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OPTIMAL LOCATION OF UPFC FOR VOLTAGE STABILITY USING PARTICLE SWARM OPTIMIZATION

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***Abstract*— The objective of this paper is to reduce the power loss and to improve the voltage profile in transmission system. Current based model of UPFC is used, the proposed particle swarm optimization algorithm has been used for optimal sizing of Unified power flow controller (UPFC). The proposed method shows the easy manipulation of optimal power flow evaluations. The power loss and voltages are calculated for the optimal locations based on fuzzy system. In this paper, power loss reduction and voltage improvement for the various load conditions like light load, normal load and overloading cases and how the system performance is improved with the use of UPFC is demonstrated on 39 bus system.**

***Index Terms*—Flexible AC Transmission System (FACTS), Newton-Raphson Method (N-RM), Unified Power Flow Controller (UPFC), Particle Swarm Optimization (PSO).**

I. INTRODUCTION

A Flexible AC Transmission System (FACTS) device concept was described by N.G.Hingorani, in 1988s. The FACTS devices give more flexibility control for secure and economic operation of power systems. Among FACTS devices, the Unified Power Flow Controller (UPFC) concept was described by Gyugyi in 1991 [1].

Flexible AC transmission systems technology [2] has a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability, voltage, and stability constraints.

The UPFC [3] is used for the real-time control and dynamic compensation of Transmission systems, providing multifunctional flexibility required to solve many of the problems facing, while the power delivery. Within the framework of traditional power transmission concepts, the Unified Power Flow Controller [4] is able to control, simultaneously or selectively, all the parameters affecting power flow in the transmission line [5] (i.e., voltage, impedance, and phase angle), and this unique capability is signified by the adjective "unified" in its name. Alternatively, it can independently control both the real and reactive power flow in the line. It provides the flexibility to at the same time management all the transmission parameters of systems, The UPFC basically consists of two voltage source back-to-back converters, the first series converter connected through a series transformer, and another shunt converter connected through a shunt transformer. These two converters are coupled via common dc link provided by a dc storage capacitor

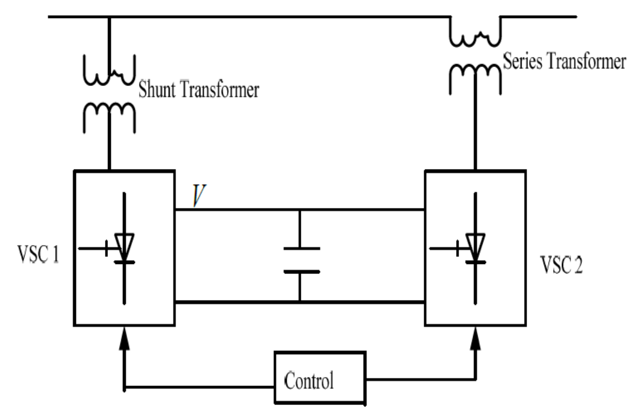

Fig 1: The Schematic diagram of UPFC

Therefore, in particle swarm optimization technique [6] is to find the best of feasible solution to a optimization problem. Consider the global optimum of an *n*-dimensional function. The PSO [7] algorithm is all particles are initiated randomly and evaluated to compute fitness together with finding the personal best (best value of each particle) and global best (best value of particle in the entire swarm) [8]. After that a loop starts to find an optimum solution. In the loop, first the particles' velocity is updated by the personal and global bests, and then each particle's position is updated by the current velocity [9].

Hence, in Section II, the equations of a current based model (CBM) are presented. In Section III, an Particle Swarm Optimization approach for the developed model is presented, comparing its performance with that of a CBM, seeking to analyze the behavior of UPFC in the New England network, of 39 bus bars. In Section IV, the Results are tabulated. In Section V, the conclusions are presented.

II. CURRENT BASED MODEL

The Current Based model introducing the current in the series converter as variable (see Fig. 1).

The voltage and current limits of the system are as follows;

Series Voltage: V_s

Series transformer impedance: Z_s

Transmission line impedance: Z'_e

$$0.90 \le V_{n,i} \le 1.10$$

$$0 \le I_{n,ij} \le I_{ijmax}$$

Let us consider i and j existent in the transmission line where the UPFC will be located, with impedance Z'_e. The bas bars j and j' are created in order to include the UPFC in the system.

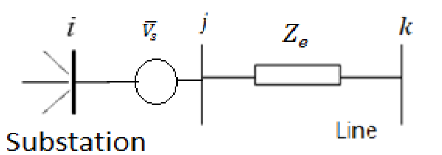

Fig 2: Equivalent model of UPFC in the electric network

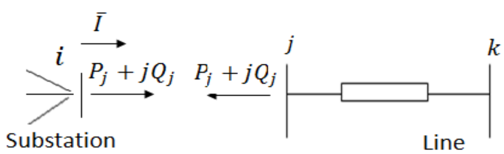

Fig 3: power Injected due to current in bus bars i and j.

The series impedance of UPFC coupling transformer Zs and the transmission line are added, resulting in the equivalent impedance $Z_e = Z'_e + Z_e$ connected to the internal node j and node j' is eliminated. The equivalent network is represented by π circuits in Fig.2, with the series voltage inserted between bus bars i and j.

A. power Injected due to current

The power consumption of the system load at bus bar i is called S_i^0.

Additional power S_i^c and S_j^c, due to current $\bar{I}$, are easily calculated according to Fig. 3. Current $\bar{I}$ introduces two variables i.e.,I,φ, related to module and phase of the current.

The power equations due to current:

$$S_i^c = \bar{V}_i I^* \qquad S_j^c = -\bar{V}_j \bar{I}^*$$

$$p_j^c = -V_j \cos(\varphi - \theta_j) \quad Q_i^c = -V_j I \sin(\varphi - \theta_j) \quad (2.1)$$

$$p_i^c = V_i I \cos(\varphi - \theta_i) \quad Q_i^c = V_i I \sin(\varphi - \theta_i) \quad (2.2)$$

And

$$P_i = P_i^0 + P_i^c \qquad P_j = P_j^c$$

$$Q_i = Q_i^0 + Q_i^c \qquad Q_j = Q_j^c \quad (2.3)$$

The new variables φ and I at n and 2n position, r new vector of variables written:

$$[x^t] = [\theta_1, \theta_2, \dots\dots, \theta_{n-1}, \varphi, V_1, V_2, \dots\dots, V_{n-1}, I]$$

B. Series Voltage Equations

The series voltage equation of the UPFC can be modeled.

The voltage equation between nodes i and j written by,

$$V_j - V_i = V_s \quad (2.4)$$

& the series voltage will be given by

$$\bar{V}_s = r V_i e^{j\delta} \quad (2.5)$$

Where r is the factor for series voltage and δ is the series voltage angle.

That equation substituted in (2.4)

$$\bar{V}_j - \left(1 + e^{j\delta}\right)\bar{V}_i = 0 \quad (2.6)$$

If r and δ are constant in regular power flow case, the complex variable are

$$A\angle\alpha = -(1 + r\angle\delta) \quad (2.7)$$

The equation (2.6) we can write

$$V_j + A\angle\alpha . V_i = 0 \quad (2.8)$$

The real and imaginary parts $F_n = 0$ and $G_n = 0$, respectively:

$$F_n = AV_i \cos(\alpha + \theta_i) + V_j \cos(\theta_j) \quad (2.9)$$

$$G_n = AV_i \sin(\alpha + \theta_i) + V_j \sin(\theta_j) \quad (2.10)$$

If r and δ are variables in an optimization case, we have

$$[x^t] = [\theta_1, \theta_2, \dots\dots, \theta_{n-1}, \varphi, V_1, V_2, \dots\dots, V_{n-1}, I, r]$$

$$F_n = V_j \cos(\theta_j) - V_i\,[\cos(\theta_i) + \cos(\theta_i + \delta)] \quad (2.11)$$

$$G_n = V_j \sin(\theta_j) - V_i\,[\sin(\theta_j) + \sin(\theta_i + \delta)] \quad (2.12)$$

The above F_n and G_n, are voltage equations

C. Power Balance Equations

The total power loss in a distribution system having 'n' number of branches is given by,

$$P_{TL} = \sum_{i=1}^{n} I_i^2 R_i \tag{2.13}$$

The power balance equation between series and shunt converters. The series power will be added to the shunt power of bus bar i .

Let us calculate the power in the series converter:

$$S^s = re^{j\delta}\overline{V}_i I\angle -\varphi \tag{2.14}$$

Splitting the equation (3.11) active and reactive powers:

$$P^s = rV_i I\cos(\theta_i + \delta - \varphi) \tag{2.15}$$

$$Q^s = rV_i I\sin(\theta_i + \delta - \varphi) \tag{2.16}$$

Active power P^s is included in node i.

D. Complex Jacobian

The Jacobian matrix, with UPFC power addition

$$J_c^0 = \begin{bmatrix} H^0 & N^0 \\ J^0 & L^0 \end{bmatrix} \tag{2.17}$$

Let us add the injected power due to current I bus bar i and j and also the voltage equation F_n(2.11) and G_n (2.12). The additional correction of the Jacobian matrix, due to the power balance equation, is also included, complementing the formulation.

$$[J] = [J_c^0] + [J_c] + [J^s] \tag{2.18}$$

The Jacobian matrix due to injection current. Where r and δ are constants:

Hterms:

$$H_{in}^c = \frac{\partial P_i^c}{\partial \varphi} = Q_i^c \qquad H_{jn}^c = \frac{\partial P_j^c}{\partial \varphi} = Q_i^c$$

$$H_{ii}^c = \frac{\partial P_i^c}{\partial \theta_i} = -Q_i^c \qquad H_{jj}^c = \frac{\partial P_j^c}{\partial \theta_j} = -Q_i^c$$

$$H_{ni} = -AV_i\sin(\alpha + \theta_i) \qquad H_{nj} = -V_j\sin(\theta_j)$$

N terms:

$$N_{in}^c = I\frac{\partial P_i^c}{\partial I} = P_i^c \qquad N_{jn}^c = I\frac{\partial P_j^c}{\partial \varphi} = P_j^c$$

$$N_{ii}^c = V_i\frac{\partial P_i^c}{\partial V_i} = P_i^c \qquad N_{jj}^c = V_j\frac{\partial P_j^c}{\partial V_j} = P_j^c$$

$$N_{ni} = AV_i\cos(\alpha + \theta_i) \qquad N_{nj} = V_j\cos(\theta_j)$$

J terms:

$$J_{in}^c = \frac{\partial Q_i^c}{\partial \varphi} = -P_i^c \qquad J_{jn}^c = \frac{\partial Q_j^c}{\partial \varphi} = P_j^c$$

$$J_{ii}^c = \frac{\partial Q_i^c}{\partial \theta_i} = P_i^c \qquad J_{jj}^c = V_j\frac{\partial Q_j^c}{\partial \theta_j} = P_j^c$$

$$J_{ni} = AV_i\cos(\alpha + \theta_i) \qquad J_{nj} = V_j\cos(\theta_j)$$

L terms:

$$L_{in}^c = I\frac{\partial Q_i^c}{\partial I} = Q_i^c \qquad L_{jn}^c = I\frac{\partial Q_j^c}{\partial \varphi} = Q_j^c$$

$$L_{ii}^c = V_i\frac{\partial Q_i^c}{\partial \theta_i} = Q_i^c \qquad L_{jj}^c = V_j\frac{\partial Q_j^c}{\partial \theta_j} = Q_j^c$$

$$L_{ni} = AV_i\sin(\alpha + \theta_i) \qquad L_{nj} = V_j\sin(\theta_j)$$

Correction in Jacobian terms due to power balance:

H terms:

$$H_{ii}^s = \frac{\partial P_s}{\partial \theta_i} = -rV_i I\sin(\theta_i + \delta - \varphi) = -Q^s$$

$$H_{in}^s = \frac{\partial P_s}{\partial \varphi} = rV_i I\sin(\theta_i + \delta - \varphi) = Q^s$$

N terms:

$$N_{in}^s = I\frac{\partial P_s}{\partial I} = rV_i I\cos(\theta_i + \delta - \varphi) = P^s$$

$$N_{ii}^s = V_i\frac{\partial P_s}{\partial V_i} = rV_i I\cos(\theta_i + \delta - \varphi) = P^s$$

Where r and δ are variables we have the following changes in the jacobian, which is no longer a square matrix.

Generally used load flow analysis like Newton-Raphson methods can be used to find the load flow in transmission systems load flow solution has been used following above equation.

E. Optimal Location S Using Funny Approach

For Optimal location of UPFC on load buses fuzzy approach is used. Fuzzy logic is considering the following two objectives (i) power loss reduction (ii) maintaining voltage profile within the acceptable limits (0.9p.u – 1.1p.u). Power loss reduction (PLI) and per unit voltages (p.u) are taken as inputs to write fuzzy rules to determine the UPFC placement suitability of each node.

$$PLI = \frac{LR(i) - LR(min)}{LR(max) - LR(min)} \tag{2.19}$$

& $$LR_i = P_i^1 - P_i^2 \tag{2.20}$$

Where i= 1 to number of load buses.

LR_i = loss reduction.

P_i^1 = Real power for normal load flow.

$P_i^2 =$ Real power for load flow by total compensation of reactive load at i^{th} node.
The LR input is normalized by the following equation, so that the values will fall between 0 to 1. Where the largest value will assign as 1 and the smallest as 0.

III. PROPOSED METHOD

A. *Particle Swarm Optimization Method*

In 1995 James Kennedy and Russell C. Eberhart proposes an algorithm known as Particle Swarm Optimization (PSO) which was inspired from birds flocks and fish schooling. It is a computational method that optimizes a problem by iteratively trying to improve a candidate solution. Population of birds or fish is known as swarm. Each candidate of swarm is known as particle. These particles are moved (or updated) around in the search-space according to a few simple formulae.

PSO is initialized with a group of random particles and the searches for optima by updating generations. In every iteration each particle is updated by following "two best" values. The first one is the best solution (fitness value) it has achieved so far. This is called P_{best}. Another value that is tracked by the particle swarm optimizer is the best value obtained so far by any particle in the population. This best value is the global best called G_{best}. After finding the best values the particles updated its velocity and position with the following equation (3.5).

The performance of the PSO is greatly affected by its parameter values. Therefore, a way to find a suitable set of parameters has to be chosen. In this case, the selection of the PSO parameters follows the strategy of considering different values for each particular parameter and evaluating its effect on the PSO performance.

B. *Original Version With Inertia Weight*

The main purpose of a standard continuous optimization technique is to find the best of all feasible solutions to a optimization problem minimizing or maximizing a continuous function with respect to several constraints.

$$\underset{x}{\text{minimiz}} = f(x), \qquad f(x): R^n \to R \qquad (3.1)$$

$$\text{subject to } g_i(x) \le 0, i = 1,2 \ldots., m$$

$$h_i(x) = 0, i = 1,2 \ldots., p$$

Where f(x) is called objective or fitness function and gi(x) and hi(x) respectively define the inequality and equality constraints.

Then the personal best position $P_{best,t}$ at the next time step, $t+1$, where $t \in [0, \ldots., n]$, is calculated as

$$P_{best,t}^{t+1} = \begin{cases} P_{best,t}^{t} & if\ f(x_i^{t+1}) > P_{best,i}^{t} \\ x_i^{t+1} & if\ f(x_i^{t+1}) \le P_{best,i}^{t} \end{cases} \qquad (3.2)$$

Where $f : R^n \to R$ is the fitness function. The global G_{best} at next time step, t is calculated as

$$G_{best} = min\{P_{best,t}^{t}\}, where\ i \in [1, \ldots, n] and\ n > 1$$

The global best position G_{best} is the best position discovered of the particles in the entire swarm. For gbest method, the velocity of particle i is calculated by

$$V_{ij}^{t+1} = V_{ij}^{t} + c_1 r_{1j}^{t}[P_{best,i}^{t} - x_{ij}^{t}] + c_2 r_{2j}^{t}[G_{best,i}^{t} - x_{ij}^{t}] \quad (3.3)$$

& $\quad X_i^{k+1} = X_i^k + V_i^{k+1}$

(3.4) V_{ij}^{t} is the velocity vector of particle i in dimension j at time t;
x_{ij}^{t} is the position vector of particle i in dimension j at time t;
$P_{best,i}^{t}$ is the persona best position of particle i in dimension j. From initialization through time t;
$G_{best,i}^{t}$ is the global best position of particle i in dimension j From initialization through time t;

c_1, c_2 are positive acceleration constants;

X_i^k Position of Particle in K^{th} iteration

r_{1j}^{t} r_{2j}^{t} are random numbers from uniform distribution $\cup (0,1)$ at time t.

C. *Inertia weight*

The inertia weight $'w'$ will at every step be multiplied by the velocity at the pervious step, i.e. V_{ij}^{t}. Therefore, in the gbest PSO, the velocity equation of the particle i with the inertia weight changes from equation (2.3) to

$$V_{ij}^{t+1} = \omega V_{ij}^{t} + c_1 r_{1j}^{t}[P_{best,i}^{t} - x_{ij}^{t}] + c_2 r_{2j}^{t}[G_{best,i}^{t} - x_{ij}^{t}]$$

The inertia weight can be implemented either as a fixed value or dynamically changing value. Initial implementations ω used a fixed value for the whole process for all particles.

Usually the large inertia value is high at first, which allows all particles to move freely in the search space at the initial steps and decreases over time. The decreasing inertia weight ω has produced good results.

$$\omega^{t+1} = \omega_{max} - \left(\frac{\omega_{max}-\omega_{min}}{t_{max}}\right) t\,, \quad \omega_{max} > \omega_{min} \tag{3.6}$$

$\omega_{max} and\ \omega_{min}$ are the initial and final value of the inertia weight respectively.

t_{max} is the maximum iteration number.

t is the current iteration number.

Constraints considered are,

$$\left.\begin{array}{l} V_i^{min} \le V_i \le V_i^{max} \\ X_i^{min} \le X_i \le X_i^{max} \end{array}\right\} \tag{3.7}$$

Data used for PSO:

nbb=39; bmva=100; nop = 150; $C1$ = 0.9; $C2$ = 0.9, $wmax$= 0.9, $wmin$ = 0.4, T= 1000.

D. PSO Algorithm to find the UPFC sizes

Step 1: The start [nop x *n*] number of particles position are generated randomly within the limits, where *n* is the number of UPFCs devices and nop is the population size.

Step 2: The [nop x n] number of initial velocities (2.20) is randomly generated within limits. The Iteration count is start.

Step 3: By placing the '*n'* UPFC devices of each particle position amd locations are mention. The load flow analysis is performed to find the real power loss PL_{upfc}. Then go to step1 again find the total real power losses. Fitness value corresponding to each particle is evaluated using the equation (3.8) for maximum loss reduction. Fitness equation to find maximum loss reduction is written by:

Fitness $F_A = P_L - P_{Lupfc}$ (3.8)

Where, PL is Original total real loss,
PLupfc is Present total real loss with UPFC.

Step 4: New velocities for the particles within the limits are calculated using equation (3.3) and the particle positions are updated using equations (3.4).

Step 5: the particles are updated, load flow analysis is starting the iteration count; new-Fitness of velocities for the particles is calculated using equation (3.5). If the new-fitness is greater than p_{best}-fitness then the corresponding particle is moved to the p_{best}-particle.

Step 6: From maximum of p_{best}-fitness particle is indicate the g_{best}-fitness and the corresponding value are stored as g_{best}-particle.

Step 7: From p_{best}-fitness maximum fitness and average fitness values are calculated. Error is calculated using the below equation.

Error = (max. fitness – avg. fitness) (3.9)

If this error less than a specified tolerance then go to step 9.

Step 8: Increase the current iteration count is incremented and if iteration count is not reached maximum next go to step 4.

Step 9: g_{best}-fitness of maximum loss reduction and g_{best}-particle gives the optimal location and UPFC sizes indicate.

The above steps are a trade-off between the number of particles and the number of iterations of the swarm and each particle fitness value has to be evaluated using a power flow solution.

IV. RESULTS

The proposed method approach is used for UPFC placement for the objectives considered, is placed on the node having maximum loss reduction and poor voltage profile which is discussed below.

Table 1: Current limits for 3 UPFCs

LINE	**UPFC**	**Current limits**
32 - 31	1	0 – 4 p.u
39 - 38	2	0 – 3 p.u
13 – 14	3	0 – 2 p.u

Table 2: Results for 39 bus system with 3 UPFCs with PSO for various locations

	CB [5]	**PSO [6]**		
Load	100%	50%	100%	160%
P_L before	918.8646	92.7872	417.498	1285.938
P_L after	624.923	56.4559	242.770	856.7589
Q before	614.9199	61.9079	278.976	861.3536
Q after	460.3050	37.6502	162.099	633.5031
% Loss reduction	**31.99**	**39.15**	**41.85**	**33.39**
Vmin Before	0.884	0.9404	0.8730	0.7754
Vmin After	0.901	0.9584	0.9134	0.8301
Time	116.2632	145.39583	152.635	221.9124
Iter	52	48	49	75

In the above table 2 show the proposed PSO model was compared with the traditional Current Based Model, showing coincident results in power flow evaluations.

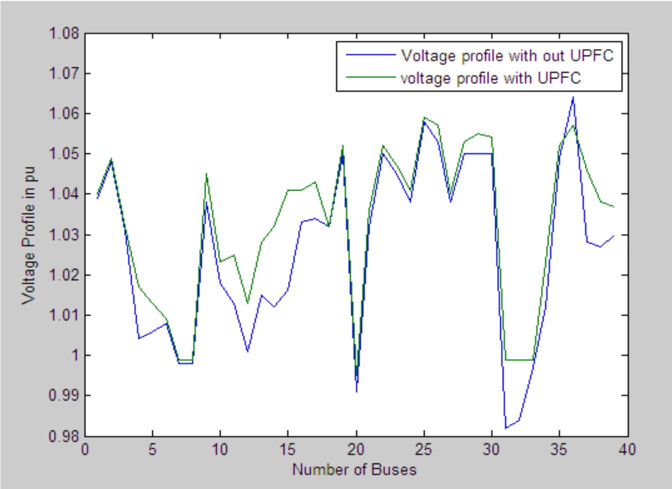

Fig 1: Voltage profiles of 39 bus With 3 UPFC

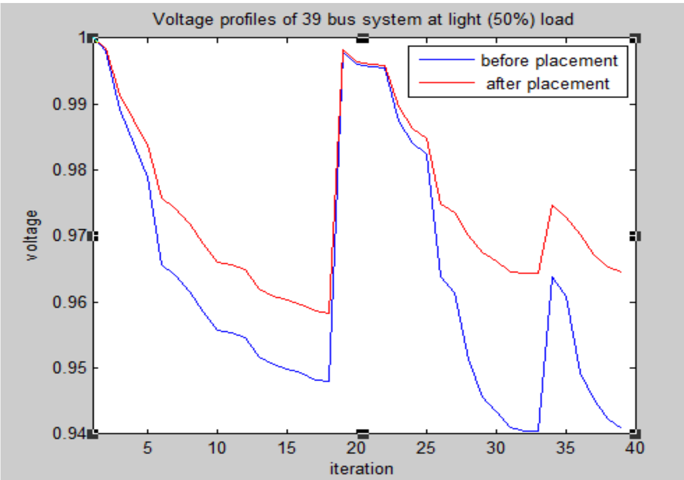

Fig 2: Voltage profiles of 39 bus system at light (50%) load

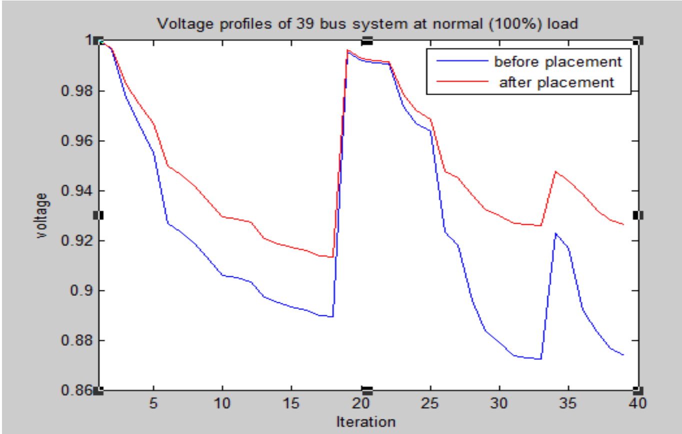

Fig 3: Voltage profiles of 39 bus system at normal (100%) load

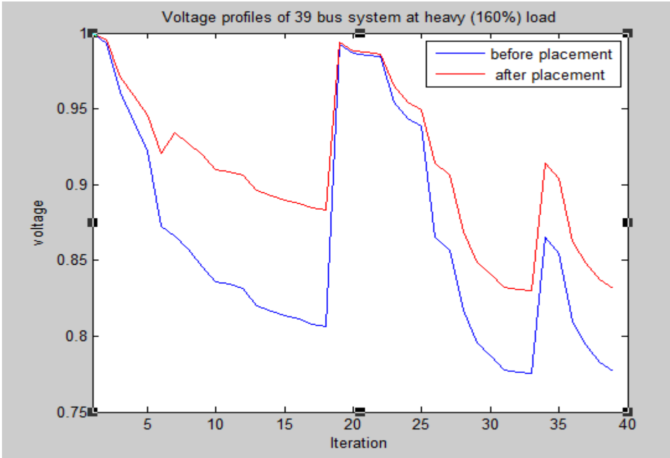

Fig 4: Voltage profiles of 39 bus system at heavy (160%) load

In the above table device shows the performance of UPFC at different or various conditions like light load (50%), normal load (100%) and Heavy loads (160%). Graphical representation of the voltages for the four loading conditions. From above table2, the min voltage is improved from 0.8730 to 0.9134 p.u.

V. CONCLUSION

The proposed fuzzy and PSO method in this paper resulted in the power loss reduction and voltage profile improvement in the transmission system. Various optimal locations were obtained for the UPFC suitability index by fuzzy approach. Optimal sizes for the respective locations are obtained by using PSO. The results show that power loss is reduced and the voltage profile is maintained with in specified limits under different load conditions like 50%, 100%, and 160% loads. The power loss reduction obtained from existing method was **31.99%** and, the power loss reduction with proposed method is **41.85%.** This implies that the system stability is improved with the proposed method.

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