_{1},\ldots,T_{NT}]\]

Objective functions

The considered objective functions such as cost minimization, emission minimization and power loss minimizations are described below:

a. Fuel cost minimization

\[
F_1 = \min(F_P(P_{G,m})) = \sum_{m=1}^{NGB} x_m P_{G,m}^2 + y_m P_{G,m} + z_m S / h
\]

where, \( x_m, y_m \) and \( z_m \) are the fuel cost coefficients of \( m \)th unit.

b. Emission minimization

\[
F_2 = \min(E(P_{G,m})) = \sum_{m=1}^{NGB} \alpha_m + \beta_m P_{G,m} + \gamma_m P_{G,m}^2 + h m \exp(\lambda_m P_{G,m}) / h
\]

c. Total power loss minimization

\[
F_3 = \min(P_{loss}) = \sum_{m=1}^{NTL} P_{loss,m} MW
\]

Constraints

To solve power system problem needs to consider following constraints:

a. Equality constraints:

\[
\sum_{m=1}^{NGB} P_{g,m} - P_{d} - P_{L} = 0, \sum_{m=1}^{NGB} Q_{g,m} - Q_{D} - Q_{L} = 0
\]

b. Inequality Constraints:

\[
V_{G,m}^{\min} \leq V_{G,m} \leq V_{G,m}^{\max} \quad \text{and} \quad Q_{G,m}^{\min} \leq Q_{G,m} \leq Q_{G,m}^{\max} \quad \forall m \in \text{NGB}
\]

\[
V_{G,m}^{\min} \leq V_{G,m}^{\max} \quad \text{and} \quad T_{m}^{\min} \leq T_{m}^{\max} \quad \forall m \in \text{NT}
\]

\[
P_{G,m}^{\min} \leq P_{G,m} \leq P_{G,m}^{\max} \quad \forall m \in \text{NGB}
\]

\[
Q_{SH,m}^{\min} \leq Q_{SH,m} \leq Q_{SH,m}^{\max} \quad \forall m \in \text{NC}
\]
Proposed Hybrid Flying Squirrel Search Algorithm (HFSSA)

This paper developed the proposed algorithm with the hybridization of existing squirrel search algorithm and arithmetic crossover operation to enhance the accuracy in dealing with power systems.

Existing Squirrel Search Algorithm (SSA)

SSA basically works on the flying squirrels locomotive mechanism for optimize the problem. According (20), there are two available food sources for flying squirrels, one is hickory nut tree which are in limited numbers. The behavioral routine of flying squirrel is to adapt the changes according to seasons as they become very active and searches for food during summer season while during winter, they become dormant but they do not sleep. Thus, during summer when they are active, they will scrupulously search for food. Flying squirrel’s gliding locomotion with hickory nut is shown in Figure 1. In this algorithm n numbers of flying squirrels and n number of total trees are considered with the assumption that one flying squirrel will be on one tree.

Proposed Hybrid Flying Squirrel Search Algorithm (HFSSA)

Random initialization

Initially all the flying squirrels are randomly allocated with any of the tree. Mathematically it can be represented as:

\[ S_{L,m} \leq S_{L,m}^{\text{max}} \quad \forall m \in \text{NTL} \]

\[ S_m = S_{\text{min}} + U(0,1) \times (S_{\text{max}} - S_{\text{min}}) \tag{4} \]

Where, \( S_{\text{min}} \) and \( S_{\text{max}} \) are the \( m^{th} \) flying squirrel min. and max. values and \( U(0,1) \) is a random number(0,1).

Generation of new location in order to search food

It can be mathematically modelled according to the three situations which are as follows:

Case A: Flying squirrels which are on acron trees and target to moves towards nut tree. Calculate new location as below equations:

\[ S_a^{t+1} = S_a^t + g_d \times g_c \times R_1 \times (S_h^t - S_a^t) \quad \text{if} \quad R_1 \geq 0.1 \tag{5} \]

\[ S_a^{t+1} = \text{Random position will be allocated} \quad \text{if} \quad R_1 < 0.1 \]

where, \( g_c = 1.9 \) (20) and \( g_d \) is the random gliding distance of flying squirrel. \( S_a^t \) is the previous position of flying squirrel at acron tree and \( S_h^t \) is the current position of flying squirrel at hickory nut tree at \( t^{th} \) iteration.

Case B: Flying squirrels and target to moves towards acron trees. So, the new location can be determined as follows:

\[ S_n^{t+1} = S_n^t + g_d \times g_c \times R_2 \times (S_a^t - S_n^t) \quad \text{if} \quad R_2 \geq 0.1 \tag{6} \]

\[ S_n^{t+1} = \text{Random position will be allocated} \quad \text{if} \quad R_2 < 0.1 \]
where, \( S^t_n \) is the previous position of flying squirrel at normal tree at \( t^{th} \) iteration.

**Case C:** Flying squirrels and target to moves towards hickory nut trees. So, the new location can be determined as follows:

\[
S^{t+1}_n = S^t_n + g_d \times g_c \times R_3 \times (S^t_h - S^t_n) \quad \text{if } R_3 \geq 0.1
\]

\[
S^{t+1}_n = \text{Random position will be allocated} \quad \text{if } R_3 < 0.1
\]

### Seasonal monitoring of flying squirrel

As discussed, the behaviour change of flying squirrel with season changes is modelled as:

\[
SC^t = \sqrt{\sum_{m=1}^{d}(S^t_{a,m} - S^t_{h,m})^2}
\]

\[
SC_{\min} = \frac{10e^{-06}}{365^{t/\text{iter}/2.5}}
\]

where, \( t \) is the current iteration number. Thus, this condition must be satisfied: quickly. Mathematically arithmetic crossover operation.

\[
SC^t < SC_{\min}
\]

**At the end of winter season flying squirrel are randomly re-allocated**-

As the levy distribution makes exploration more effective so it is calculated by following equation:

\[
Levy(x) = 0.01 \times \frac{r_1}{|r_2|^{\alpha}} \times \gamma
\]

where \( r_1 \) and \( r_2 \) are random number between (01,1) and

\[
\gamma = \frac{\Gamma(1+\alpha) \times \sin(0.5 \pi \alpha)}{\Gamma(1+\alpha) \times \alpha \times 2^{\alpha-1}}
\]

where, \( \alpha \) is a constant 1.5(1).

The re-allocation is mathematically modelled as:

\[
S^\text{new}_m = S_{\min} + Levy \times (S_{\max} - S_{\min})
\]

### Arithmetic crossover operation

As in existing method Levy distribution control the exploration and to equalize the exploitation and exploration, this arithmetic crossover operation is implemented so that final result can be achieved efficiently in less iteration. As arithmetic crossover operation \((38, 39)\) updates the generated locations and thus convergence occurs faster. Thus, the hybridization helps to get the optimum values can be expressed as \((18)\):

\[
S^{t+1}_m = (1-\xi) \times S^t_h + \xi \times S^{t+1}_m
\]

where, \( \xi \) is a random number between 0 and 1. After

---

**Table 1.** Optimal result of Himmelblau’s function.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PSO</th>
<th>HCSA</th>
<th>HFSSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>3.01744</td>
<td>3.00126</td>
<td>3.58442</td>
</tr>
<tr>
<td>X2</td>
<td>1.96808</td>
<td>1.99933</td>
<td>-1.84813</td>
</tr>
<tr>
<td>Minimum Function Value</td>
<td>0.01726</td>
<td>4.96e-05</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Source: Balasubba (2017)

**Table 2.** Optimal result of Booth’s function.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PSO (Balasubba RM 2017)</th>
<th>HCSA(Balasubba RM 2017)</th>
<th>HFFA et al (2022))</th>
<th>HFSSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>1.012698676</td>
<td>1.0043728</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>X2</td>
<td>2.989245453</td>
<td>2.9969812</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Minimum Function Value</td>
<td>0.000292035</td>
<td>3.557e-05</td>
<td>1.2364e−08</td>
<td>2.8075e-10</td>
</tr>
</tbody>
</table>

Source: Balasubba (2017)
re-allocation of flying squirrel the location is updated by Equation (12).

**Pseudo code of proposed Hybrid Squirrel Search Algorithm (HSSA)**

Step 1: **Input**- Read bus data, line data, generator data and cost data for the given electric system.
Step 2: Set maximum iteration count, flying squirrels.
Step 3: Initially generate the random location for the flying squirrels using Equation (4).
Step 4 Map the algorithm variables with the load flow data and then evaluate them for obtaining the solution of the single objective problems.
Step 5: Calculate each flying squirrels fitness and sort ascending order of their fitness values.
Step 6: The 3 fit values will be of flying squirrel on acron trees and then remaining will be on normal trees.
Step 7: Randomly select one of the flying squirrel which are on normal trees and target them to move toward hickory nut tree and remaining to the acron trees. While (the condition not satisfied)

Step 8: for *i=1 to no.of flying* squirrels

if $R1 \geq 0.1$

\[ S_{a}^{t+1} = S_{a}^{t} + R_{1} \times (S_{h}^{t} - S_{a}^{t}) \]

else

\[ S_{a}^{t+1} = \text{Random position will be allocated} \]

end

Step 9: for $i=1$ to $fs2$

if $R2 \geq 0.1$

\[ S_{n}^{t+1} = S_{n}^{t} + R_{2} \times (S_{a}^{t} - S_{n}^{t}) \]

else

\[ S_{n}^{t+1} = \text{Random position will be allocated} \]

end

Step 10: for $i=1$ to $fs3$ (number of flying squirrels which are on normal trees and target to moves towards hickory nut tree)

if $R3 \geq 0.1$

\[ S_{n}^{t+1} = S_{n}^{t} + R_{3} \times (S_{h}^{t} - S_{n}^{t}) \]

else

\[ S_{n}^{t+1} = \text{Random position will be allocated} \]

end

Step 11: Find seasonal constant using Equation (8).
Step 12: Verify the seasonal monitoring condition, if it found valid then find levy flight operator using Eq. (10) and randomly relocate the flying squirrel using Equation (10).
Step 13: Update the location of flying squirrels with arithmetic crossover operation using Equation (12).
Step 14: Determine the minimum value of seasonal constant using Equation (9). Go to step 8.

end

Step 15: Output- The flying squirrel which is on hickory
Figure 3. Convergence curve of Booth’s function.
Source: Balasubba (2016)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>HSCA(BalaaRM (2017)</th>
<th>(BaasubarRM(2017)</th>
<th>HFFA(Ijaz A et al 2022)</th>
<th>HFSSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>MW</td>
<td>176.87</td>
<td>178.556</td>
<td>179.312</td>
<td>174.865</td>
</tr>
<tr>
<td>P₂</td>
<td>MW</td>
<td>49.8862</td>
<td>48.6032</td>
<td>48.265</td>
<td>46.4864</td>
</tr>
<tr>
<td>P₈</td>
<td>MW</td>
<td>20.8796</td>
<td>20.7414</td>
<td>19.8629</td>
<td>18.5053</td>
</tr>
<tr>
<td>P₁₁</td>
<td>MW</td>
<td>11.6168</td>
<td>11.7702</td>
<td>23.3402</td>
<td>13.7922</td>
</tr>
<tr>
<td>P₁₃</td>
<td>MW</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12.5602</td>
</tr>
<tr>
<td>V₁</td>
<td>p.u.</td>
<td>1.057</td>
<td>1.1</td>
<td>1.1</td>
<td>1.097</td>
</tr>
<tr>
<td>V₂</td>
<td>p.u.</td>
<td>1.0456</td>
<td>0.9</td>
<td>1.057</td>
<td>1.086</td>
</tr>
<tr>
<td>V₅</td>
<td>p.u.</td>
<td>1.0184</td>
<td>0.9642</td>
<td>1.067</td>
<td>1.058</td>
</tr>
<tr>
<td>V₈</td>
<td>p.u.</td>
<td>1.0265</td>
<td>0.9887</td>
<td>1.07</td>
<td>1.069</td>
</tr>
<tr>
<td>V₁₁</td>
<td>p.u.</td>
<td>1.057</td>
<td>0.9403</td>
<td>1.02523</td>
<td>0.97</td>
</tr>
<tr>
<td>V₁₃</td>
<td>p.u.</td>
<td>1.057</td>
<td>0.9284</td>
<td>1.09248</td>
<td>1.099</td>
</tr>
<tr>
<td>T₆₋₉</td>
<td>p.u.</td>
<td>1.0254</td>
<td>0.9848</td>
<td>1.04532</td>
<td>1.02</td>
</tr>
<tr>
<td>T₆₋₁₀</td>
<td>p.u.</td>
<td>0.9726</td>
<td>1.0299</td>
<td>0.98004</td>
<td>0.945</td>
</tr>
<tr>
<td>T₄₋₁₂</td>
<td>p.u.</td>
<td>1.006</td>
<td>0.9794</td>
<td>1.09611</td>
<td>1.0086</td>
</tr>
<tr>
<td>T₂₈₋₂₇</td>
<td>p.u.</td>
<td>0.9644</td>
<td>1.0406</td>
<td>10.2131</td>
<td>0.97887</td>
</tr>
<tr>
<td>QC₁₀</td>
<td>p.u.</td>
<td>25.3591</td>
<td>9.0931</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>QC₂₄</td>
<td>p.u.</td>
<td>10.6424</td>
<td>21.665</td>
<td>29.6709</td>
<td>6.8638</td>
</tr>
<tr>
<td>fuel cost</td>
<td>$/h</td>
<td>802.034</td>
<td>803.454</td>
<td>800.996</td>
<td>799.86</td>
</tr>
<tr>
<td>Emission</td>
<td>ton/h</td>
<td>0.365688</td>
<td>0.3701</td>
<td>NA</td>
<td>0.25822</td>
</tr>
<tr>
<td>Power loss</td>
<td>MW</td>
<td>9.466955</td>
<td>9.9403</td>
<td>NA</td>
<td>8.78778</td>
</tr>
</tbody>
</table>

Source: Balasubba (2017)

nut tree will be the optimal value of considered objective function.
Table 4. OPF result for minimizing emission ton/h.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>HCSA (18)</th>
<th>PSO</th>
<th>HFSSA</th>
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</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>MW</td>
<td>63.7401</td>
<td>64.326</td>
<td>67.6486</td>
</tr>
<tr>
<td>$P_2$</td>
<td>MW</td>
<td>68.2844</td>
<td>67.7681</td>
<td>70.6352</td>
</tr>
<tr>
<td>$P_3$</td>
<td>MW</td>
<td>50</td>
<td>50</td>
<td>40.94208</td>
</tr>
<tr>
<td>$P_6$</td>
<td>MW</td>
<td>35</td>
<td>35</td>
<td>25.37218</td>
</tr>
<tr>
<td>$P_{11}$</td>
<td>MW</td>
<td>30</td>
<td>30</td>
<td>21.42841</td>
</tr>
<tr>
<td>$P_{13}$</td>
<td>MW</td>
<td>40</td>
<td>40</td>
<td>35.71543</td>
</tr>
<tr>
<td>$V_1$</td>
<td>p.u.</td>
<td>1.0563</td>
<td>1.06</td>
<td>1.05276</td>
</tr>
<tr>
<td>$V_2$</td>
<td>p.u.</td>
<td>1.0082</td>
<td>1.0448</td>
<td>0.98645</td>
</tr>
<tr>
<td>$V_5$</td>
<td>p.u.</td>
<td>1.0354</td>
<td>1.0062</td>
<td>1.02549</td>
</tr>
<tr>
<td>$V_8$</td>
<td>p.u.</td>
<td>1.0393</td>
<td>1.0086</td>
<td>1.03141</td>
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<td>$V_{11}$</td>
<td>p.u.</td>
<td>1.057</td>
<td>1.0819</td>
<td>0.95834</td>
</tr>
<tr>
<td>$V_{13}$</td>
<td>p.u.</td>
<td>1.0377</td>
<td>1.07079</td>
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<tr>
<td>$T_{6-9}$</td>
<td>p.u.</td>
<td>1.0197</td>
<td>0.9875</td>
<td>0.97565</td>
</tr>
<tr>
<td>$T_{6-10}$</td>
<td>p.u.</td>
<td>0.9594</td>
<td>0.9596</td>
<td>0.98752</td>
</tr>
<tr>
<td>$T_{4-12}$</td>
<td>p.u.</td>
<td>0.9196</td>
<td>0.93</td>
<td>0.93584</td>
</tr>
<tr>
<td>$T_{28-27}$</td>
<td>p.u.</td>
<td>0.9796</td>
<td>0.9699</td>
<td>0.98798</td>
</tr>
<tr>
<td>$Q_{c10}$</td>
<td>p.u.</td>
<td>22.7301</td>
<td>25</td>
<td>24.5614</td>
</tr>
<tr>
<td>$Q_{c24}$</td>
<td>p.u.</td>
<td>24.5998</td>
<td>21.985</td>
<td>17.654</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$$/h$</td>
<td>946.5282</td>
<td>945.849241</td>
<td>890.455</td>
</tr>
<tr>
<td>Emission</td>
<td>ton/h</td>
<td>0.2048</td>
<td>0.20563812</td>
<td>0.20374</td>
</tr>
<tr>
<td>Power loss</td>
<td>MW</td>
<td>3.6245</td>
<td>3.6943449</td>
<td>3.5366</td>
</tr>
</tbody>
</table>

Source: Balasubba (2017)

Figure 4. Convergence curve of generation fuel cost.  
Source: Balasubba (2016)

RESULTS AND ANALYSIS

Validation of proposed algorithm on benchmark test functions

Two standard test functions were considered to justify the effectiveness of the proposed algorithm, which is mentioned below:

1. Himmelblau’s function

$$f(x, y) = (x^2 + y - 11)^2 + (x + y^2 - 7)^2$$
2. Booth’s function \( f(x, y) = (x + 2y - 7)^2 + (2x + y - 5)^2 \)

It can be seen from Tables 1 and 2, that the proposed algorithm optimizes the function more efficiently as compared to the other methods available. Booth’s function achieves its minimum value that is, 0.0, which is the desired output with best minima and for Himmelblau’s function least value i.e. 2.8075e-10 is obtained which is less as compare to the existing methods. The convergence curves are shown in Figures 2 and 3 for both function from which, it can be seen that proposed algorithm converges at lesser number of iterations and initially it starts will less value of function as compared to the existing algorithm. Thus, this validates the robustness and efficiency of the proposed HFSS algorithm.

Electric IEEE-30 bus system

The IEEE 30 bus system is considered to test the proposed HFSA algorithm. In this system total 6 generators and 4 tap changing transformers and 2 shunt capacitors are available. To optimize considered objective functions proposed method runs 100 iterations.

Minimization of generation fuel cost

The considered control variables are optimized for IEEE-30 bus system is shown in Table 3. It could be seen from Table. 3 and Figure 4, that the generation cost obtained by proposed algorithm is 799.86 $/h which is lower than the generation cost obtained by existing algorithms. It could be analyzed from Figure 4 that proposed algorithm converges at 22nd iteration by which it is proven that its convergence is very fast as compared to other algorithms and least value starts early.

Minimization of emission

Minimization of emission is second objective function. The considered control variables are optimized for IEEE-30 bus system is shown in Table 4. It could be observed from Table 4 and Figure 5, that emissions got minimized to 0.20374 ton/h which is less in comparison to the emissions obtained by existing algorithms. It can also be observe from Figure 5 that convergence curve starts will less value of emission and converge at 18th iteration which is the best result in comparison to the existing observations.

Minimization of transmission losses

Minimization of transmission loss is third objective function. The considered control variables are optimized for IEEE-30 bus system is shown in Table 5. It could be observed from Table 5 and Figure 6, that the transmission loss minimized to 3.167MW which is the best result obtained with the implementation of proposed algorithm. This also converges fast as compared to other algorithms.

Observation can be made from Tables 3-5 that when generation fuel cost is to minimize then power generated
Table 5. OPF result for minimizing transmission loss

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>HCSA (Balasub (2017))</th>
<th>HFFA (et al (2022))</th>
<th>PSO</th>
<th>HFSSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>MW</td>
<td>51.608</td>
<td>64.5787</td>
<td>98.3715</td>
<td>68.6275</td>
</tr>
<tr>
<td>$P_2$</td>
<td>MW</td>
<td>80</td>
<td>73.1716</td>
<td>80</td>
<td>65.2697</td>
</tr>
<tr>
<td>$P_3$</td>
<td>MW</td>
<td>50</td>
<td>49.1044</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$P_4$</td>
<td>MW</td>
<td>35</td>
<td>34.6496</td>
<td>20</td>
<td>28.566</td>
</tr>
<tr>
<td>$P_{11}$</td>
<td>MW</td>
<td>30</td>
<td>29.3441</td>
<td>20</td>
<td>30.2568</td>
</tr>
<tr>
<td>$P_{13}$</td>
<td>MW</td>
<td>40</td>
<td>36.3133</td>
<td>20</td>
<td>39.693</td>
</tr>
<tr>
<td>$V_1$</td>
<td>p.u.</td>
<td>1.057</td>
<td>1.035</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>$V_2$</td>
<td>p.u.</td>
<td>1.0562</td>
<td>1.0295</td>
<td>1.07135</td>
<td>1.0858</td>
</tr>
<tr>
<td>$V_5$</td>
<td>p.u.</td>
<td>1.0383</td>
<td>1.0297</td>
<td>1.06827</td>
<td>1.1</td>
</tr>
<tr>
<td>$V_8$</td>
<td>p.u.</td>
<td>1.0461</td>
<td>1.0217</td>
<td>1.0735</td>
<td>0.9897</td>
</tr>
<tr>
<td>$V_{11}$</td>
<td>p.u.</td>
<td>1.057</td>
<td>1.0249</td>
<td>0.95708</td>
<td>0.9658</td>
</tr>
<tr>
<td>$V_{13}$</td>
<td>p.u.</td>
<td>1.057</td>
<td>1.0293</td>
<td>1.03229</td>
<td>0.9365</td>
</tr>
<tr>
<td>$T_{6-9}$</td>
<td>p.u.</td>
<td>1.0134</td>
<td>1.0648</td>
<td>1</td>
<td>1.0985</td>
</tr>
<tr>
<td>$T_{6-10}$</td>
<td>p.u.</td>
<td>0.9629</td>
<td>0.9786</td>
<td>1.08182</td>
<td>0.9685</td>
</tr>
<tr>
<td>$T_{4-12}$</td>
<td>p.u.</td>
<td>0.9802</td>
<td>0.981</td>
<td>1.1</td>
<td>0.9796</td>
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<tr>
<td>$T_{28-27}$</td>
<td>p.u.</td>
<td>0.9654</td>
<td>0.9597</td>
<td>1.03477</td>
<td>0.9342</td>
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<tr>
<td>$Qc_{10}$</td>
<td>p.u.</td>
<td>21.4206</td>
<td>13.1375</td>
<td>20.5299</td>
<td></td>
</tr>
<tr>
<td>$Qc_{24}$</td>
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<td>16.5347</td>
<td>17.1374</td>
<td>24.0383</td>
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<tr>
<td>fuel cost</td>
<td>$/h</td>
<td>967.9202</td>
<td>940.44</td>
<td>899.618</td>
<td>920.552</td>
</tr>
<tr>
<td>Emission</td>
<td>ton/h</td>
<td>0.2072</td>
<td>NA</td>
<td>0.23835</td>
<td>0.2063</td>
</tr>
<tr>
<td>Power loss</td>
<td>MW</td>
<td>3.208</td>
<td>3.718</td>
<td>4.97153</td>
<td>3.1687</td>
</tr>
</tbody>
</table>

Source: Balasubba et al (2022)

Figure 6. Convergence curve of transmission loss.
Source: Balasubba (2016)

from slack bus is maximum and power generated for second PV bus is minimum while the minimization of transmission loss and emission power generated from slack bus is minimum and power generated at second PV
bus in maximum.

Conclusion
A novel algorithm was proposed by hybridizing SSA and arithmetic crossover operation; proposed named as HFSSA.

The proposed algorithm is validated on benchmark test function that is, Himmelblau’s and Booth’s functions followed by IEEE-30 bus system, and it has been observed that with the crossover operation the algorithm converges very fast and effectively. It has been observed that the proposed method minimizes the considered objective functions optimally when compared to resent literature. The single objectives of OPF such as generation fuel cost, emission and power losses are optimized to the best value. Thus, the proposed method is superior to the other methods. In future work we extend this work to be implemented to the larger and real power system, so to validate it in more critical and complex situations.

CONFLICT OF INTERESTS
The authors have not declared any conflict of interests.

REFERENCES