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Loss Optimization for Voltage Stability Enhancement Incorporating UPFC Using Particle Swarm Optimization

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Abstract – The placement of the UPFC is the major concern to ensure the full potential of utilization in the transmission network. Voltage stability enhancement with the optimal placement of UPFC using stability index such as modal analysis, Voltage Phasor method is made and the loss minimization including UPFC is formulated as an optimization problem. This paper proposes particle swarm optimization for the exact real power loss minimization including UPFC. The implementation of loss minimization for the optimal location of UPFC was tested with IEEE-14 and IEEE-57 bus system.

Keywords: Voltage stability, sensitivity analysis, voltage phasor approach, particle swarm optimization

1. Introduction

The problem of voltage stability is one of the major concerns in the operation of power system. Better utilization of power with minimum loss by installing new FACTS devices such as SSSC, STATCOM & UPFC has become imperative.

It is known that power through an AC transmission line is the function of line impedance, voltage magnitude and phase angle between the sending end and receiving end voltages. FACTS devices can be utilized to change the power flow by changing the parameters of the network. Thus the power transmission capabilities can be improved and loss can be minimized in turn minimizes the device cost.

The objective of this study is to develop a loss minimization algorithm incorporating UPFC .The strategic locations of the compensating devices are based on the voltage stability index. This will minimize the investment cost of the compensators.

Various mathematical techniques are available in solving voltage stability problems. These techniques are normally based on continuation power flow, voltage stability indices such as L-index, Line flow index. These techniques are considered for placement strategy of FACTS devices for voltage stability enhancement. However optimal placement of the UPFC play a significant role in the power system operation, control and planning.

The optimal placement of the UPFC improves the voltage stability margin along with the minimization in the loss which contributes in realizing the investment cost of the UPFC. In general, conventional optimization methods are not able to locate the global optimum but only leads to a local optimum.

The premature convergence of the genetic algorithm degrades the performance and reduces its search capability, by which it leads a higher property of local minimum. The particle swarm optimization (PSO) can generate high quality solutions within short time with high global searching ability at the beginning of the iteration and the local search near the end of the iteration. Therefore, in this paper PSO is used for the loss minimization, incorporating UPFC, based on the stability index. The voltage stability enhancement and loss minimization is evaluated for IEEE 14 and IEEE 57 bus system incorporating UPFC at its optimal location obtained using PSO technique.

The results indicate that PSO is capable of undertaking a global search with a fast convergence rate and feature of robust computation.

2. Static Voltage Stability Analysis

Static voltage stability analysis may be carried out considering (i) Q-V sensitivity analysis (ii) Voltage Phasor approach

2.1 Q-V Sensitivity Analysis

Power system network can be represented in a linearized form [15] as shown in equation (1)

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{1}$$

Where

ΔP- incremental change in bus real power

ΔQ - incremental change in bus reactive power

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$\Delta\theta$ – incremental change in bus voltage angle

ΔV – incremental change in bus voltage magnitude

From equation (1) it is clear that system voltage stability is affected by both P and Q. Based on the above considerations the voltage stability is evaluated by considering the incremental relationship between Q and V keeping P constant. This is analogous to Q-V curve approach. Let $\Delta P=0$ in equation 1. Then

$$\Delta Q = J_R \Delta V \tag{2}$$

Where

$$J_R = \left[J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV} \right] \tag{3}$$

and JR-1 is the reduced matrix of the system . From the equation (2) we may write

$$\Delta V = J_R^{-1} \Delta Q \tag{4}$$

The V-Q sensitivity is calculated by solving equation (2).Voltage stability characteristics of the system can be identified by computing the Eigen values and Eigen vectors of the reduced Jacobian matrix J_R. Let

$$J_R = \xi \Lambda \eta \tag{5}$$

Where

ξ - right eigen vector of the matrix J_R

Λ - left eigen vector of the matrix J_R

η - diagonal Eigen value of the matrix λi of J_R

If $\lambda_i > 0$, the ith modal reactive power variations are along the same directions, indicating that the system voltage is stable. If $\lambda_i < 0$, the ith modal reactive power variations are along the opposite directions, indicating that the system voltage is unstable. From the above considerations the degree of stability of the ith modal voltage can be determined. However, When $\lambda_i = 0$, the modal voltage collapses because any change in reactive power causes infinite change in the voltage.

In the ith mode, the relative participation of bus k can be expressed by the bus participation factor.

$$P_{ki} = \xi_{ki}\, \eta_{ik} \tag{6}$$

P_{ki} determines the contribution of λ_i to the V-Q sensitivity at bus k.

The size of the bus participation P_{ki} indicates the effectiveness of the remedial action in stabilizing the particular mode.

Similarly the branch participation factor can be expressed for jth branch as shown in equation (7)

$$P_{ji} = \frac{\Delta Q_{loss}\, for\ the\ branch\ j}{\max imum\ \Delta Q_{loss}\ for\ all\ branches} \tag{7}$$

From the above equation, it may be concluded that branch with high participation factor P_{ji} are either weak links or heavily loaded. This knowledge of branch participation factor may be useful for identifying remedial measures to alleviate voltage stability problems.

2.2 Voltage Phasor Approach

To identify the critical transmission path with respect to the loading the voltage collapse proximity index (VCPI) using voltage phasor approach (VPA) is considered. In this approach, the transmission path stability index (TPSI) is considered as Voltage stability index and is defined as shown in equation (8), where V_g is the reference voltage and ΔV_a' sum of the voltage drop along the transmission path. The corrected voltage drop of a line segment ΔV_{ai}' which is the projection of the receiving end bus voltage of that line segment on the generator bus. The initial point of the transmission path [2] is expressed using the equation (9).

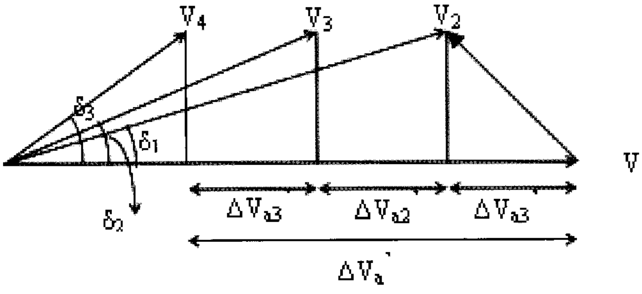

Fig. 1. Phasor diagram of a 4 bus system

$$TPSI = 0.5V_g - \Delta V_a^{'} \tag{8}$$

Where, Vg is the voltage of the generating bus,

$\Delta V_a^{'} = \sum \Delta V_{ai}^{'}$ of the whole transmission path being analyzed.

$$\Delta V_{ai}^{'} = \left(V_i - V_{i+1} \cos\delta_{i+1} \right) \cos\delta_{i+1} \tag{9}$$

Where, i vary from bus 1 to bus n-1

Active and reactive power transmission path (APTP & RPTP) is defined through the declining phase angle and voltage magnitudes with respect to the generator bus, is used to identify the TPSI. The power transfer stability through the transmission path will be decided on the value of this TPSI which also identifies the voltage collapse proximity index.

From the knowledge of the TPSI value the voltage instability problems along any transmission line can be identified and analyzed.

3. Unified Power Flow Controller

The problems associated with the voltage stability margin, as analyzed in section 2, is normally corrected by installing a compensating device like SVC, STATCom and UPFC.

The model of UPFC as shown in fig 2 where a controllable series voltage source V_s is placed between nodes i and j and in series with the line reactance X_s [4-5]. The effect of the controlled voltage V_s on the system is expressed as shown in equation (10) and (11).

$$V_i^{'} = V_s + V_i \qquad (10)$$

The series voltage source Vs is controllable in magnitude and phase

$$V_i^{'} = rV_r e^{j\gamma} \qquad (11)$$

Where $0<r< r_{max}$ and $0<\gamma<2\pi$

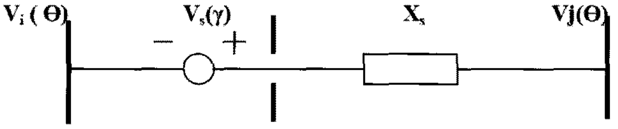

Fig. 2. Voltage source model of UPFC

For the shunt/current injection model of UPFC is obtained by replacing the voltage source by an equivalent current source given by $I_s = -j\, b_s V_s$ in parallel with the line, where $b_s = 1/X_s$.

To incorporate the UPFC effect on load flow analysis the admittance matrix is modified by adding a reactance with X_s between nodes i and j. This modifies the Jacobian matrix and hence can improve the stability margin by injecting appropriate power (real and reactive) into the system.

4. Formulation of Objective Function for Loss Minimization

For an N bus system the loss equation can be written as shown in equation (12) [12]

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right)\right] \qquad (12)$$

Where Pi, Pj and Qi, Qj respectively, are real and reactive power injected at bus i and j, α_{ij} and β_{ij} are the loss coefficients defined by

$$\left.\begin{aligned} \alpha_{ij} &= \frac{r_{ij}}{|V_i||V_j|}\cos(\delta_i - \delta_j) \\ \beta_{ij} &= \frac{r_{ij}}{|V_i||V_j|}\sin(\delta_i - \delta_j) \end{aligned}\right\} \qquad (13)$$

Where, rij is the real part of the ijth element of the Z_{bus} matrix. With UPFC incorporated in any one line (j) the total loss can be written as follows [9]

$$P_{lj} = \left(P_{ljc}\left[P_{ic} + P_{kc}\right]\right) \qquad (14)$$

The above loss equation stated in (14) if minimized by incorporating the UPFC the optimal amount of power will be available for supplying without overloading the line with an acceptable voltage margin. Thus optimal location of UPFC influences the possible increase in power flow capacity of the network in particular to the respective transmission line. Keeping this objective, the optimization problem is formulated as shown in equation (15)

Objective function is

Min (F,u)

$$\text{PL}(V,\delta) = \sum_{i=1}^{n} P_{Li} \qquad (15)$$

Subject to $f(v,\delta) = 0$

$f_1(s) < m1$

$f_2(s) > m2$

P_{Li} is the total power loss with and without UPFC device in a power system network

$f_1(v,\delta)$: conventional power flow constraints

f_1 (s) and f_2 (v) are inequality constraints for UPFC and conventional power flows.

The effect of UPFC device is virtually changed the power system parameters. These parameters when substituted on the objective function give different results for various locations of UPFC. To solve this type of combinational problem, the particle swarm optimization technique is proposed.

5. Particle Swarm Optimization

5.1 Basic PSO

Particle swarm optimization is a well known novel optimization method developed by Kennedy and Eberhart [16] and is being used in different fields for optimization.

This technique initialized with a group of random particles search for optima by updating generations. Each particle is treated as a point in a D dimensional space.

The ith particle is represented as

$$X_i = (X_{i1}, X_{i2, \dots\dots\dots\dots} X_{id})$$

The best previous position of the ith particle is recorded and represented as

$$P_{besti} = (P_{besti1}, P_{besti2}, \dots\dots P_{bestid})$$

The index of the best particle among the entire particle in the population is represented by the symbol $g_{best\ id}$. The rate of the position change (velocity) for the particle is represented as

$$V_i = (V_{i1}, V_{i2, \dots\dots\dots\dots} V_{id})$$

After the search procedure for the Pbest id and gbest id the modified velocity and position of each particle can be calculated using the current velocity and the distance from P_{best} id to $g_{best\ id}$ as shown in the following equation.

$$\begin{aligned} V_{id}(t+1) &= W * V_{id}(t) + C_1 * rand() * (P_{best\ id} - X_{id}(t)) \\ &+ C_2 * rand() * (g_{best\ id} - X_{id}(t)) \end{aligned} \quad (16)$$

Where,

i =1,2,3,…..n

d = 1,2,3,…..m

n: number of particles

m: solution's dimensions i.e., the number of control variables

$V_{id}(t)$: current velocity of the particle i at iteration t

V_{id} (t+1):modified velocity of particle i

Rand: random number between 0 and 1

X_{id} (t): current position of particle i at iteration t

$P_{best\ id}$: P_{best} of particle i

$g_{best\ id}$: g_{best} of particle i

W: weight function for velocity of particle i

C_i: weight coefficient of each term

The first term on the RHS of the equation is the previous velocity of the particle. The second and third term are utilized to change the velocity of the particle. Without the second and third term, the agent will keep on flying in the same direction until it hits in the boundary. In the end the particles will try to converge to the P_{best} or g_{best}.

V_{max}: So from the convergence V_{max} is obtained V_{max} that is the maximum change in one particle can take during the iteration, which if too high the particle must fly past good solutions, similarly if it is too small particles may not explore sufficiently beyond the local solution.

C: The constant C_1 and C_2 represent acceleration constants or learning factors, usually considered equal and ranges from [0,4] when C_1=C_2=2

W: To control the impact of previous history of velocities on the current velocity the inertia weight W is employed which influences the trade off between global and local exploration abilities of the flying point. Thus suitable selection of inertia weight W can provide a balance between global and local exploration abilities and will require less iteration on average to find the optimum. W can be calculated according to the following equation,

$$W = W_{max} - \frac{W_{max} - W_{min}}{iter_{max}} \times iter \quad (17)$$

$Iter_{max}$ is the maximum number ojf iterations

Iter –is the number of iterations until the current stage

Where W_{max} =0.9 and W_{min} =0.4

Using the above equation, a certain velocity that gradually gets close to P_{best} and g_{best} can be calculated, which can be further used to calculate the current position with the following equation,

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \quad (18)$$

X_{id} (t): current position of particle i at iteration t

X_{id} (t+1): current position of particle i at iteration t+1

V_{id} (t+1): modified velocity of particle i

5.2 PSO Algorithm

The following PSO algorithm is used to obtain the optimal location of UPFC for loss minimization

Step 1: Initial searching points and velocities are randomly generated within their limits

Step 2: Pbest is set to each initial searching points. The best evaluated values among the P_{bests} are set to g_{best}.

Step 3: New Velocities are calculated using equation (16).

Step 4: If $V_{id}(t+1)<V_{dmin}$
then $V_{id}(t+1)=V_{dmin}$ and if $V_{id}(t+1)>V_{dmax}$
then $V_{id}(t+1)=V_{dmax}$

Step 5: New searching points are calculated using eqn (18).

Step 6: Check the capacity limits constraints,
If $P_{id}(t+1)>P_{dmax}$
then $P_{id}(t+1)=P_{dmax}$ and if $P_{id}(t+1)<P_{dmin}$
then $P_{id}(t+1)=P_{dmin}$

Step 7: Evaluate the fitness values for new searching point. If evaluated value of each agent is better than previous P_{best} then set to P_{best}. If the best P_{best} is better than g_{best} then set to g_{best}.

Step 8: If the maximum iteration is reached stop the process otherwise go to step 3.

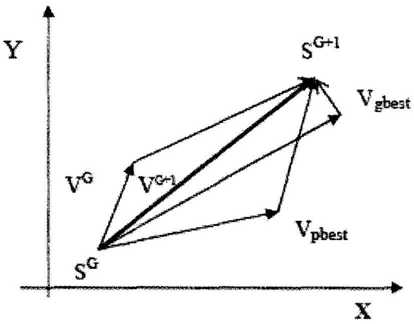

Fig. 3. Concept of modification searching points in PSO

6. Simulation results

Power flow is solved with the help of Mat lab 7.0. Simulation was carried out on IEEE 14 and IEEE 57 bus test system. To verify the effectiveness of the proposed PSO based exact loss minimization by incorporating UPFC in the system.

6.1 Case Study - I

Both modal analysis and voltage phasor approach (VPA) are applied at the base case loading condition of the IEEE-14 bus system. From the analysis the smallest eigen value is 1.407 and the corresponding mode is 6. Thus mode 6 is the critical mode or the least stable mode. Bus participation factors for this mode are generated to identify the critical bus in the system. It is identified that bus 14 with the highest bus participation factor of 0.56692 is found to be weakest or closest to instability.

From fig 5 the major zone of voltage dip lies in the region of buses 14, 9 and 10.Placing the UPFC in this zone will improve the voltage profile.

With VPA analysis various APTPs and RPTPs are shown in fig 4. From fig 4 TPSI for the path A1 is minimum for the APTP and RPTP. The path A1 corresponds to line segment (2-4), (4-9) is also shown. Hence the line segment 4-9 is considered for the placement of UPFC because line 2-4 is the generator line. The results are not at par with the modal analysis.

Fig 5 shows the voltage profile of IEEE 14 bus system with UPFC when placed in the line 13-14 and 4-9. It can be visualized from the fig 5 that both the locations are almost giving the same voltage profile. The exact transmission line loss, PL, of the system is calculated. The transmission line loss when UPFC placed in the line 13-14 is given by 0.7288p.u and on line 4-9 is given by 0.7379 p.u. To identify the optimal placement of UPFC line losses are formulated as an optimization problem.

The loss minimization algorithm is then carried out with PSO for both locations. The PSO algorithm is made to run for 50 iterations. The value of the loss (P_L), which is the objective function, gradually converges to an optimal value of 0.7207p.u. and 0.73228 p.u. for bus location 14-13 and 4-9 p.u respectively. The optimum voltage profile which results in the corresponding minimized value of the exact transmission loss (P_L) is represented graphically for the location 14-13 and 4-9 respectively.

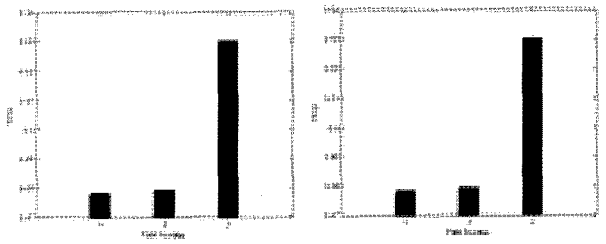

Fig. 4. TPSI for APTP and RPTP at the base case loading condition.

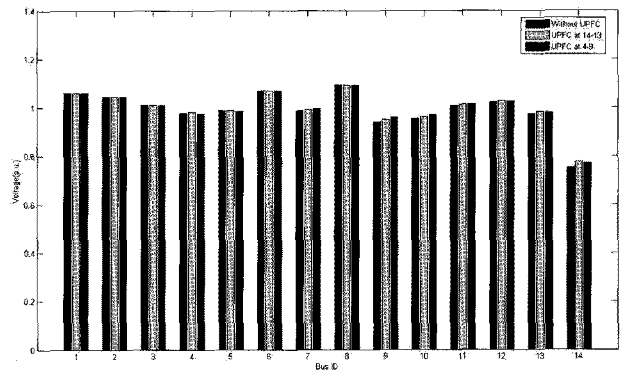

Fig. 5. Voltage profile with and without UPFC in the line 14-13 and 4-9

Fig 6 shows the convergence characteristics for UPFC of the PSO for 50 numbers of iterations with two different locations between 14-13 and 4-9.

It is seen from the fig 6 that the convergence for the location 4-9 is smoother and settles faster than 14-13 location. From the data it is understood that line segment 4-9 is a having transformer hence cannot be considered for the optimal location. Hence line segment 14-13 is considered for the optimal location of UPFC.

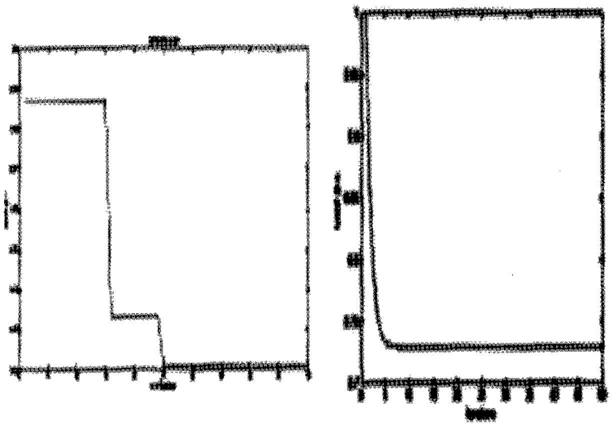

Fig. 6. Convergence characteristics for UPFC in the bus location 14-13 and 4-9

6.2 Case Study -II

Both modal analysis and the VPA approach is applied to IEEE-57 bus system at the base case loading condition. The smallest Eigen value is 0.50468.and the corresponding mode is 16. Thus mode 16 is the critical mode. Bus 24 with the highest participation factor of 0.20851 is the weakest bus.

Table 1. Comparison of real power loss with and without UPFC before and after Optimization for IEEE 14 bus.

Bus Location	P_L without UPFC	Loss with UPFC	Loss after optimization with UPFC
14-13	0.7644	0.7288	0.7207
4-9	0.7644	0.7379	0.7308

The major zone of voltage dip lies in the region of bus number 20 to 30. Placing the UPFC in this zone will improve the voltage profile.

VPA is now applied to the system. In this, there are 14 APTP and 8 RPTP transmission paths are identified and then TPSI values for the APTP and RPTP are then computed. Fig.7 reveals that the APTP path A3 and the RPTP path R3 showing the minimum value of TPSI. The path corresponds to line segment 1-15 and 15-14.

But 14-15 does not fall in the weakest voltage profile. Hence this can not be considered for the placement of UPFC. Bus 24 is identified as optimal placement of UPFC based on the voltage profile and through modal analysis.

The loss minimization algorithm is carried out with UPFC using PSO for the location of 24-25.

Fig 9 shows the voltage profile of the IEEE 57 bus system with and without UPFC after optimization in the location 24-25.

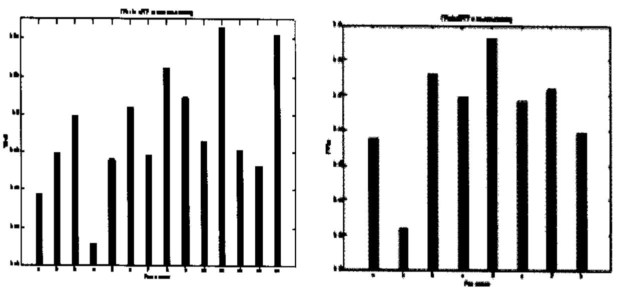

Fig. 7. TPSI for APTP and RPTP at the base case condition of IEEE 57 bus system

Table 2. Comparison of real power loss with and without UPFC before and after Optimization for IEEE 57 bus.

Bus Location	P_L without UPFC	Loss with UPFC	Loss after optimization with UPFC
24-25	0.3218	0.2971	0.2518

Fig 8 shows the convergence characteristics of the system with PSO for 50 iterations.

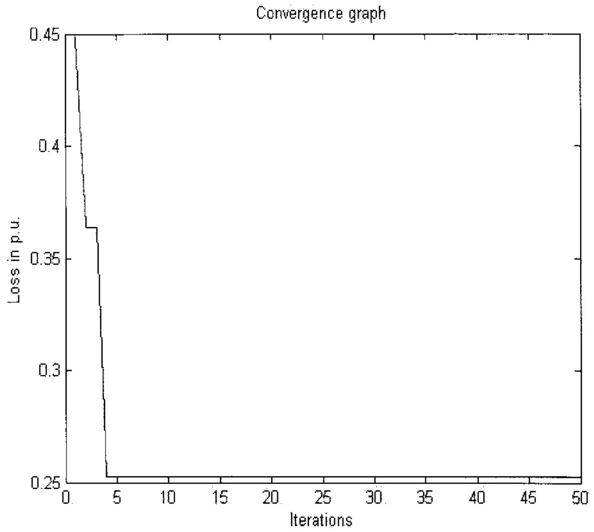

Fig. 8. Convergence characteristics for UPFC in the bus location 24-25

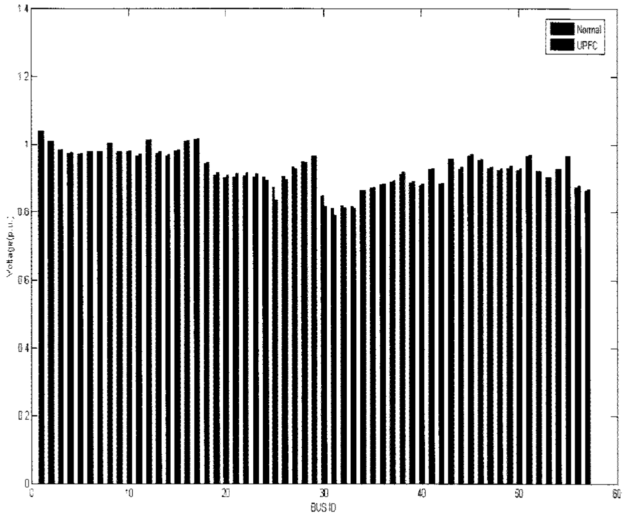

Fig. 9. Voltage profile of IEEE 57 bus system with and without UPFC

5. Conclusion

In this study a new method is presented for the optimal placement of UPFC to enhance the system voltage stability. This method is based on the particle swarm optimization. The algorithm is easy to implement and is capable of finding the global optimum solution for the loss minimization giving decision about the minimal loss location is the location of the UPFC. For large power systems PSO could have a significant advantage compared to the exhaustive and other methods, by giving better solutions with less computational effort.

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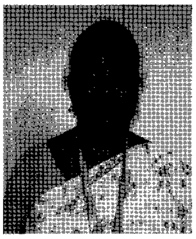

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