Optimal Power Flow Solution for multi-fuel system using Tree Growth Algorithm

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Abstract

This paper presents a reliable approach to solve the optimal power flow (OPF) problem. The proposed approach employs Tree Growth Algorithm (TGA) for optimal settings of OPF problem control variables. TGA is being inspired by the competitive nature of trees for acquiring food and light. The proposed approach has been examined and tested on the standard IEEE 30-bus test system by minimizing generation fuel cost and results are compared with reported literature. Then, multi-fuels are provided as input to generating station which further minimizes the generation fuel cost and emission to the better values as compared to the single fuel as input. The results are promising and show the effectiveness and robustness of the proposed approach.

Keywords: *Tree Growth Algorithm (TGA), multi-fuel generation fuel cost, multi-fuel emission, Optimal Power Flow*

1. Introduction

Optimal power flow (OPF) plays a vital role for effective and economical operation of power system. OPF deals to control variables including generators real output power and voltages, transformer tap setting, phase shifters, switched capacitors optimizing the objectives like generation fuel cost and emission. Minimization of these objectives helps in managing the economics and protect environment from the pollution caused by the power plants.

Another alternative for reducing pollution is by reducing consumption of coal as input fuel because generation cost and emission caused by coal-fired thermal stations is very high, thus the use of multi-fuel is a better solution which helps to minimize the dependency over the coal and consequently helps in minimizing the generation cost and emission more efficiently.

Recently, many meta-heuristics algorithms have been developed by researchers which can efficiently solve the economic dispatch problem with proper handling the non-linear, constraint bounded functions as compared to the classical approaches[1]-[3] which are used in last decade. These heuristic algorithms including Genetic Algorithm (GA) [4], Evolutionary Programming (EP) [5], Biogeography Based Optimization (BBO) [6], Moth Flame Optimization (MFO) [7], Criss-Cross Algorithm (CCA) [8], Fruit Fly Algorithm (FFA) [9], Ant Colony Optimization (ACO) [10], Ant Lion Optimization (ALO) algorithm [11], and many more had proven their robustness in solving the economic load dispatch problems.

Similarly, a recently developed algorithm named as Tree Growth Algorithm (TGA) has been considered which yields for global optimization. Basically, TGA is being inspired by the competitive nature of trees for acquiring food and light. As it is already proven in Ref. [12] that, TGA efficiently gives global best solution in less computation time for the considered benchmark functions. Thus, this paper proposes the implementation of TGA for solving the optimal power problem of standard IEEE-30 bus system. Obtained results validate the performance of considered algorithm in comparison to the other algorithms. After that multi-fuel will be provided as input to generating station and OPF problem will be solved to prove that multi-fuel optimizes the problem more efficiently as compared to the single fuel system.

2. Problem Formulation

Optimization Problem deals to solve the steady state problem of electric power systems through minimizing the objective functions with the consideration of constraints simultaneously. Mathematically OPF is represented by:

Min $F_a(x,y) \qquad \forall a = 1,2,.......p$

Subject to: $k(x,y) = 0$,

$l(x,y) \leq 0$

where, ‘k’ and ‘l’ are the equality and inequality constraints respectively, ‘x’ is the state vector of dependent variables and ‘y’ is the control vector of system and p is the total number of objectives functions.

The state vector may be represented by:

$$x^T = [P_{G,1}, V_{l,1} .... V_{l,NL}, Q_{G,1} .... Q_{G,NG}, S_{l,1} .... S_{l,NT}]$$

The control vector may be represented by:

$$y^T = [P_{G,2} ..... P_{G,NB}, V_{G,1} .... V_{G,NB}, Q_{SH,1} .... Q_{SH,NC}, T_1 .... T_T]$$

where $P_{G,1}$ is the real power, $V_{l,1}$ is the load bus voltage, , $Q_{G,1}$ is the reactive power of generator, $S_{l,1}$ is the apparent power of generator $V_{G,1}$ is the generator voltage of slack bus. NL, NG, NT, NC and T are the total number of PQ buses, PV buses, transmission lines, shunt compensators and off-nominal tap transformers respectively.

2.1. Objective Functions

In this paper, objective functions including generation fuel cost and emission are minimized considering single and multi-fuel as input, which are mathematically expressed below:

a. Generation fuel cost (for single fuel system)-

$$F_1 = min(F_p(P_{g,m})) = \sum_{m=1}^{NGB} x_m P_{g,m}^2 + y_m P_{g,m} + z_m \$/h \qquad (1)$$

where, x_m, y_m and z_m are the fuel cost coefficients of m^{th} unit.

b. Generation fuel cost (for multi-fuel system)-

Usually, a generating station possesses different types of fuel including coal, fossil fuel, oil and gas for generation. Thus, the multi-fuel cost function can be formulated as:

$$F_2 = \left(\sum_{i=1}^{2} F_i(P_i) \right) + \left(\sum_{i=3}^{NG} F_i(P_i) \right) \qquad (2)$$

$$F_i(P_i) = \begin{cases} a_{i1}P_i^2 + b_{i1}P_i + c_{i1} + \left| e_{i1} \times \sin\left(f_{i1} \times \left(P_i^{\min} - P_i \right) \right) \right| & ; \; P_i^{\min} \le P_i \le P_i^1 \\ a_{i2}P_i^2 + b_{i2}P_i + c_{i2} + \left| e_{i2} \times \sin\left(f_{i2} \times \left(P_i^{\min} - P_i \right) \right) \right| & ; \; P_i^1 \le P_i \le P_i^2 \\ \ldots & \\ a_{ik}P_i^2 + b_{ik}P_i + c_{ik} + \left| e_{ik} \times \sin\left(f_{ik} \times \left(P_i^{\min} - P_i \right) \right) \right| & ; \; P_i^{k-1} \le P_i \le P_i^{\max} \end{cases}$$

where $a_{ik}, b_{ik}, c_{ik}, e_{ik}, f_{ik}$ are the fuel cost-coefficients of the i^{th} unit with valve-point effects for fuel type k.

c. Emission (for single fuel system)-

$$F_2 = min(E(P_{g,m})) = \sum_{m=1}^{NGB} \alpha_m + \beta_m P_{g,m} + \gamma_m P_{g,m}^2 + \xi_m \, exp(\lambda_m P_{g,m}) \, ton/h \qquad (3)$$

where, α_m, β_m, γ_m, λ_m and ξ_m are the emission coefficients of m^{th} unit.

d. Emission (for multi-fuel system)-

The emission for multi-fuel generating units can be defined as

$$F_4 = \left(\sum_{i=1}^{2} E_i(P_i) \right) + \left(\sum_{i=3}^{N_G} E_i(P_i) \right) \qquad (4)$$

$$E_i(P_i) = \begin{cases} \alpha_{i1} + \beta_{i1}P_{G_i} + \gamma_{i1}P_{G_i}^2 + \xi_{i1} \exp^{\left(\lambda_{i1} P_{G_i} \right)} & ; \; P_i^{\min} \le P_i \le P_i^1 \\ \alpha_{i2} + \beta_{i2}P_{G_i} + \gamma_{i2}P_{G_i}^2 + \xi_{i2} \exp^{\left(\lambda_{i2} P_{G_i} \right)} & ; \; P_i^1 \le P_i \le P_i^2 \\ \ldots & \\ \alpha_{ik} + \beta_{ik}P_{G_i} + \gamma_{ik}P_{G_i}^2 + \xi_{ik} \exp^{\left(\lambda_{ik} P_{G_i} \right)} & ; \; P_i^{k-1} \le P_i \le P_i^{\max} \end{cases}$$

where $\alpha_{ik}, \beta_{ik}, \gamma_{ik}, \xi_{ik}$ and λ_{ik} are emission coefficients of the i^{th} generator for fuel type k.

2.2. Constraints

The equality and in-equality constraints are as follows:

a. Equality constraints

$$\sum_{m=1}^{NGB} P_{G,m} - P_D - P_L = 0 \;, \quad \sum_{m=1}^{NGB} Q_{G,m} - Q_D - Q_L = 0$$

b. Inequality Constraints

(i). Generator constraints

$$V_{G,m}^{min} \le V_{G,m} \le V_{G,m}^{max} \text{ and}$$

$$Q_{G,m}^{min} \le Q_{G,m} \le Q_{G,m}^{max} \qquad \forall m \in NG$$

(ii). Voltage at bus and discrete transformer tap settings

$$V_{G,m}^{min} \le V_{G,m} \le V_{G,m}^{max} \text{ and}$$

$$T_m^{min} \le T_m \le T_m^{max} \qquad \forall m \in T$$

(iii). Active power generation limits

$$P_{G,m}^{min} \le P_{G,m} \le P_{G,m}^{max} \qquad \forall m \in NG$$

(iv). Reactive power supply by the capacitor banks

$$Q_{SH,m}^{min} \le Q_{SH,m} \le Q_{SH,m}^{max} \qquad \forall m \in NC$$

(v). Transmission line loadings

$$S_{l,m} \le S_{l,m}^{max} \qquad \forall m \in NT$$

3. Tree Growth Algorithm (TGA)

Basically, TGA is inspired by the competitive behavior of trees for acquiring maximum light and food as shown in Figure 1. This algorithm has four main groups which include:

- **Best tree group** **(** N_1 **)** - Those trees which are getting optimal amount of light and competing for food. They are tall, smooth and old trees which are competing for food in roots only.
- **Competitions for light group** **(** N_2 **) -** Those trees which reach the light and move towards the close best trees under different angles.
- **Remove and replace group** **(** N_3 **) -** Those trees which do not have growth and are cut by foresters and replaced with new trees**.**
- **Reproduction group** **(** N_4 **) -** These are the best trees as growth rate is fast and they easily multiply and create new plants. As the mother tree inherit some of the factors from that location.

Figure 1. Tree's competition for light

The algorithm is detailed below:

1. Initialize the parameters of the proposed algorithm such as maximum number of iterations, dimensions, population of trees (number of search agents), lower and upper bounds.
2. Randomly generate the initial population of trees and calculate their fitness.
3. Identify the global best tree, T_{GB}^{j} .
4. N_1 (Best trees) compete over food and reduce their growth rate due to aging. Check several local searches for N_1 (best tree group) better solutions using Eq. (5) and if new solution is better than replace the initial values.

   $$T_i^{j+1} = \frac{T_i^j}{\theta} + rT_i^j \qquad (5)$$

   where, θ is the reduction rate of trees, r is a uniformly distributed random number which lies between $[0,1]$.

5. Now, N_2 (goodish trees) will compete over light. So, move N_2 solutions to distance between close best solutions with different α angles. For tis, initially find the distance between the selected trees and remaining trees using Eq. (6)

$$d_i = \left(\sum_{i=1}^{N_1+N_2} \left(T_{N_2}^{j} - T_i^{j} \right)^2 \right)^{1/2} \quad \& \quad d_i = \begin{cases} d_i & \text{if} \quad T_{N_2}^{j} \neq T_i^{j} \\ 0 & \quad\;\; T_{N_2}^{j} = T_i^{j} \end{cases} \tag{6}$$

   Then choose two solutions x_1 and x_2 with minimal distance and to achieve a linear combination between the trees using Eq. (7).

$$y = \lambda x_1 + (1-\lambda) x_2 \tag{7}$$

   where, λ is a uniformly distributed random number which lies between [0,1].

6. Finally, top move the adjacent trees with an α_i=U(0,1) angles using Eq. (8).

$$T_{N_2}^{j} = T_{N_2}^{j} + \alpha_i y$$

7. Then remove the worse solutions N_3 (poor trees) and use randomly generated solutions.
8. Create new population N, (N= N_1 $N_2 + N_3$)
9. Generate N_4 (reproducing trees) and randomly change new solutions by mask operator with respect to best solution from N_1 and add it to the new population (new population= new population+ N_4).
10. Sort the new population and consider it as initial population for the next iteration.
11. Repeat from step 3 till then stopping criteria is not satisfied.

4. Results and Analysis

In Ref. [12], TGA is being implemented on benchmark test functions and it can be seen that it provides better quality of results. It is also being observed that TGA is simple to code and searches the best optimal solution. Thus, considering these observation initially TGA is validated by solving the OPF problem for IEEE-30 bus system and results are compared with other existing algorithms. Then, TGA solves the OPF problems for the system possessing multi-fuels as input to generating stations and results are being compared with single fuel.

Generally, this system consists of 6 generators which are located on the buses 1, 2, 5, 8, 11 and 13, four tap changing transformers installed between the buses 6-9, 6-10, 4-12 and 27-28 and two shunt capacitors installed at buses 10 and 24. Relevant data is taken from Ref. [13].

4.1. Illustrative example

For validating the performance of considered TGA in solving OPF problem, generation fuel cost is minimized. The set of optimal solutions obtained for the control variables of IEEE 30- Bus system is tabulated in **Table 1.** It can be clearly observed that generation fuel cost is optimized to a better solution i.e. 800.1839 $/h by using TGA as compared to other existing algorithms. Comparison of convergence characteristic of different algorithms is shown in **Figure 2** and it can be observed that TGA converges very fast as compared to other algorithms and initially it starts with the least value of generation fuel cost.

Table 1. Optimal power flow result for minimization of generation fuel cost $/h

Variables	**PSO [14]**	**CCA[15]**	**HCSA [14]**	**HFFA [16]**	**TGA**
PG1, MW	178.556	173.6794	176.87	179.3122	176.8495
PG2, MW	48.6032	44.4255	49.8862	48.26495	48.33307
PG5, MW	21.6697	22.9575	21.6135	20.9265	21.23229
PG8, MW	20.7414	25.9530	20.8796	19.86292	21.88727
PG11, MW	11.7702	13.2210	11.6168	23.3402	11.99989
PG13, MW	12	12.0000	12	12	12
VG1, p.u.	1.1	1.1000	1.057	1.1	1.1
VG2, p.u.	0.9	1.0499	1.0456	1.057	1.013888
VG5, p.u.	0.9642	1.0877	1.0184	1.067	1.059522
VG8, p.u.	0.9887	1.0985	1.0265	1.07	1.066581
VG11, p.u.	0.9403	1.1000	1.057	1.025229	1.047513
VG13, p.u.	0.9284	1.1000	1.057	1.092478	1.097091
Tap 6-9, p.u.	0.9848	1.0323	1.0254	1.045322	1.048118
Tap 6-10, p.u.	1.0299	1.0151	0.9726	0.980038	1.037124
Tap 4-12, p.u.	0.9794	0.9793	1.006	1.096105	1.051245
Tap 28-27, p.u.	1.0406	1.0588	0.9644	10.2131	1.001151
Qc 10, p.u.	9.0931	30.0000	25.3591	5	25.27941
Qc 24, p.u.	21.665	5.4662	10.6424	29.67086	17.1447
Generation fuel cost $/h	**803.454**	**802.2545**	**802.034**	**800.9964**	**800.1839**

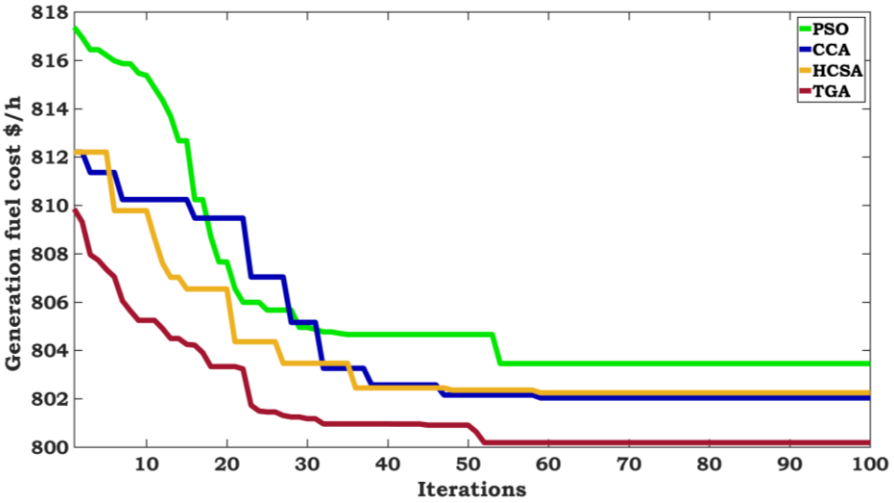

Figure 2. Convergence curve of generation fuel cost, $/h

4.2. Minimization of generation fuel cost

In this section, generation fuel cost has been minimized for the IEEE-30 bus system with considering system with single fuel as well as multi-fuels, for analyzing the performance using TGA. The formulated objective functions for generation fuel cost for single fuel and multi-fuels are given by Eq. (1) and (2) respectively. When TGA is implemented, it can be seen from **Table 2** that generation station with multi-fuels will have generation fuel cost optimized to 652.548 $/h which is less than the cost obtained using a single fuel. Thus, we can say that generating station with multiple fuels helps in minimizing the fuel cost as well as helps in maintaining the continuity in generation of electrical power.

Table 2. Comparison of OPF solution of generation fuel cost function

Variables	Generation fuel cost, $/h	
	Single fuel input	Multi-fuel input
PG1, MW	176.8495	139.8628
PG2, MW	48.33307	54.84361
PG5, MW	21.23229	25.11085
PG8, MW	21.88727	26.28021
PG11, MW	11.99989	21.32455
PG13, MW	12	23.4917
VG1, p.u.	1.1	1.052995
VG2, p.u.	1.013888	0.996811
VG5, p.u.	1.059522	0.989478
VG8, p.u.	1.066581	1.010949
VG11, p.u.	1.047513	1.030321
VG13, p.u.	1.097091	1.029622
Tap 6-9, p.u.	1.048118	0.979911
Tap 6-10, p.u.	1.037124	0.946277
Tap 4-12, p.u.	1.051245	0.996882
Tap 28-27, p.u.	1.001151	0.957243
Qc 10, p.u.	25.27941	23.57578
Qc 24, p.u.	17.1447	10.38865

Generation fuel cost, $/h	**800.1839**	**652.5482**
Emission, ton/h	0.365393	0.22945

4.3. Minimization of emission

Now, emission has been minimized for the IEEE-30 bus system with considering system with single fuel as well as multi-fuels. The formulated objective functions for emission for single fuel and multi-fuels are given by Eq. (3) and (4) respectively. When TGA is implemented, it can be seen from **Table 3** that system with multi-fuels emission obtained is 0.1862 ton/h which is less than the emission obtained using a single fuel. Thus, we can say that generating station with multiple fuels helps in minimizing the emission which will help in making generation environment friendly.

Table 3. Comparison of formulated multi-fuel emission function

Variables	**Emission, ton/h**	
	Single fuel input	**Multi-fuel input**
PG1, MW	64.11094	77.36542
PG2, MW	67.85469	54.97139
PG5, MW	50	50
PG8, MW	35	35
PG11, MW	30	30
PG13, MW	40	40
VG1, p.u.	1.1	1.062192
VG2, p.u.	0.993914	1.029647
VG5, p.u.	1.062597	1.024648
VG8, p.u.	1.092725	1.028026
VG11, p.u.	0.921526	1.006663
VG13, p.u.	0.905674	0.988792
Tap 6-9, p.u.	0.956305	0.995677
Tap 6-10, p.u.	1.075433	1.042148
Tap 4-12, p.u.	0.970284	0.996908
Tap 28-27, p.u.	1.008473	1.013052
Qc 10, p.u.	20.55576	28.51182
Qc 24, p.u.	24.72756	17.02492
Generation fuel cost, $/h	956.652	828.5697
Emission (ton/h)	**0.204798**	**0.186218**

5. Conclusion

In this paper, a novel algorithm is implemented for solving the optimal power flow problem named as Tree Growth Algorithm (TGA) which is being developed by considering the competition among trees for acquiring the food and light. It was already known that TGA gives better quality of solutions, so it has been used to solve OPF problem and it has been observed that generation fuel cost minimized to a better solution as compared to the values obtained using other reported algorithm.

Then TGA is used to optimize the generation fuel cost and emission for the IEEE-30 bus system possessing multi-fuels as input to generating station and it has been observed that it yields to the better solutions as compared to the single fuel as input. TGA also results in better convergence and attain optimal values in less number of iteration. Thus, this proves the effectiveness and robustness of proposed algorithm for multi-fuel system.

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