

## Optimal Power Flow With UPFC Using Fuzzy- PSO With Non-Smooth Fuel Cost Function

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### Abstract

This paper presents an efficient and reliable evolutionary based approach to solve the Optimal Power Flow problem in electrical power network. The Particle Swarm Optimization method is used to solve optimal power flow problem in power system by incorporating a powerful and most versatile Flexible Alternating Current Transmission Systems device such as Unified power Flow Controller. It is a new device in FACTS family and has great flexibility that can control Active power, Reactive power and voltage magnitudes simultaneously. In this paper optimal location is found out using Fuzzy approach and control settings of UPFC are determined by PSO. The proposed approach is examined on IEEE-30 bus system with different objective function that reflects fuel cost minimization and fuel cost with valve point effects. The test results show the effectiveness of robustness of the proposed approach compared with the existing results in the literature.

**Keywords:** OPF, particle swarm Optimization, UPFC, Fuel cost, L-Index, Fuel cost with valve point loading effects.

### I. INTRODUCTION

The power flow control [1-3] and economic operation such as Optimal Power Flow (OPF) including the Flexible Alternating Current Transmission Systems (FACTS) devices has become an important aspect in the present day power system operation and planning. OPF is part of the standard tools of the supervisory, control and data acquisition (SCADA) and energy management system (EMS). It schedules power system controls to optimize an objective function while satisfying linear equality and non-linear equality constraints.

In the last two decades, the problem of Optimal Power Flow (OPF) has received much attention and it is of current interest of many utilities with that it has been marked as one of the most operational needs. The OPF solution aims to optimize a selected objective function via optimal adjustment of the power system control variables, at the same time satisfying various equality and inequality constraints. The OPF problem is a large-scale highly constrained non-linear non-convex optimization problem, it has taken decades to develop efficient algorithms for its solution [4].

Many classical techniques have been reported in the literature [5-7], are nonlinear programming (NLP), quadratic programming (QP) and linear programming (LP). The gradient based methods [8] and Newton methods [9] suffer from the difficulty in handling inequality constraints. The quadratic programming technique is a special kind of non-

linear programming whose objective function is quadratic with linear constraints. Quadratic programming based techniques has drawback associated with the piecewise quadratic cost approximation. Newton-based techniques have a disadvantage of the convergence characteristics that are sensitive to the initial conditions and they may even fail to converge due to selection of inappropriate initial conditions. Although the linear programming methods are fast and reliable, but they have some drawbacks associated with the piecewise linear cost approximation. The interior point method converts the inequality constraints to equalities by the introduction of non-negative slack variables. This method has been reported as computationally efficient. But, if the step size is not chosen properly, the sub-linear problem may have a solution that is infeasible in the original non-linear domain [6-7].

The OPF problem is a highly non-linear and a multimodal optimization problem, i.e. there exist more than one local optima. Hence, local optimization techniques are not suitable for such a problem. Moreover, there is no criterion to decide whether the local solution is the global solution or not. Therefore, it is essential to develop optimization techniques that are efficient to overcome these drawbacks.

The OPF has renewed interest in a variety of formulations through use of evolutionary optimization techniques to alleviate the limitation of classical optimization techniques. A wide and variety of advanced optimization techniques have been

applied in solving the OPF problems such as genetic algorithm [10,11], simulated annealing [12], Tabu Search [13]. The results reported were promising and encouraging for further research in this direction.

The proposed approach of Particle swarm Optimization algorithm [14] has the following advantages : finding the true global minimum regardless of the initial parameter values, fast in convergence, and a few control parameters. Being simple, fast, easy to use and very easily adaptable for integer and discrete optimization, quite effective in non-linear constraint optimization including penalty functions and useful for optimizing multi-modal search space are the other important features of PSO.

Unified Power Flow Controller (UPFC) is a versatile FACTS device consists of series and shunt connected converters can independently or simultaneously control the active, reactive power, and the bus voltage and also minimize losses. This controller offers substantial advantages for the static and dynamic operation of power system. However, to achieve such functionality it is important to find the optimal location of UPFC device to be installed in power system with appropriate parameters. The active power loss reduction, the stability margin improvement and the power transmission capacity increasing are the factors that can be considered in selection to incorporate UPFC. In this paper optimal location of UPFC is identified using Fuzzy approach and control settings of series and shunt controllers of UPFC are determined by PSO. The proposed approach is examined on IEEE-30 bus system with different objective function that reflects fuel cost minimization and minimization of fuel cost with valve point effects. The proposed Fuzzy-PSO with UPFC provides very remarkable results compared to those reported in the literature.

## II. VOLTAGE STABILITY INDEX (L-INDEX)

Consider a transmission system having 'n' total number of buses with 1, 2 ... g; generator buses, and g+1..... n remaining (n-g) load buses. For a given system operating condition, using the load-flow (state-estimation) results, the Voltage-Stability Index (L- index) [15] is computed as

$$L_j = \left| 1 - \sum_{i=1}^g F_{ji} \frac{V_i}{V_j} \right| \quad \dots(1)$$

Where  $j = g + 1, \dots, n$  and all the terms within the sigma on the right hand side are complex quantities. The values of  $F_{ji}$  are complex and are determined from the network Y-bus matrix, for a given operating condition

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad \dots(2)$$

Where,  $I_G, I_L, V_G,$  and  $V_L$  denotes complex current and voltage vectors at the generator buses and load buses.  $[Y_{GG}], [Y_{GL}], [Y_{LL}]$  and  $[Y_{LG}]$  are corresponding sectionalized portions of the network Y-bus matrix. Rearranging the above Equation (2), we obtain

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad \dots(3)$$

$$\text{Where, } F_{LG} = [Y_{LL}]^{-1} [Y_{LG}]^{-1} \quad \dots(4)$$

For voltage stability, the index  $L_j$  should not be violated the maximum limit of 1 at any bus  $j$  (load bus). As the load (or) generation increases, the voltage magnitude and angles change near maximum power-transfer condition and the voltage-stability index  $L_j$  values for load buses reaches to close to unity, indicating that the system is close to voltage collapse [15]. Among the various methods for voltage-stability and voltage collapse prediction, the L-index gives exact consistent results.

## III. POWER FLOW MODEL OF UPFC

The UPFC is an advanced power systems device capable of providing simultaneous control of voltage magnitude and active and reactive power flows, and, it is well placed to solve most issues relating to power flow control while enhancing considerably transient and dynamic stability. Fig.1 shows the equivalent circuit of a UPFC power flow model [16], this circuit consists of two coordinated synchronous voltage sources represent the UPFC adequately for the purpose of fundamental steady-state analysis, the UPFC voltage sources are:

$$V_{sh} = V_{sh} (\cos \delta_{sh} + j \sin \delta_{sh}) \quad (5)$$

$$V_{se} = V_{se} (\cos \delta_{se} + j \sin \delta_{se}) \quad \dots(6)$$

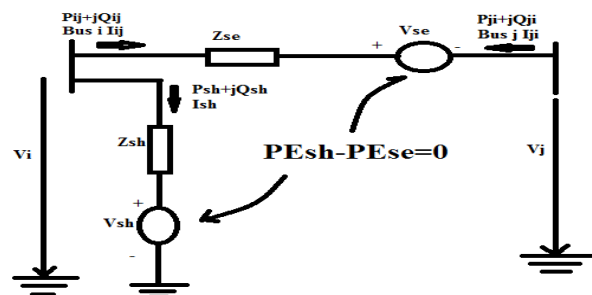


Fig. 1. Unified power flow controller equivalent circuit

where  $V_{sh}$  is the shunt voltage source magnitude;  $\delta_{sh}$  is the shunt voltage source angle;  $V_{se}$  is the series voltage source magnitude; and  $\delta_{se}$  is the series voltage source angle.

Based on the equivalent circuit and on (5) and (6) the active and reactive power equations are:

$$P_{sh} = V_i^2 g_{sh} - V_i V_{sh} (g_{sh} \cos(\theta_i - \theta_{sh}) + b_{sh} \sin(\theta_i - \theta_{sh})) \dots (7)$$

$$Q_{sh} = -V_i^2 b_{sh} - V_i V_{sh} (g_{sh} \sin(\theta_i - \theta_{sh}) + b_{sh} \cos(\theta_i - \theta_{sh})) \dots (8)$$

$$P_{ij} = V_i^2 g_{ij} - V_i V_j (g_{ij} \cos \theta_{ij} + b_{ij} \sin \theta_{ij}) - V_i V_{se} (g_{ij} \cos(\theta_i - \theta_{se}) + b_{ij} \sin(\theta_i - \theta_{se})) \dots (9)$$

$$Q_{ij} = -V_i^2 b_{ij} - V_i V_j (g_{ij} \sin \theta_{ij} - b_{ij} \cos \theta_{ij}) - V_i V_{se} (g_{ij} \sin(\theta_i - \theta_{se}) - b_{ij} \cos(\theta_i - \theta_{se})) \dots (10)$$

$$P_{ji} = V_j^2 g_{ij} - V_i V_j (g_{ij} \cos \theta_{ji} + b_{ij} \sin \theta_{ji}) + V_j V_{se} (g_{ij} \cos(\theta_j - \theta_{se}) + b_{ij} \sin(\theta_j - \theta_{se})) \dots (11)$$

$$Q_{ji} = -V_j^2 b_{ij} - V_i V_j (g_{ij} \sin \theta_{ji} - b_{ij} \cos \theta_{ji}) + V_j V_{se} (g_{ij} \sin(\theta_j - \theta_{se}) - b_{ij} \cos(\theta_j - \theta_{se})) \dots (12)$$

where

$$g_{sh} + jb_{sh} = 1/Z_{sh}, \quad g_{ij} + jb_{ij} = 1/Z_{se}$$

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

The above power flow equations are used to incorporate UPFC in PSO based Optimal Power Flow.

#### IV. OPTIMAL POWER FLOW PROBLEM

The OPF problem solution aims to optimize a selected objective function via optimal adjustment of the power system control variables, while satisfying various equality and inequality constraints. Mathematically, the OPF problem can be formulated as follows:

Min  $J(x,u)$

Subject to:  $g(x,u) = 0$

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

where  $J$  is objective function to be minimized.

$x$  is the vector of dependent variables (state vector)

$u$  is the vector of independent variables (control variables) consisting of:

1. Generator voltage  $V_G$  at PV buses.
2. Generator real power output  $P_G$  at PV buses except at the slack bus  $P_{G1}$ .
3. Transformer tap setting  $T$ .
4. Shunt VAR compensators.

$$u^T = [P_{G1} \dots P_{G_{NG}}, V_{G1} \dots V_{G_{NG}}, Q_{C1} \dots Q_{C_{NC}}, T_1 \dots T_{NT}]$$

where,  $NT$  and  $NC$  are the number of the tap changing transformers and VAR compensators, respectively.

$g$  is the equality constraints and  $h$  is operating constraints

The UPFC is located to improve the system performance while minimizing certain objective functions, maintaining thermal limits and voltage constraints. Mathematically, the OPF problem after incorporating the UPFC can be formulated with the following objective functions:

#### 4.1 Smooth cost function using quadratic form:

The objective function  $f$  is the total generation cost expressed in a simple form as follows:

The objective function =  $\min(F)$

$$f_1 = \left[ \sum_{i=1}^{NG} (a_i P_{Gi}^2 + b_i P_{Gi} + c_i) \right] \dots (13)$$

Where;  $NG$  is the number of generating units,  $P_{Gi}$  is the active power generation at unit  $i$  and  $a_i, b_i$  and  $c_i$  are the cost coefficients of the  $i^{\text{th}}$  generator.

#### 4.2 Non-smooth Cost Function with Valve-Point Loading Effects:

The valve-point loading effect is taken in consideration by adding a sine component to the cost of the generating units. Typically, the fuel cost function of the generating units with valve-point loadings is represented as follows

$$f_2 = \sum_{i=1}^{NG} (a_i P_{Gi}^2 + b_{gi} + c_i) + \left| d_i \sin \left( e_i (P_{Gi}^{\min} - P_{Gi}) \right) \right| \dots (14)$$

$d_i$  and  $e_i$  are the cost coefficients of the generating unit with valve-point loading effects.

The minimization problem is subjected to the following two categories of constraints such as:

**1.Equality Constraints:** These are the sets of nonlinear power flow equations that govern the power systems, i.e.,

$$P_{Gi} - P_{Di} - \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \dots (15)$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) = 0 \dots (16)$$

where,  $P_{Gi}$  and  $Q_{Gi}$  are the real and reactive power outputs injected at bus- $i$  respectively, the load demand at the same bus is represented by  $P_{Di}$  and  $Q_{Di}$ , and elements of the bus admittance matrix are represented by  $|Y_{ij}|$ .

**2.Inequality Constraints:** These are the set of constraints that represent the system operational and security limits like the bounds on the following:

(1). Generators real and reactive power outputs

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max}, i=1,2,\dots,NG \dots (17)$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}, i=1,2,\dots,NG \dots (18)$$

(2). Voltage magnitudes at each bus in the network

$$V_i^{\min} \leq V_i \leq V_i^{\max}, i=1,2,\dots,N \dots (19)$$

(3). Transformer tap settings

$$T_i^{\min} \leq T_i \leq T_i^{\max}, i=1,2,\dots,NT \dots (20)$$

(4). Reactive power injections due to capacitor banks

$$Q_{Ci}^{\min} \leq Q_{Ci} \leq Q_{Ci}^{\max}, i=1,2,\dots,CS \dots (21)$$

(5). Transmission lines loading

$$S_i \leq S_i^{\max}, i=1,2,\dots,NL \dots (22)$$

(6). Voltage stability index

$$L_{ji} \leq L_{ji}^{\max}, i=1,2,\dots,NLD \dots (23)$$

**UPFC constraints:**

UPFC Series injected voltage limits :

$$V_{se\ min} \leq V_{se} \leq V_{se\ max} \dots(24)$$

$$\theta_{se\ min} \leq \theta_{se} \leq \theta_{se\ max} \dots(25)$$

UPFC Shunt injected voltage limits :

$$V_{sh\ min} \leq V_{sh} \leq V_{sh\ max} \dots(26)$$

$$\theta_{sh\ min} \leq \theta_{sh} \leq \theta_{sh\ max} \dots(27)$$

The above constraints are controlled using Particle swarm Optimization Technique which is discussed in subsequent section.

**V. PARTICLE SWARM OPTIMIZATION**

PSO is motivated by the social behavior of organisms, such as birds flocking and fish schooling. It is an optimization tool, provides a population based search procedure in which individuals called Particles change their positions with time. In this algorithm, particles fly around the 'd' dimensional problem space. During flight, each particle adjust its position according to its own experience as well as by the best experience of other neighboring particles. The basic elements of PSO technique are briefly described as follows:

**5.1 Particles Position,  $X_i$ :**

Each individual represents a candidate solution within the population and it is represented by 'd' dimensional vector. Let us consider  $X_i = (X_{i1}, X_{i2}, \dots, X_{id})$  be the position of the  $i^{th}$  particle.

**5.2 Particle Velocity,  $V_i$ :**

It is the velocity of the moving particles represented by a d-dimensional vector. The velocity of the  $i^{th}$  particle is given by  $V_i = (V_{i1}, V_{i2}, \dots, V_{id})$  and it is bounded between the limits  $V_{minid} \leq V_{id} \leq V_{maxid}$

**5.3 Individual Best,  $Pbest_i$ :**

When a particle moves through the search space, it compares its fitness value at the current position to the best previous fitness value. The best position of the  $i^{th}$  particle that is associated with the best fitness encountered so far is called  $Pbest_i$  and its vector representation is given by  $Pbest_i = (P_{i1}, P_{i2}, \dots, P_{id})$ . The fitness of the objective function for the  $Pbest$  of the  $i^{th}$  particle is determined by the following relation

$$F(P_i) \leq F(X_i), \quad i=1,2,\dots,d.$$

**5.4 Global Best,  $gbest_i$ :**

It is the best position among all individual best positions achieved so far and is given by  $gbest_i = (P_{g1}, P_{g2}, \dots, P_{gid})$ . The global best can be determined by  $F(P_{gi}) \leq F(P_i), \quad i=1,2,\dots,d.$

**5.5 Velocity Updation:**

Using the global best and individual best of each particle, the  $i^{th}$  particle velocity in the  $d^{th}$  dimension is updated according to the following equation.

$$V(k+1)_{id} = W * V(k)_{id} + C_1 * rand1 * (P_{id} - X_{id}) + C_2 * rand2 * (P_{gid} - X_{id}) \dots (28)$$

where  $C_1$  and  $C_2$  are the acceleration constants, which represent the weighting to stochastic acceleration terms that pull each particle towards  $Pbest$  and  $gbest$  positions.

**5.6 Position Updation:**

Based on the updated velocities, each particle changes its position according to the following equation:

$$X(k+1)_{id} = X(k)_{id} + V(k+1)_{id} \dots(29)$$

**5.7 Stopping criteria:**

It is the condition under which the search process will terminate. The search will terminate if the number of iterations reaches the maximum allowable number.

Inertia weight is calculated using below equations for better exploration of the search space [17-18].

$$w = w_{max} - \frac{(w_{max} - w_{min})}{iter_{max}} * iter \dots(30)$$

Where,  $w_{max}$ , are the constraints for inertia weight factor. From the above discussion the Step by Step Procedure for PSO-Based OPF Algorithm is:

- Step 1: Assume the population size and maximum number of generations.
- Step 2: Initialize the particle position vector between the limits of each control variable and depending on population size. The velocity vector of each particle is also initialized.
- Step 3: Calculate the value of objective function of each generation.
- Step 4: Obtain the values of  $Pbest$  i.e the control variables corresponding to the minimum objective function value in each generation, and  $gbest$  i.e minimum objective function value among all generations, respectively.
- Step 5: Update the velocity vector according to Eq. (28) and check the control variable's limits violation. If there is any violation, set the value of the velocity vector corresponding to their limits.
- Step 6: Update the particle position vector according to Eq. (29).
- Step 7: If the value of control variables (new  $Pbest$ ) corresponding to minimum value objective function of current generation is less than previous  $Pbest$ , then the current value is set to be  $Pbest$ . If the  $Pbest$  is better than  $gbest$ , value is set to be  $gbest$ .

Step 8: If the number of generations reaches the maximum value, then go to the next step. Otherwise, go to step 3.

Step 9: The individual that generates the latest gbest is the optimal set of control variables with the global minimum value of the objective function.

## VI. SIMULATION RESULT

The proposed method is tested on IEEE 30-bus system to evaluate the effectiveness of the problem. The network line, load and bus data have been taken [19] and the minimum and maximum limits on control variables along with the initial operating point are given in [20]. The system consists of six generator buses, 24 load buses and 41 lines including four transformers with off-nominal tap ratio. This system is tested in MATLAB simulation Environment for finding weak nodes in the system using fuzzy to locate UPFC. The corresponding test results are tabulated in Table 1.

Table.1:Fuzzy severity to find weak nodes.

S.No	Bus No	Severity	Voltage	L-Index	Rank
1	30	51.0083	0.9743	0.1478	1
2	29	50.0000	0.9860	0.1263	2
3	27	50.0000	1.0039	0.0219	3
4	26	50.0000	1.0062	0.0948	4

From the Table.1 the bus 30 has highest severity treated as weakest node in the system and ranked according to the severity. The line between 29-30 is selected as optimal location of UPFC and the corresponding parameter settings of PSO are shown in Table.2.

Table.2: Parameter settings of PSO.

S.No	Parameter	PSO
1	Population size	50
2	No.of iterations	150
3	Cognitive constant( $C_1$ )	2
4	Social Constant( $C_2$ )	2
5	Inertia weight	0.3-0.95

The OPF in the system after placing UPFC between 29-30 buses for fuel cost and fuel cost with valve point loading effects are shown in Table.3 and Table.4 respectively.

Table.3:Comparison of results:PSO with PSO-UPFC

Parameter	LIMITS		NR	PSO	PSO UPFC
	MIN	MAX			
$P_{G1}$	0.5	2.0	0.9921	1.7426	1.7392
$P_{G2}$	0.2	0.8	0.800	0.5270	0.5327
$P_{G3}$	0.1	0.35	0.2000	0.2105	0.2089
$P_{G4}$	0.1	0.3	0.2000	0.1193	0.1188
$P_{G5}$	0.1	0.5	0.5000	0.2140	0.2138
$P_{G6}$	0.12	0.4	0.2000	0.1200	0.1200
$V_{G1}$	0.95	1.10	1.0500	1.0833	1.1000
$V_{G2}$	0.95	1.10	1.0450	1.0634	1.0859
$V_{G3}$	0.95	1.10	1.0100	1.0337	1.0653
$V_{G4}$	0.95	1.10	1.0500	1.0167	1.0009
$V_{G5}$	0.95	1.10	1.0100	1.0297	1.0587
$V_{G6}$	0.95	1.10	1.0500	1.0605	1.0595
Cost (\$/h)			901.91	800.42	800.052
$P_{loss}$ (P.u)			0.2180	0.0994	0.0934
$L_I$			0.1483	0.1478	0.1379

Table.3: Comparison of results:PSO with PSO-UPFC

Parameter	LIMITS		NR	PSO	PSO UPFC
	MIN	MAX			
$P_{G1}$	0.5	2.0	0.9921	1.9708	1.9707
$P_{G2}$	0.2	0.8	0.800	0.3761	0.3786
$P_{G3}$	0.1	0.35	0.200	0.1920	0.1906
$P_{G4}$	0.1	0.3	0.200	0.1240	0.1246
$P_{G5}$	0.1	0.5	0.500	0.150	0.1500
$P_{G6}$	0.12	0.4	0.2000	0.120	0.1200
$V_{G1}$	0.95	1.10	1.0500	1.1000	1.1000
$V_{G2}$	0.95	1.10	1.0450	1.0783	1.0776
$V_{G3}$	0.95	1.10	1.0100	1.0656	1.0607
$V_{G4}$	0.95	1.10	1.0500	1.0384	1.0357
$V_{G5}$	0.95	1.10	1.0100	1.0507	1.0494
$V_{G6}$	0.95	1.10	1.0500	1.1000	1.0695
Cost (\$/h)			1071.7	950.4	949.2
$P_{loss}$ (P.u)			0.2180	0.1005	0.0990
$L_I$			0.1483	0.1330	0.1128

From Table:3 and Table:4 it is observed that the operating cost is reduced with PSO-UPFC compared to NR and PSO and also improved voltage stability with reduction in power loss. The corresponding graphical representation of the cost curves are shown in Fig.2 and Fig.3 respectively.

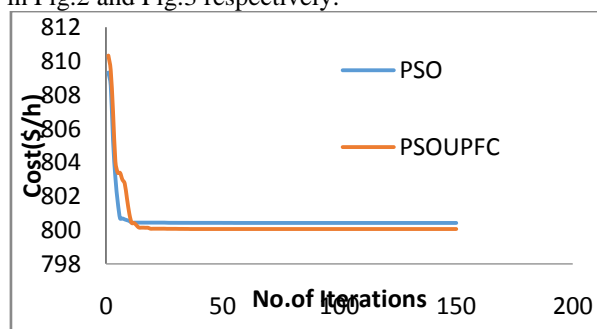


Fig.2: Smooth generating cost Versus No. of iterations.

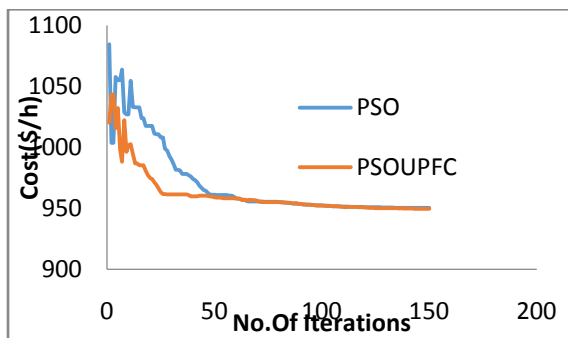


Fig.3: Non-smooth generating cost Versus No. of iterations.

## VII. CONCLUSIONS

In this paper, particle swarm optimization technique with UPFC has been formulated and applied to OPF problem with competing fuel cost and non-smooth fuel cost functions as objectives. UPFC is located close to weak node which was determined by Fuzzy which effectively improved the system performance. From the results it has been observed that the proposed technique reduced the fuel cost of both smooth and non-smooth cost function and also improved voltage stability with reduced power loss. It can be concluded that for a large power system, PSO algorithm can have significant advantage over exhaustive search by giving better solutions with lesser computational effort.

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