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Adaptive FPA Algorithm based OPF with Unified Power Flow Controller

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Abstract

In this work a novel modified flower pollination algorithm has been developed to solve the problem of single and multi-objective Optimal Power Flow operations for Unified power Flow Controller in Flexible Alternating Current Transmission Systems. In the proposed Adaptive Flower Pollination Algorithm the best initial solution can be chosen from the fittest and also the weights are adaptively adjusted to get better convergence characteristics. The nature of the objective functions is non-linear and difficult to get best possible solutions within the boundary conditions of total power demand. The weak nodes are determined in the system to locate the UPFC with Fuzzy approach considering input parameters as L-Index and voltage magnitudes. The projected method is validated using IEEE-30 and IEEE-57 bus systems for three objective functions, namely, system real power loss minimization, fuel cost minimization and the combination of total generating cost and system real power loss. Results of Fuzzy- Adaptive Flower Pollination Algorithm based OPF optimization for UPFC produced optimum results for the considered objectives of total fuel cost, real power loss and for the multiobjective.

Keywords: OPF, Adaptive FPA, Fuzzy, FACTS, UPFC

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1. Introduction

The power system is a largest man made system due to its wide geological coverage, a diversity of transactions among different utilities, and diversity in the layouts of electric power industries, size and the connected equipments. There is a necessity of advanced methods to optimally investigate, monitor and manage an assortment of aspects of such complicated system that take account of Unit Commitment (UC), Automatic Generation Control (AGC), state estimation, Economic Dispatch (ED) and Optimal Power Flow (OPF). The OPF is treated as the spinal column technique which was expansively researched since 1962 [1].

OPF is a static nonlinear problem that optimizes an objective function which suits a set of operational and physical constraints forced by apparatus restrictions as well as security needs. Numerous successful OPF techniques [2–4] have been projected to yield a best OPF solution.

Evolutionary algorithms with multiple objectives [5-6] have been examined to work out different OPF problems to defeat the shortfalls of orthodox methods. Diversified hybrid techniques were developed called hybrid EP with tabu search [7], firefly and particle swarm optimization [8] enroot for steadfastness ED problem for valve point fuel cost functions.

For the past twenty years, the ever-increasing developments in computational astuteness tools have been providing best solutions in the area of metaheuristics optimization techniques. Some of them are: Artificial Bee and Ant Colony and Bacterial Foraging algorithms [9-11], Cuckoo Search [12], Tabu Search [13], Harmony Search Algorithm [14], Black Hole Based Optimization [15], Improved GA [16-17] etc.

Flower Pollination Algorithm (FPA), is one of the latest optimization algorithms that intended to provide solutions for individual and combined objective optimization problems [18-20] introduced by X. S. Yang in the year 2012. This natural world inspired technique is developed from the distinctiveness of flowering plants with fascinating characteristics that lend a hand to travel around the viable groom in the neighbourhood and globally. In the recent times, it has gained increased attention to solve the OPF problem [21-22] to discover the most select settings of the controllable variables [23].

In the past three decades several research articles were published on OPF solution with FACTS devices. A decomposition scheme developed by Taranto et al. [24] to get to the bottom of OPF solution in the presence of FACTS. [25] Presented the FACTS modeling in OPF solution and discussed the task of that modeling. [26] published the OPF technique by placing the FACTS using Newton's method that led to an exceedingly dynamic solution. However, it has been identified that the solutions of OPF becomes a non-convex solution with series compensation that results, the traditional methods may struck at local optimum. To assuage the afore said complicatedness many advanced techniques have been projected by many researchers viz., [27] proposed with MDE, Hybrid DA-PSO in [28] to solve OPF problem by incorporating FACTS.

The main intention of this article is to put forward an Adaptive Flower Pollination Algorithm (AFPA) with UPFC for single and Multi-objective optimization problems. The modifications proposed in the Flower pollination algorithm to obtain AFPA are given in section-4. Here weak nodes are identified through fuzzy to identify the best location of UPFC. The three considered single and multi objectives are optimized using AFPA algorithm by controlling the shunt compensators, tap settings of the transformers along with UPFC series and shunt controllers. The L-Index is a voltage stability index is also considered as one of the constraints along with equality and inequality constraints to maintain the stability of the system while optimizing the considered objectives. The step by step procedure is represented in the block diagram given in Figure 1.

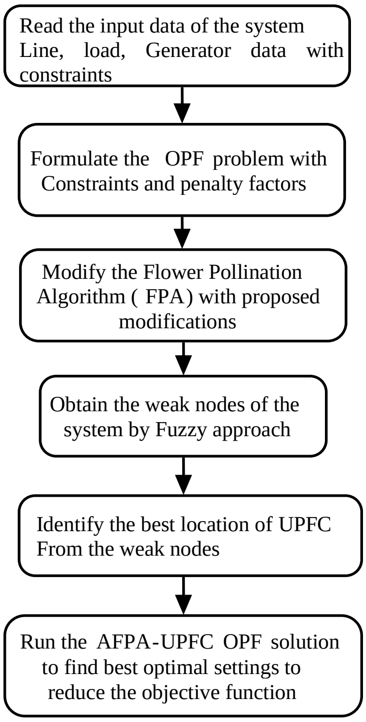

Figure 1. Proposed AFPA block diagram

2. Fuzzy Approach To Find Weak Nodes

The proposed fuzzy approach uses L-index bus voltage profiles to identify the weak nodes in the system.

2.1 L-index

A transmission system chosen with 'n' buses consists of 'g' generator buses, 'n-g' P-Q buses. L-Index [29] of the network is given by:

$$L_k = \left| 1 - \sum_{i=1}^{g} F_{ki} \frac{v_i}{v_k} \right| \tag{1}$$

Where, k = g +1,....,n. The F_{ki} values of Y-bus matrix are complex in nature.

$$\text{i.e. } F_{LG} = \left[Y_{LL}\right]^{-1}\left[Y_{LG}\right]^{-1} \tag{2}$$

where,[Y_{LG}] and [Y_{LL}] are the sub parts of Y-bus. For the system to be stable, at any P-Q bus k the maximum value of L_k should be 1 [29].

The bus voltage profile and L-index values are expressed in fuzzy set notation. The severity index of each bus as an output are also divided into different categories. The fuzzy rules are used to evaluate the severity of each bus in the system.

2.2. Bus voltage profiles

The bus voltage profiles are divided into three categories using fuzzy-set notations: low voltage (LV), below 0.95 p.u.; normal voltage (NV), 0.95-1.05 p.u.; and over voltage (OV), above 1.05 p.u.

2.3. Voltage stability Index

The L-indices are divided into five categories using fuzzy set notation; very small (VS),0-0.1; small (S), 0.1-0.3; medium (M), 0.3-0.6; high (H), 0.6-0.8; very high (VH) 0.8-0.9.

The output membership functions to evaluate the severity of a week nodes are divided into five categories using fuzzy set notations: Very Less Severe (VLS), Less Severe (LS), Below Severe (BS), Above Severe (AS) and More Severe (MS).

Table 1. Decision matrix to find weak nodes of the system

AND		VOLTAGE STABILITY INDEX				
		VLI	LI	MI	HI	VHI
VOLTAGE (p.u)	LV	LS	LS	S	HS	MS
	NV	VLS	LS	LS	S	HS
	HV	LS	S	HS	MS	MS

The severity index of each bus in the system is found using the formula

$$SI = SI_{VP} + SI_{VSI} \tag{3}$$

Where, SI_{VP} and SI_{VSI} are the severity indexes of post-contingent voltage profile and voltage stability indexes, respectively.

3. Modeling of UPFC

UPFC is one of the sophisticated device from FACTS, can offer instant control of real, reactive power and voltage. The power injection model of the UPFC with two harmonized synchronous voltage sources shown in Figure 2.The voltage sources of UPFC are:

$$\overrightarrow{V_{sh}} = \overrightarrow{V_{sh}}\left(\cos\delta_{sh} + j\sin\delta_{sh}\right) \tag{4}$$

$$\overrightarrow{V_{se}} = \overrightarrow{V_{se}}\left(\cos\delta_{se} + j\sin\delta_{se}\right) \tag{5}$$

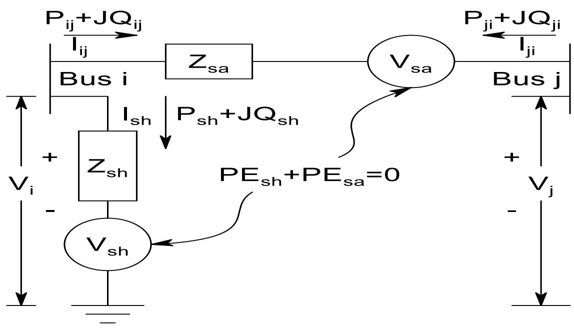

Figure 2. UPFC-Power injection model

Where, $V_{sh}, V_{se}, \delta_{sh}, \delta_{se}$ are the voltage magnitude and angle of Shunt and series converter respectively.

With the help of equations (4) and (5) derived from the model, real and reactive power expressions can be obtained as:

$$P_{sh} = V_i^2 g_{sh} - V_i V_{sh}\begin{pmatrix} g_{sh}\cos(\theta_i - \theta_{sh}) \\ +b_{sh}\sin(\theta_i - \theta_{sh}) \end{pmatrix} \tag{6}$$

$$Q_{sh} = -V_i^2 b_{sh} - V_i V_{sh}\begin{pmatrix} g_{sh}\sin(\theta_i - \theta_{sh}) \\ +b_{sh}\cos(\theta_i - \theta_{sh}) \end{pmatrix} \tag{7}$$

$$\begin{aligned} P_{ij} &= V_i^2 g_{ij} - V_i V_j\left(g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij}\right) \\ &- V_i V_{se}\left(g_{ij}\cos(\theta_i - \theta_{se}) + b_{ij}\sin(\theta_i - \theta_{se})\right) \end{aligned} \tag{8}$$

$$\begin{aligned} Q_{ij} &= -V_i^2 b_{ij} - V_i V_j\left(g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij}\right) \\ &- V_i V_{se}\left(g_{ij}\sin(\theta_i - \theta_{se}) + b_{ij}\cos(\theta_i - \theta_{se})\right) \end{aligned} \tag{9}$$

$$\begin{aligned} P_{ji} &= V_j^2 g_{ij} - V_i V_j\left(g_{ij}\cos\theta_{ji} + b_{ij}\sin\theta_{ji}\right) \\ &+ V_j V_{se}\left(g_{ij}\cos(\theta_j - \theta_{se}) + b_{ij}\sin(\theta_j - \theta_{se})\right) \end{aligned} \tag{10}$$

$$\begin{aligned} Q_{ji} &= -V_j^2 b_{ij} - V_i V_j\left(g_{ij}\sin\theta_{ji} - b_{ij}\cos\theta_{ji}\right) \\ &+ V_j V_{se}\left(g_{ij}\sin(\theta_j - \theta_{se}) + b_{ij}\cos(\theta_j - \theta_{se})\right) \end{aligned} \tag{11}$$

where

$g_{sh} + jb_{sh} = \dfrac{1}{z_{sh}}, g_{ij} + jb_{ij} = \dfrac{1}{z_{se}}$ and

$\theta_{ij} = \theta_i - \theta_j, \theta_{ji} = \theta_j - \theta_i$

4. Formulation of OPF Problem

The solution of OPF focus at optimizing a preferred objective with the best promising amendment of the power network control parameters satisfying both equality and inequality constraints. OPF problem is formulated as:

$$\min j(x,u)$$

Subjected to:

$$g(x,u) = 0$$

$$h_{\min} \le h(x,u) \le h_{\max}$$

where, J is the objective function;
x is dependent variable;
g and h are equality and operating constraints;
u is the control variable vector such as:
1. Generator voltages at PV buses.
2. Real power at PV buses excluding P_{G1} swing bus.
3. Tap settings of transformer.
4. Shunt compensators.

Optimal location of UPFC is calculated to optimize the particular objective function to improve the performance of the system where as thermal limits and voltage constraints should be satisfied. OPF problem formulation is given. After UPFC installation for the following objective functions:

4.1 Fuel cost function

The total fuel cost as objective function 'f_1' by daunting the constraints is as follows:

$$f_1 = \left[\sum_{i=1}^{NG}\left(a_i P_{Gi}^2 + b_i P_{Gi} + c_i\right)\right] + KP\left(P_{G1} - P_{G1}^{lim}\right)^2 + KV\left(\sum_{i=1}^{NL}\left(V_i - V_{lim}\right)^2\right) + KQ\left(\sum_{i=1}^{N}\left(Q_{G,i} - Q_{G,i}^{lim}\right)^2\right) + KS\left(\sum_{i=1}^{nl} abs\left(S_i - S_i^{lim}\right)^2\right) + KL\left(\sum_{j=1}^{NL}\left(L_j - L_j^{lim}\right)^2\right) \quad (12)$$

Where, NG=No. of generator units, PG_i=Active power generation at i^{th} unit, a_i,b_i and c_i are the cost coefficients of i^{th} generator and KP,KV,KQ,KS and KL are penalty factors for the limit violation. NL represents number of load buses, nl represent number of transmission lines and X^{lim} is restrictive values reliant variable given as:

$$X^{\lim} = \begin{cases} X^{\max}; X > X^{\max} \\ X^{\min}; X < X^{\min} \end{cases} \quad (13)$$

4.2 Power loss

The power loss minimization can be articulated as follows:

$$f_2 = \sum_{i=1}^{nl} G_{ij}\left(V_i^2 + V_j^2 - 2V_iV_j\cos\left(\delta_i - \delta_j\right)\right) + KP\left(P_{G1} - P_{G1}^{lim}\right)^2 + KV\left(\sum_{i=1}^{NL}\left(V_i - V_{lim}\right)^2\right) + KQ\left(\sum_{i=1}^{N}\left(Q_{G,i} - Q_{G,i}^{lim}\right)^2\right) + KS\left(\sum_{i=1}^{nl} abs\left(S_i - S_i^{lim}\right)^2\right) + KL\left(\sum_{j=1}^{NL}\left(L_j - L_j^{lim}\right)^2\right) \quad (14)$$

Where G_{ij}=Conductance belongs to i-jth line

The amalgamation of objective function 1&2 is expressed as multi objective function.

$$f3 = \left[\sum_{i=1}^{NG}\left(a_i P_{Gi}^2 + b_i P_{Gi} + c_i\right)\right] + \sum_{i=1}^{nl} G_{ij}\left(V_i^2 + V_j^2 - 2V_iV_j\cos\left(\delta_i - \delta_j\right)\right) + KP\left(P_{G1} - P_{G1}^{lim}\right)^2 + KV\left(\sum_{i=1}^{NL}\left(V_i - V_{lim}\right)^2\right) + KQ\left(\sum_{i=1}^{N}\left(Q_{G,i} - Q_{G,i}^{lim}\right)^2\right) + KS\left(\sum_{i=1}^{nl} abs\left(S_i - S_i^{lim}\right)^2\right) + KL\left(\sum_{j=1}^{NL}\left(L_j - L_j^{lim}\right)^2\right) \quad (15)$$

The optimization problem can be solved underneath the subsequent constraints:

4.3 Equality constraints

Nonlinear load flow equations that govern the power systems is given by,

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n}|V_i||V_j||Y_{ij}|\cos\left(\theta_{ij} - \delta_i + \delta_j\right) = 0 \quad (16)$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^{n}|V_i||V_j||Y_{ij}|\sin\left(\theta_{ij} - \delta_i + \delta_j\right) = 0 \quad (17)$$

Where, $P_{Gi}, P_{Di}, Q_{Gi}, Q_{Di} = i^{th}$ bus real, reactive power generation and demands respectively and $|Y_{ij}|$ is Bus admittance matrix.

4.4 Inequality constraints

Security and operational constraints are given as:

Real and reactive power outputs of Generators

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}, i = 1,2,...N_G \quad (18)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, i = 1,2,...N_G \quad (19)$$

2) Bus voltage magnitudes

$$V_i^{\min} \le V_i \le V_i^{\max}, i = 1,2,...N \quad (20)$$

3) Transformer tap positions

$$T_i^{\min} \le T_i \le T_i^{\max}, i = 1,2,...N_T \quad (21)$$

4) shunt capacitor VAR injections

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max}, i = 1,2,...C_S \quad (22)$$

5) Line Loadings

$$S_i \le S_i^{\max}, i = 1,2,...N_L \quad (23)$$

6) Voltage stability index

$$L_{ji} \le L_{ji}^{\max}, i = 1,2,...N_{LD} \quad (24)$$

4.5 UPFC Constraints

UPFC Series injected limits:

$$V_{se}^{\min} \le V_{se} \le V_{se}^{\max} \quad (25)$$

$$\theta_{se}^{\min} \le \theta_{se} \le \theta_{se}^{\max} \quad (26)$$

Shunt injected limits:

$$V_{sh}^{\min} \le V_{sh} \le V_{sh}^{\max} \quad (27)$$

$$\theta_{sh}^{\min} \le \theta_{sh} \le \theta_{sh}^{\max} \quad (28)$$

5. Flower Pollination Algorithm (FPA)

The following rules have been established for FPA technique to illustrate an ideal pollination process [30]:

Rule I: Self-pollination is treated as neighborhood pollination, happened by the natural world through the air stream or precipitation.

Rule II: Cross-pollination is treated as a comprehensive pollination and the pollinators (birds or insects) that are moving from long distance carry the pollens which would be treated as Levy flights.

Rule III: Local pollination have been occurring in the midst of the plant flowers itself or from the same class flowers.

Rule IV: The above mentioned two processes could be constrained by a control probability function $P_a \in [0, 1]$. Because of the corporeal flower immediacy and the other characteristics airstream or precipitation, self pollination could have a momentous part on the whole pollination progression [31-32].

FPA optimization technique can be formulated from the afore mentioned rules, as follows:

Let y_i be the control vector of considered control variables that mentioned the i^{th} flower. The cross-pollination is conceded out by producing arbitrary statistics L(λ) given below:

$$y_i^{t+1} = y_i^t + L(\lambda).(y_i^t - g^*) \quad (29)$$

The dot (*) in the above equation means element wise multiplication. The stride length L(λ) is haggard commencing a conformity Levy circulation; the equation was named a Levy flight which impersonates pollinator's deeds. Mantegna's approximation was used to engender Levy random numbers [33].

Self pollination has been carried out with the step length as homogeneously disseminate systematic number vector c_1 exists among 0 to1 to organize the enormity of the elements metamorphosis of the upcoming flower generation.

$$y_i^{t+1} = y_i^t + C_1.(y_i^t - y_k^t) \quad (30)$$

Here, t = present iteration, y_i^t and y_k^t are the present pollen from the diverse flowers of the same class. It can be represented as, if y^{t+1} and y^t are of same class, this homogeneously becomes a narrow random saunter.

The Levy flights can be changed to haphazard walks with a switching likelihood factor P_a as per the following rule:

If Pa > rand (0,1)

Do levy flights: $y_i^{t+1} = y_i^t + L(\lambda).(y_i^t - g^*)$

Else

Do random walks: $y_i^{t+1} = y_i^t + C_1.(y_i^t - y_k^t)$

End

6. Adaptive Flower Pollination Algorithm (AFPA)

Most important aspects of FPA are the preliminary stage population and moving from self pollination to global pollination. It has a significant brunt on the computational encumber and the elucidation convergence. The following modifications were proposed to enhance the performance of the algorithm.

6.1 Looking for the best initial condition

The earliest alteration is, opening from a nearer or fittest solution by concurrently inspecting the conflicting guess. With this modification, the initial best solution can be chosen from the fittest (either from opposite guess). The probability theory reveals that, the probability of two contradictory solutions which belongs to the identical feasible class has an opportunity of 50% that one is well again than the further. Therefore, beginning from the fittest of the two such as either presumption or contradictory presumption will be the impending to encompass an initial position more rapidly to the most advantageous way out. To achieve this, A contradictory vector to be required [34].

Let y be a present solution and the contradictory solution vector Y can be obtained by it apparatus as:

$$Y_i = a_i + b_i - y_i, \qquad i=1,2\ldots\ldots\ldots n \tag{31}$$

Where $[a_i, b_i]$ are upper and lower limits of y_i.

Quasi-oppositional point: The elucidation point is distinct from the preceding conflicting position and it has been demonstrated to furnish improved solution than the regular conflicting vector [35]. Let $y \in \square^n$ be a solution point, $y \in \square^n$ be its conflicting point mentioned as in (31) and also $y_m = \frac{a+b}{2}$ be the midpoint among the limits [a, b]. The rudiments of the quasi contradictory solution vector Y_q is defined as:

If $y_i < y_{mi}$

$$y_{qi} = y_{mi} + c\left(y_i - y_{mi}\right)$$

Else

$$y_{qi} = y_i + c\left(y_{mi} - y_i\right)$$

End

Where c = [0,1]and i= 1,2……..n.

6.2 Moving from local to global pollination process

Another amendment proposed based on the methods proposed in reference [36]. It is based on the combining of equations (29) and (30) by means of scalar dynamic auto adjusted weights w_1 and w_2 which may vary based on the generation counter 't'. The weight variations are obtained as follows:

$$w_1 = w_1^{\max} + t\left(\frac{w_1^{\max} - w_1^{\min}}{t_{\max}}\right) \tag{32}$$

$$w_2 = \frac{\min\left(F(t), \overline{F}\right)}{\max\left(F(t), \overline{F}\right)} \tag{33}$$

Where, $w_1^{\max}$, $w_1^{\min}$ are the limits of w_1

$t_{\max}$ = Highest generation number.
F(t) = Fitness value at generation t.

$\overline{F}$ =Average of the fitness functions of the present population. As a final point, accumulate an arbitrary scale factor γ(considered 0.15here) and a Gaussian distribution vector (ε_2=N(0,1))as an alternative of a uniform distribution to self random walks, the modified equation is:

$$y_i^{t+1} = y_i^t + w_1 L(\lambda).(y_i^t - g^*) + \gamma w_2 \varepsilon_2.(y_i^t - y_k^t) \tag{34}$$

This amendment moves the use of the probability. Switch P_a and Levy flights and Brownian motion have been merged into a solitary random walk expression.

7. Simulation results and discussion

The proposed technique was validated on IEEE-30 and IEEE-57 bus system in MATLAB programming environment.

7.1 Case 1: Testing on IEEE-30 Bus System

The considered test system has six generators inter related with 41 lines with a load demand of 283.4 MW and 126.2 MVAR [37]. The shunt VAR suppliers are provided at buses 10, 12, 15, 17, 20, 21, 23, 24 and 29 [38].Upon identifying the weak buses on the system using Fuzzy by considering L-Indices and voltage magnitudes and consequent results of top weak nodes are tabulated in Table 2.

Table 2. Weak nodes of the system

S. No	Bus No	Voltage (p.u)	L-Index	Severity	Rank
1	27	1.0326	0.0827	26.8642	1
2	22	1.0318	0.0813	26.2389	2
3	23	1.0301	0.0842	25.7536	3
4	29	1.0248	0.1113	25.0000	4
5	26	1.0075	0.1041	24.8783	5
6	24	1.0267	0.0822	24.8333	6
7	16	1.0321	0.0576	24.5239	7
8	19	1.0236	0.0829	23.6591	8
9	25	1.0251	0.0822	23.5564	9
10	12	1.0414	0.0579	17.8208	10

The bus 27 has utmost severity and treated as feeble node in the system as given in Table 1. The line between 27-30 is elected as the best location of UPFC. AFPA-OPF

UPFC results of the network for minimization of fuel cost and power loss were shown in Table 3 and Table 5 respectively.

Table 3. Simulation results of FPA, AFPA & AFPA-UPFC

Parameter	LIMITS Min	Max	FPA	AFPA	AFPA UPFC
P_{G1}	0.5	2.0	1.7588	1.7460	1.7605
P_{G2}	0.2	0.8	0.4852	0.4754	0.4712
P_{G5}	0.1	0.35	0.2139	0.2021	0.1992
P_{G8}	0.1	0.3	0.1202	0.1170	0.1228
P_{G11}	0.1	0.5	0.2037	0.2132	0.2076
P_{G13}	0.12	0.4	0.1210	0.1091	0.1200
V_{G1}	0.9	1.10	1.0729	1.0500	1.0600
V_{G2}	0.9	1.10	1.0567	1.0354	1.0451
V_{G5}	0.9	1.10	1.0452	1.0212	1.0423
V_{G8}	0.9	1.10	1.0261	1.0127	1.0120
V_{G11}	0.9	1.10	1.0241	1.0130	1.0294
V_{G13}	0.9	1.10	1.0529	1.0400	1.0116
T_{11}	0.9	1.10	1.0469	1.0683	1.0107
T_{12}	0.9	1.10	1.0240	1.0078	0.9768
T_{15}	0.9	1.10	0.9642	0.9701	1.0205
T_{36}	0.9	1.10	0.9396	0.9856	1.0312
Q_{C10}	0.0	0.2	0.2000	0.0431	0.0214
Q_{C12}	0.0	0.2	0.1305	0.0000	0.0331
Q_{C15}	0.0	0.2	0.0448	0.2000	0.1120
Q_{C17}	0.0	0.2	0.0567	0.0000	0.0000
Q_{C20}	0.0	0.2	0.0470	0.1288	0.0333
Q_{C21}	0.0	0.2	0.1445	0.0734	0.1823
Q_{C23}	0.0	0.2	0.0000	0.0836	0.0089
Q_{C24}	0.0	0.2	0.0340	0.0525	0.0323
Q_{C29}	0.0	0.2	0.0512	0.0448	0.1087
Cost ($/h)			800.15	799.15	798.01
P_{loss} (P.u)			0.0889	0.0875	0.0851
L_i^{max}	0.0	0.5	0.1350	0.1338	0.1209
V_{se}	0.0	0.2			0.0502
V_{sh}	0.9	1.1			0.9712

It is found that, total generating cost in proposed scheme is reduced to 798.01 $/h with respect to FPA yielding 800.15$/h and AFPA yielding 799.15$/h. Figure 3 shows the comparison of above results. It is also noted that, the L-Index is decreased to 0.1209 with respect to FPA yielding 0.1350 and AFPA yielding 0.1338 that gives enhanced voltage stability and the resultant graphical representations is as shown in Figure 4. The variations of voltage magnitudes of FPA and AFPA and AFPA with UPFC are shown in Figure 5.

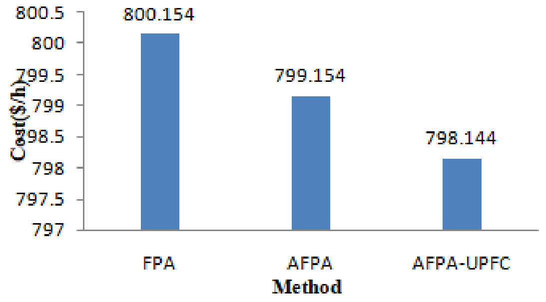

Figure 3. Fuel cost for different OPF techniques

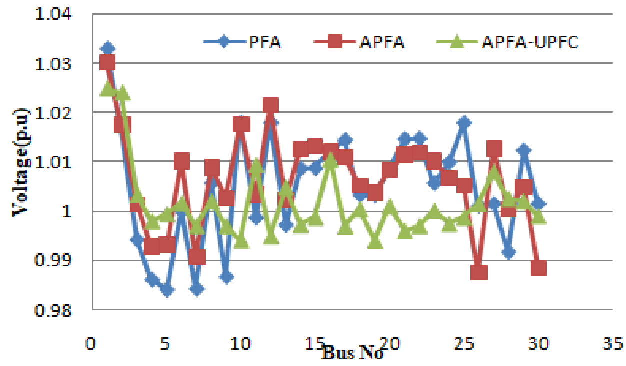

Figure 4. Bus voltages for different OPF techniques

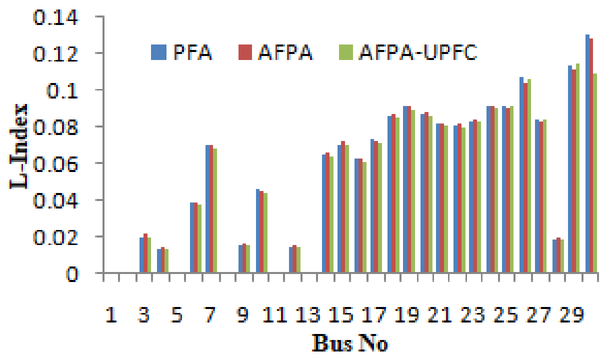

Figure 5. L-indices for different OPF techniques

Table 4. Fuel cost comparison for different techniques

S.No	Method	Fuel Cost ($/h)
1	EP[39]	802.9070
4	IEP[39]	802.4650
5	SADE-AIM[40]	802.4040
6	PSO[38]	800.4136
7	PSO-DV[41]	800.2314
8	EAPSO-DV[41]	800.1010
9	FPA	800.15
10	AFPA	799.150
11	AFPA-UPFC	798.014

From the above it is apparent that the projected technique provides remarkable results with respect to the literature.

Table 5. OPF Results with Power loss as an objective

Parameter	LIMITS Min	Max	PFA	AFPA	AFPA UPFC
P_{G1}	0.5	2.0	1.7608	1.7529	1.7625
P_{G2}	0.2	0.8	0.4774	0.4750	0.4848
P_{G5}	0.1	0.35	0.2120	0.2031	0.2110
P_{G8}	0.1	0.3	0.1202	0.1201	0.1201
P_{G11}	0.1	0.5	0.2126	0.2112	0.2152
P_{G13}	0.12	0.4	0.1210	0.1200	0.1200
V_{G1}	0.9	1.10	1.0833	1.0937	1.0829
V_{G2}	0.9	1.10	1.0634	1.0756	1.0667
V_{G5}	0.9	1.10	1.0337	1.0483	1.0442
V_{G8}	0.9	1.10	1.0167	0.9830	1.0161
V_{G11}	0.9	1.10	1.0297	1.0389	1.0341
V_{G13}	0.9	1.10	1.0605	1.0272	1.0829
T_{11}	0.9	1.10	1.0322	1.0929	1.0469
T_{12}	0.9	1.10	1.0026	1.0222	1.0240
T_{15}	0.9	1.10	0.9823	0.9854	0.9642
T_{36}	0.9	1.10	0.9526	1.0124	0.9396
Q_{C10}	0.0	0.2	0.1633	0 .0510	0.2000
Q_{C12}	0.0	0.2	0.0550	0.0000	0.1305
Q_{C15}	0.0	0.2	0.1323	0 .0934	0.0448
Q_{C17}	0.0	0.2	0.1052	0 .0819	0.0567
Q_{C20}	0.0	0.2	0.0335	0. 0507	0.0470
Q_{C21}	0.0	0.2	0.0115	0.1042	0.1445
Q_{C23}	0.0	0.2	0.0431	0 .0000	0.0000
Q_{C24}	0.0	0.2	0.0000	0.1313	0.0340
Q_{C29}	0.0	0.2	0.0123	0. 0290	0.0000
P_{loss} (P.u)			0.0712	0.0695	0.0591
L_i^{max}	0.0	0.5	0.1254	0.1267	0.1209
V_{se}	0.0	0.2			0.0521
V_{sh}	0.9	1.1			0.9734

From Table 4, It is apparent that the system real power loss in proposed scheme has been reduced to 5.91MW where it is 7.12 MW and 6.95 MW in FPA and AFPA respectively. The proposed method results obtained for the multi-objective function are tabulated in Table 6.

Table 6. OPF results for multi-objective function (f_3)

Parameter	Limits Min	Max	PFA	AFPA	AFPA UPFC
P_{G1}	0.5	2.0	1.3654	1.2757	1.2412
P_{G2}	0.2	0.8	0.3988	0.4001	0.4033
P_{G5}	0.1	0.35	0.1897	0.1933	0.1917
P_{G8}	0.1	0.3	0.1004	0.1000	0.1001
P_{G11}	0.1	0.5	0.1500	0.1500	0.1500
P_{G13}	0.12	0.4	0.1200	0.1202	0.1200
V_{G1}	0.9	1.1	1.0977	1.1000	1.0998
V_{G2}	0.9	1.1	1.0750	1.0778	1.0773
V_{G5}	0.9	1.1	1.0583	1.0570	1.0553
V_{G8}	0.9	1.1	1.0485	1.0654	1.0298
V_{G11}	0.9	1.1	1.0484	1.0502	1.0459
V_{G13}	0.9	1.1	1.0897	1.0840	1.0732
T_{11}	0.9	1.1	1.0035	0.9981	1.0704
T_{12}	0.9	1.1	1.0408	1.0753	0.9996
T_{15}	0.9	1.1	1.0151	0.9000	0.9000
T_{36}	0.9	1.1	0.9604	0.9920	1.0125
Q_{C10}	0.0	0.2	0.0000	0.0803	0.1853
Q_{C12}	0.0	0.2	0.1732	0.0000	0.0000
Q_{C15}	0.0	0.2	0.0693	0.0061	0.0897
Q_{C17}	0.0	0.2	0.2000	0.0000	0.0000
Q_{C20}	0.0	0.2	0.0635	0.0708	0.0730
Q_{C21}	0.0	0.2	0.1103	0.1997	0.0777
Q_{C23}	0.0	0.2	0.0000	0.0614	0.0000
Q_{C24}	0.0	0.2	0.0000	0.0207	0.0218
Q_{C29}	0.0	0.2	0.0329	0.0493	0.2000
Cost ($/h)			833.56	846.21	852.16
f_3			800.23	799.38	798.01
L_i^{max}	0.0	0.5	0.1232	0.1301	0.1300
V_{se}	0.0	0.2			0.0518
V_{sh}	0.9	1.1			0.9949

From the Table 6, it is evident that the projected AFPA method with UPFC is also provided an optimum solution for multi-objective function.

7.2 Case 2: Testing on IEEE-57 bus system

The IEEE-57 bus system has 80 transmission lines together with 17 tap changing transformers, 7 generators and 50 PQ buses with a overall loading of P = 1250.80 MW and Q = 336.40 MVAR and 11 shunt VAr compensators which are located at 18, 19, 23, 25, 27, 28, 29, 30, 32, 35 and 41 buses. The best five weak nodes presented in Table 7.

Table 7. Fuzzy severity of weak nodes

S. No	Bus No	Voltage (p.u)	L-Index	Severity	Rank
1	57	0.9376	0.2649	43.0895	1
2	56	0.9400	0.2104	37.6400	2
3	50	0.9658	0.2537	34.558	3
4	32	1.0346	0.247	30.651	4
5	33	1.0325	0.2487	29.6435	5

The bus 57 has utmost severity treated as weakest node and the line between 56-42 is preferred for the most favourable location of UPFC. The AFPA-OPF results of the system with UPFC are given in subsequent tables.

Table 8. Comparison of FPA, AFPA & AFPA-UPFC results

Parameter	Limits		FPA	AFPA	AFPA UPFC
	Min	Max			
P_{G1}	0.00	5.7588	1.9231	1.8674	1.8445
P_{G2}	0.00	1.0000	1.0000	1.0000	1.0000
P_{G3}	0.00	1.400	0.5772	0.5759	0.5426
P_{G4}	0.00	1.0000	1.0000	1.0000	1.0000
P_{G5}	0.00	5.5000	3.5045	3.2213	3.1100
P_{G6}	0.00	1.0000	0.6421	0.7768	0.7121
P_{G7}	0.00	4.100	4.1000	3.9500	3.8481
V_{G1}	0.90	1.10	0.9773	1.0125	1.0284
V_{G2}	0.90	1.10	0.9654	1.0152	1.0321
V_{G3}	0.90	1.10	0.9725	1.0120	1.0123
V_{G4}	0.90	1.10	0.9845	1.0134	1.0157
V_{G5}	0.90	1.10	0.9763	1.0008	1.0071
V_{G6}	0.90	1.10	0.9684	1.0451	1.0152
V_{G7}	0.90	1.10	0.9825	0.9946	1.0005
T_1	0.90	1.10	1.0511	1.0080	1.0376
T_2	0.90	1.10	0.9300	0.9724	0.9492
T_3	0.90	1.10	0.9100	0.9657	1.0565
T_4	0.90	1.10	0.9421	0.9231	1.1000
T_5	0.90	1.10	1.0003	0.9745	1.1000
T_6	0.90	1.10	0.9811	1.0245	1.0253
T_7	0.90	1.10	0.9051	0.9889	0.9829
T_8	0.90	1.10	0.9000	0.9957	0.9462
T_9	0.90	1.10	0.9235	0.9494	0.9413
T_{10}	0.90	1.10	0.9100	0.9345	0.9788
T_{11}	0.90	1.10	0.9231	0.9702	0.9879
T_{12}	0.90	1.10	0.9123	0.9978	1.1000
T_{13}	0.90	1.10	0.9421	0.941	0.9412
T_{14}	0.90	1.10	0.9624	0.9862	0.9325
T_{15}	0.90	1.10	1.0221	0.9629	0.9000
T_{16}	0.90	1.10	0.9769	1.0163	0.9103
T_{17}	0.90	1.10	0.9314	1.0612	0.9764
Q_{C1}	0.00	0.20	0.1215	0.1414	0.0523
Q_{C2}	0.00	0.20	0.1542	0.1804	0.0473
Q_{C3}	0.00	0.20	0.1725	0.0524	0.1702
Q_{C4}	0.00	0.20	0.1214	0.0151	0.0583
Q_{C5}	0.00	0.20	0.0312	0.0389	0.1700
Q_{C6}	0.00	0.20	0.0601	0.0645	0.0400
Q_{C7}	0.00	0.20	0.1032	0.0742	0.0862
Q_{C8}	0.00	0.20	0.0021	0.0502	0.0103
Q_{C9}	0.00	0.20	0.0310	0.0624	0.0125
Q_{C10}	0.00	0.20	0.0134	0.0545	0.0425
Q_{C11}	0.00	0.20	0.0426	0.0831	0.0524
Cost ($/h)			42506	42481	42235
P_{loss} (P.u)			0.1359	0.1468	0.1202
L_i^{max}	0.00	0.50	0.2796	0.2941	0.1787
V_{se}	0.00	0.20			0.0200
θ_{se}					122.876

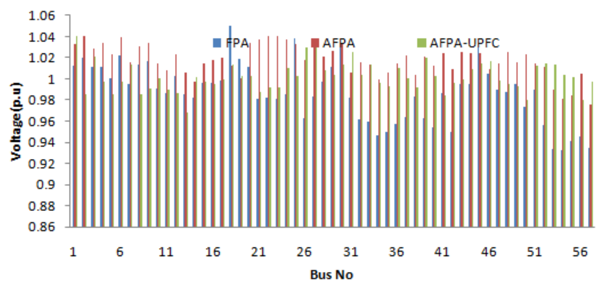

Figure 6. Bus voltages for different OPF methods

Table 9. OPF results with Power loss as an objective

Parameter	Limits		FPA	AFPA	AFPA UPFC
	Min	Max			
P_{G1}	0.00	5.7588	2.136	1.9466	2.1102
P_{G2}	0.00	1.0000	0.1079	0.7898	0.6452
P_{G3}	0.00	1.400	1.1379	1.1400	1.0621
P_{G4}	0.00	1.0000	0.9001	1.0000	0.9631
P_{G5}	0.00	5.5000	2.9174	3.1548	3.4621
P_{G6}	0.00	1.0000	0.7740	0.3757	0.1158
P_{G7}	0.00	4.100	3.910	4.1000	3.8910
V_{G1}	0.90	1.10	0.9946	1.0185	1.0214

V_{G2}	0.90	1.10	0.9954	1.0491	1.0412
V_{G3}	0.90	1.10	0.998	1.016	1.0351
V_{G4}	0.90	1.10	1.0222	1.1000	1.0157
V_{G5}	0.90	1.10	1.0152	1.007	1.0002
V_{G6}	0.90	1.10	0.9994	1.027	1.0208
V_{G7}	0.90	1.10	1.0998	0.9821	1.0176
T_1	0.90	1.10	1.1000	0.9841	1.0364
T_2	0.90	1.10	0.9823	0.9586	1.0263
T_3	0.90	1.10	0.9293	1.0434	1.0484
T_4	0.90	1.10	1.0968	0.9399	0.9850
T_5	0.90	1.10	0.9466	0.9835	0.9919
T_6	0.90	1.10	1.0398	1.0033	0.9000
T_7	0.90	1.10	0.9624	0.9648	0.9000
T_8	0.90	1.10	0.9000	0.9834	0.9000
T_9	0.90	1.10	1.0308	0.9931	1.0000
T_{10}	0.90	1.10	0.9307	0.9864	0.9543
T_{11}	0.90	1.10	0.9000	0.9609	0.9488
T_{12}	0.90	1.10	1.0033	1.0163	0.9564
T_{13}	0.90	1.10	0.9326	0.9493	0.9432
T_{14}	0.90	1.10	0.9238	1.0119	1.0035
T_{15}	0.90	1.10	1.0237	0.9736	0.9651
T_{16}	0.90	1.10	0.9139	1.0100	0.9720
T_{17}	0.90	1.10	0.9601	0.9714	0.9000
Q_{C1}	0.00	0.20	0.0938	0.1127	0.0677
Q_{C2}	0.00	0.20	0.135	0.1634	0.1292
Q_{C3}	0.00	0.20	0.0736	0.1162	0.0120
Q_{C4}	0.00	0.20	0.0713	0.0493	0.0574
Q_{C5}	0.00	0.20	0.0204	0.1203	0.1178
Q_{C6}	0.00	0.20	0.0637	0.0530	0.0146
Q_{C7}	0.00	0.20	0.0723	0.1192	0.0754
Q_{C8}	0.00	0.20	0.0821	0.0580	0.0825
Q_{C9}	0.00	0.20	0.0206	0.0738	0.0167
Q_{C10}	0.00	0.20	0.0674	0.0000	0.0597
Q_{C11}	0.00	0.20	0.0387	0.0426	0.0236
Cost ($/h)			44865	46213	45219
P_{loss} (P.u)			0.129	0.1154	0.1032
L_i^{max}	0.00	0.50	0.2805	0.2974	0.2231
V_{se}	0.00	0.20			0.0629
θ_{se}					114.66

Table 10. OPF results for multi-objective function (f_3)

Parameter	Limits Min	Limits Max	FPA	AFPA	AFPA UPFC
P_{G1}	0.00	5.7588	2.073	1.8856	2.5276
P_{G2}	0.00	1.0000	0.8257	0.7842	0.1023
P_{G3}	0.00	1.4000	1.3457	1.4000	1.1279
P_{G4}	0.00	1.0000	2.6864	3.1489	2.8174
P_{G5}	0.00	5.5000	3.8689	4.0000	3.9001
P_{G6}	0.00	1.0000	0.7945	0.8757	0.7640
P_{G7}	0.00	4.1000	3.7200	3.8000	4.0000
V_{G1}	0.90	1.10	1.028	1.0261	1.0259
V_{G2}	0.90	1.10	1.0357	1.0357	1.0379
V_{G3}	0.90	1.10	1.0397	1.0397	1.0274
V_{G4}	0.90	1.10	1.0495	1.0495	1.0181
V_{G5}	0.90	1.10	1.0442	1.0442	1.0214
V_{G6}	0.90	1.10	1.0416	1.0416	0.9961
V_{G7}	0.90	1.10	1.0525	1.0525	1.0443
T_1	0.90	1.10	0.9870	1.0441	1.0585
T_2	0.90	1.10	0.9310	0.9845	0.9541
T_3	0.90	1.10	1.0743	1.0665	1.0314
T_4	0.90	1.10	0.937	0.9491	1.0220
T_5	0.90	1.10	0.9528	1.0300	0.9910
T_6	0.90	1.10	1.0202	0.9742	0.9605
T_7	0.90	1.10	0.9808	1.0083	0.9000
T_8	0.90	1.10	0.9945	0.9221	0.9494
T_9	0.90	1.10	0.9817	0.9877	1.0048
T_{10}	0.90	1.10	0.9620	0.9626	0.9426
T_{11}	0.90	1.10	0.9528	0.9243	0.9107
T_{12}	0.90	1.10	0.912	1.0153	0.9996
T_{13}	0.90	1.10	1.005	0.9881	1.0677
T_{14}	0.90	1.10	1.0123	1.0036	1.0021
T_{15}	0.90	1.10	0.988	0.9693	0.9664
T_{16}	0.90	1.10	1.036	0.9678	0.9512
T_{17}	0.90	1.10	0.918	1.0069	1.0116
Q_{C1}	0.00	0.20	0.127	0.0618	0.0938
Q_{C2}	0.00	0.20	0.134	0.1919	0.135
Q_{C3}	0.00	0.20	0.162	0.0774	0.0736
Q_{C4}	0.00	0.20	0.093	0.0412	0.0703
Q_{C5}	0.00	0.20	0.103	0.0358	0.0254
Q_{C6}	0.00	0.20	0.030	0.0738	0.0661
Q_{C7}	0.00	0.20	0.192	0.0000	0.0415
Q_{C8}	0.00	0.20	0.080	0.0469	0.0708
Q_{C9}	0.00	0.20	0.038	0.0856	0.1904
Q_{C10}	0.00	0.20	0.0214	0.0972	0.0624
Q_{C11}	0.00	0.20	0.0426	0.1793	0.0701
f_3			42494	42453	42332
L_i^{max}	0.00	0.50	0.1391	0.1318	0.1209
V_{se}	0.00	0.20			0.0191
θ_{se}					112.47

From the Table 7, 8 & 9, it is evident that proposed AFPA technique with UPFC is very efficient to acquire optimum solution for single and multi-objective function.

8. Conclusion

Standard test networks IEEE-30 & IEEE-57 bus systems were selected to check the efficacy of the projected method for the considered single and multi objective functions. Fuzzy approach has been used to find the location of UPFC in the considered test system that effectively eliminated the masking effect in contingency ranking of the other proposed methods.

The proposed method i.e AFPA with UPFC was very effective in eliminating the drawbacks of FPA and AFPA while finding the best possible control settings of the control variables. The proposed method reduced the fuel cost from 802.9$/h to 798.01$/h i.e 4.89$/h compared to existing literature and the power loss has been reduced to 83% of FPA where as in the case of multi-objective function the reduction in the weighted sum from 800.23 to 798.01 with respect to FPA. Here, in addition to proposed objectives, the inclusion of UPFC in the projected technique enhanced the stability margin and reduces voltage deviation too.

This research work may also be extended by placing multiple facts devices in optimal places for single and multi objective optimization problems and also be extended to support the system under contingency conditions which gains lot of attention especially for planning and operation of the complex power systems.

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