Comparative Analysis of Voltage Stability using Classical Methods and Particle Swarm Optimization

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***Abstract*— During analysis of voltage stability determination of voltage collapse point is very necessary by using an efficient approach. This determination of voltage collapse point is very helpful in planning and operation of power system. There are so many methods are available but these methods involve several power flow computations. And also do not consider the power limit of generators and the optimal operating conditions as well. Particle swarm optimization is an efficient approach which determines voltage stability limit/voltage collapse point directly by considering limits and conditions mentioned above. The IEEE 6-bus test system is used to apply the above approach for voltage stability analysis. The performance of the proposed approach is compared with that of classical method called continuation power flow method.**

Keywords—Voltage stability analysis, voltage collapse point, continuation power flow method, particle swarm optimization.

I. INTRODUCTION

Today's scenario of electricity demand is progressively increasing. It is because of shortage in installed capacities. To fulfill our progressive demand we have to operate our power systems in the vicinity of voltage stability limit. Due to operation of our system very near to the Voltage Collapse Point (i.e. voltage stability limit), the fast dynamic events such as large disturbances pushes power system outside the stability limit. Hence there is the problem of voltage stability[1] arises. To get rid of the above problem we have to determine the voltage stability limit and operate our system within stability limit. Voltage stability limit or voltage collapse point is a point in time where the voltage becomes uncontrollable.

There are various methods to determine VCP. The MULTIPLE POWER FLOW METHOD (MPF), THE CONTINUATION POWER FLOW METHOD (CPF) AND AN OPTIMIZATION BASED METHOD. CPF and MPF methods determine VCP but do not considering optimal operating condition. NR method and PSO are two optimization based method, PSO is most preferred method because it considers optimal operating conditions (OOC).

VSP are not new in electric power system. These VSPs are now receiving special attention in electric power industry. Previously these problems are associated to only weak/highly loaded systems and long transmission lines. But today's scenario is that now VSP are occurring in highly developed network because of high demand and limited installed capacity of power generation.

In the recent years voltage instability has been responsible for several major network collapses. The list of some network collapse is given below:

1) Northern India system disturbance of July 30-31, 2012.

2) Brazil and Paraguay system disturbance of November 10-11, 2009.

3) Java and Bali system disturbance of August 18, 2005.

4) Italy system disturbance of September 28, 2003.

5) United States and Canada system disturbance of August 14-15, 2003.

6) India system disturbance of January 2, 2001.

There are so many causes behind VSP. The very first and very common cause is disturbances in the power system[17]. The rest causes of VSP those lead to voltage collapse are reactive power limit, load characteristics/load demand, characteristics of reactive power compensation devices and the working of transformers ULTC[14].

The basic reasons behind VSP are.

1) High load.

2) Generation units are too far from the load centers.

3) The generation power is too low.

4) Reactive power deficiency.

Voltage collapse is a process in which voltage stability problem arises due to the events as mentioned above. And after which the result is a low unacceptable voltage profile in a significant part of power system arises.

Reactive power demand is varying in nature because of change in reactive load at the consumption side[4]. The increased reactive power demand is supplied by the capacitor bank or many other reactive power reserve devices. But sometimes the demand is more than the reserves, which causes VSP leading to voltage collapse.

Voltage collapse occurs because of following reasons:

1) Due to large generation units are out of service.
2) Triggering of heavily loaded transmission lines.
3) Tap changing operation transformers.
4) Delay between control and protective system.

As previously said that there are various methods to determine VSL. These are CPF method, MPF method and NR method (an optimization based method). The CPF method is a mathematical method. This method is used to solve system of nonlinear equations. With the help of CPF method it can be tracked solution branch around the VCP[5]. VCP is the turning point of PV-curve. In MPF method usual power flow is performed by increasing LF/LM. The CPF and MPF methods determine VCP accurately but are time consuming for large systems[6],[7].

Optimization based method consist in maximizing the LF/LM, while satisfying bus voltage, PFs, reactive power limit and other operating limits. NR method is used as an optimization tool to determine VCP[9].

The major drawbacks of NR method are[10]:

1) It ignores voltage correction when generators reach to their reactive power limits.

2) Slack bus generator is assumed as infinite power generation.

3) It does not say about optimal operating condition.

PSO method is an optimization technique to determine voltage collapse point without several power flow computations. This method also considers optimal operating condition[12], [16].

The system under study in this paper is a 6-bus system consisting one slack bus, two PV-buses and three PQ- buses. A simulation software program known as MATLAB/SIMULINK software has been used to simulate the system performance. The system's voltage stability analysis could thus be achieved through computer programming prior to practical realization.

The objective of the study is to determine voltage collapse point/voltage stability limit for the 6-bus test system [15] using PSO method and the result is compared with that of CPF method. The standard data is taken for the system analysis.

The remaining paper is outlined as follows. The section II contains step by step problem formulation using CPF method. In the section III the same problem is step by step formulated using PSO approach. Section IV contains results and discussion part of the paper.

Abbreviations

PFE	Power flow equations
NR	Newton-Rapson
VCP	Voltage collapse point
VSL	Voltage stability limit
PFS	Power flow solution
CPF	Continuation power flow
LPCT	Linear parameterized continuation technique
LF/LM	Load flow/Load margin
VSA	Voltage stability analysis
PF	Power factor
VSP	Voltage stability problem
ULTC	Transformer under load tape changer
MPF	Multiple power flow
PF	Power factor
PSO	Particle swarm optimization

II CONTINUATION POWER FLOW METHOD

CPF method is a simple mathematical technique. It is used to solve nonlinear equations. CPF method can be used to track a solution branch around the VCP. This is the turning point of the PV curve. Hence CPF method is more attractive than NR method for determination of VCP.

The principle of the CPF method is simple. It uses a predictor-corrector scheme. This scheme is used to find the solution path of a set of PFEs. The PFEs are simply modified by including a load parameter called LF/LM. The fig.1 shows that CPF method starts from a known solution. First of all it uses a tangent at different values of LFs to predict the solution at the same values of LFs respectively. This step in CPF method is called predictor step. After that this predicted value is corrected by simply using corrector steps. The correction of predicted value is simply done by using NR technique. The LPCT is identifying each point along the solution path. It also plays an integral part in avoiding singularity in the Jacobian.

Step 1:

To apply LPCT in the power flow problem, it is necessary to insert a LF/LM in the PFEs. Hence in general the PFEs can be represented as below.

$$F(x, \lambda) = 0 \quad (1)$$

Step 2:

After introducing LF/LM in the PFEs

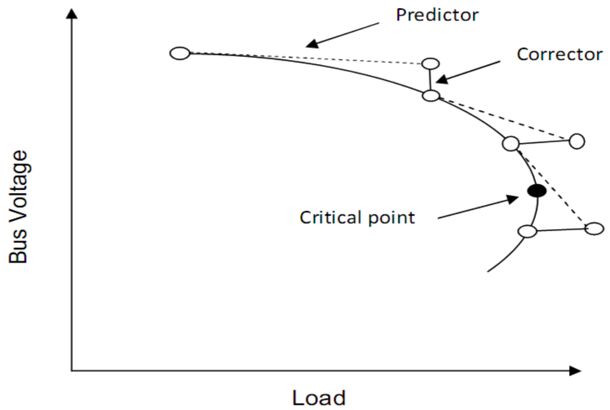

Fig. (1)

$P_{Gi}(\lambda) - P_{Li}(\lambda) - P_T = 0$ (2)

$Q_{Gi} - Q_{Li}(\lambda) - Q_{Ti} = 0$ (3)

Where

P_{Gi} = generation power.

P_{Li} = load power.

P_{Ti} = injected power.

These all powers are for any i^{th} bus. The load powers are formulated as follows

$$Pti = |Vi| \sum_{j=1}^{n} |V j||Yij|\cos(\delta i - \delta j - \theta ij) \quad (4)$$

$$Qti = |Vi| \sum_{j=1}^{n} |Vj||Yij|\sin(\delta i - \delta j - \Theta ij) \quad (5)$$

Where

V_i = voltage at bus i.

Y_{ij} = (i, j)th element of system admittance matrix.

Due to introduction of LF/LM in PFEs, the load powers of LFEs are significantly changed. The equations for load powers can be broken into two parts. First part shows original load on the bus and another part is dependent on load parameter.

The PFEs for load buses after introducing LF/LM are as follows.

$P_{Li}(\lambda) = P_{Lio} + \lambda * (K_{Li} * S_{\Delta base} * \cos\Psi_i)$ (6)

$Q_{Li}(\lambda) = Q_{Lio} + \lambda * (K_{Li} * S_{\Delta base} * \cos\Psi)$ (7)

Where

P_{Lio} = original active load power.

Q_{Lio} = original reactive load power.

λ = LF/LM.

K_{Li} = multiplier.

$S_{\Delta base}$ = a give quantity of apparent power.

$\cos\Psi_i$ = PF of load buses.

The modified equation for active power generation

$P_{Gi}(\lambda) = P_{Gi0}(1 + \lambda K_{Gi})$ (8)

Where

P_{Gi0} = active power generation at base load.

K_{Gi} = multiplier.

The equation no. (1) can be reformulated as follows.

$F(\delta, V, \lambda) = 0 \qquad 0 <= \lambda <= \lambda_{critical}$ (9)

Step 3:

In the third step the prediction process is started. First of all the solution at the base load (LF/LM=0) is calculated. The next solution is predicted by simply drawing a tangent at base load and selecting an appropriate step size.

The tangent at any point of curve is calculated by simply taking derivative of equation no.9 on both sides.

$d[f(\delta, V, \lambda)] = f_\delta d\delta + f_v dV + f_\lambda d\lambda = 0$

After factorizing the above equation.

$$[f\delta \ fV \ f\lambda] \begin{bmatrix} d\delta \\ dV \\ d\lambda \end{bmatrix} = 0 \quad (10)$$

The above equation is solved by selecting a nonzero tangent vector.

Let

$$t = \begin{bmatrix} d\delta \\ dV \\ d\lambda \end{bmatrix}, t\kappa = \pm 1 \quad (11)$$

These results in

$$\begin{bmatrix} f\delta \ fV \ f\lambda \\ ek \end{bmatrix} [t] = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \quad (12)$$

After solving the above equation the prediction can be made as follows.

$$\begin{bmatrix} \delta * \\ V * \\ \lambda * \end{bmatrix} = \begin{bmatrix} \delta \\ V \\ \lambda \end{bmatrix} + \sigma \begin{bmatrix} d\delta \\ dV \\ d\lambda \end{bmatrix} \quad (13)$$

Where

'*' = predicted solution for LF/LMs.

σ = constant scalar as step size.

Step 4:

After prediction of the solution for different values of LF/LMs we need a process to correct the values. Before correcting to the approximate solution we need a parameterization process. Every continuation technique employs a parameterization scheme. Here we use LPCT. In LPCT the original set of equations are augmented by one equation. The reformulated power flow equation (i.e. equation no. 9), who's state variables are expressed in the equation form given below.

$$X = \begin{bmatrix} \delta \\ V \\ \lambda \end{bmatrix}, X \in R^{2n1+n2+1} \tag{14}$$

Where

X=represent set state variable.

n1=PQ buses.

n2=PV buses.

Let

$X_k = \eta$

Where

$\eta = k^{th}$ element of X.

Here only 3 state variables are present in the PFEs.

After implementing , new set of equation are given below.

$$\begin{bmatrix} f(x) \\ Xk - \eta \end{bmatrix} = [0] \tag{15}$$

After selecting suitable parameter we can correct the predicted values for different LF/LMs.

Step 5:

Choice of continuation parameter is a major concern for the solution of power flow problem using CPF method. Continuation parameter corresponds to the state variable that has maximum rate of change at the solution. The solution is started at base load. At base load LF/LM has the maximum rate of change. But as far as solution goes near the voltage stability limit (i.e. VCP) the continuation parameter is changes. In the vicinity of VCP the rate of change of voltage magnitude and that of phase angle maximum. Hence near the VCP voltage and phase angle are chosen as continuation parameter. If the choice of continuation parameter is made for first step, the next successive steps are handled with the help of the following equation.

$$Xk: |tk| = \max\{|t1|, |t2|, \ldots\ldots\ldots |tm|\} \tag{16}$$

Where

t=tangent vector.

$m = 2n_1 + n_2 + 1$.

K=corresponds to maximal tangent vector.

Step 6:

The stopping criterion is identified very easily. At the VCP the tangent vector becomes zero. After passing critical point the tangent vector becomes negative and also LF/LM is decreasing.

Flow chart for the solution of power flow problem using CPF method is given below[6].

Flow chart:

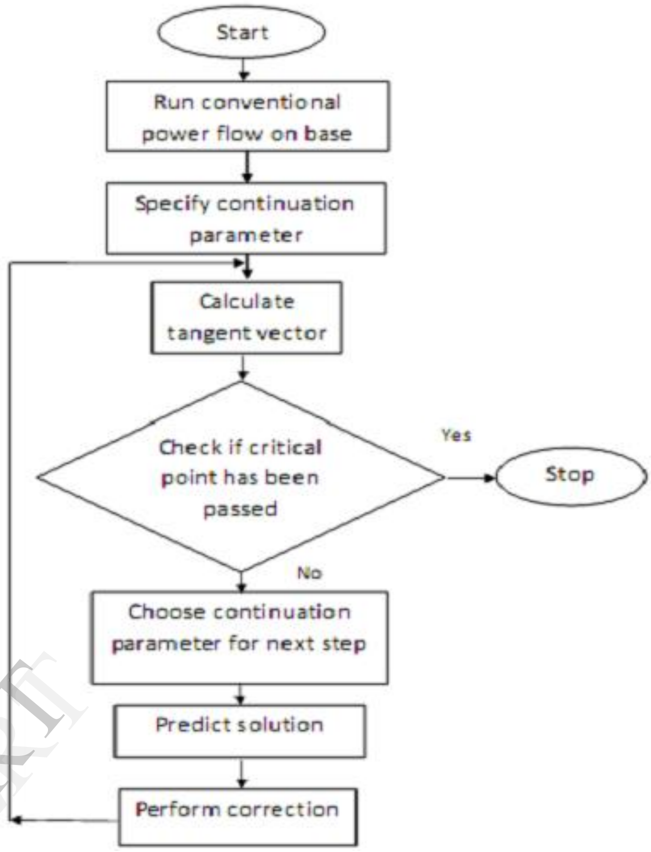

Fig. (2)

III. PARTICLE SWARM OPTIMIZATION

The PSO method is based on mainly the characteristics of certain group of living things. These living groups may be the swarm of insects, a flock of birds or a school of fish. The whole group of these living things is called swarm and every single living thing is called particle. Each particle in the swarm behaves in a distributed way through its own intelligence and that of the whole swarm.

For example the swarm of insects is searching for food which is least distance from their home. If a small group of insects discovers a good path to food which is very near to their home. Then rest of the insects will follow them even their location is far away in the swarm. In case of multivariable optimization problem all the variables are called the attributes of a particle. The problem is solved by taking a fixed value of particles. Each particle has two characteristics: one is position another one is velocity. Initially the particles are located at random position and moving around in designed space. These particles remember the best position. The adjustment of its position and velocity is based on its own intelligence and the information received on a good position. The voltage stability problem solved by using PSO approach is formulated as below.

Step 1

The value of coefficients and factors used in the velocity updation are given below.

C	1.0
w	0.9
c_1	2.0
c_2	2.0

Table (1)

Step 2

No. of particles are selected 10. Initializing each particles attribute (i.e. voltage magnitude and phase angle). Phase angle is initialized using a simple MATLAB command written below.

Delta (δ) = <lb> + <ub - lb>.*rand<popsize, bus no.> (17)

Delta (δ) is phase angle, lb and ub show the lower and upper ranges in between phase angle is initialized and popsize represents no. of particles. Second attribute i.e. voltage magnitude of PQ buses is initialized using the formula given below.

$$|V_i|^k = -\frac{\sum_{\substack{r=1 \\ r\neq i}}^{n} |V_r|^{(k)} |Y_{ir}| \{tan\phi_i . \cos((\theta_{ir} - \delta_i^{(k)} + \delta_r^{(k)}) + \sin(\theta_{ir} - \delta_i^{(k)} + \delta_r^{(k)})\}}{|Y_{ii}|(tan\phi_i . cos\theta_{ii} + sin\theta_{ii}))} \quad (18)$$

Step 3

Objective function is selected as the active power of 6^{th} bus.

Step 4

Active and reactive powers are calculated using equation no. (4) and (5). Change in active power with respect to scheduled active power is calculated as follows.

For PV buses

$$\Delta P_i^{(k)} = P_{i,sch} - P_i^{(k)} \quad (19)$$

For PQ buses

$$\Delta P_i^{(k)} = K_{l,i} . P_l - P_i^{(k)} \quad (20)$$

According to change in active power, phase angle delta is also change, so as to inject or withdraw power. Phase angle delta changes as follows.

If $\Delta P_i^{(k)} > 0$

$$\delta_i^{(k),new} = \delta_i^{(k),old} + \Delta\delta^+ \quad (21)$$

And, if $\Delta P_i^{(k)} < 0$

$$\delta_i^{(k),new} = \delta_i^{(k),old} - \Delta\delta^- \quad (22)$$

This phase angle adjustment is continued until the following condition does not violate.

$$\mathrm{Max}|\Delta P_i^{(k),new}| \leq \varepsilon \quad (23)$$

Step 5

After active power limit, reactive power limit is also checked and accordingly objective power is changed. Reactive power limit is checked by using penalty function as follows.

If the reactive power limit violates the upper or lower limits then penalty function is defined as

$$PF_i = \sigma(Q_{i,max} - Q_i^{(k)})^2 \quad (24)$$

Otherwise

$PF_i = 0$

Voltage magnitudes of generation buses are adjusted according to reactive power injection on the basis of penalty function.

$$|V_i|^{(k),new} = -\frac{-Q_{i,max}}{|V_i|^{(k),(old)} |Y_{ii}| sin\theta_{ii} + \sum_{\substack{r=1 \\ r\neq i}}^{n} |V_r|^{(k)} |Y_{ir}| \sin(\theta_{ir} - \delta_i^{(k)} + \delta_r^{(k)})} \quad (25)$$

The new OF is obtained by subtracting the penalty function from the old OF.

Step 6

oldOF and oldgbest are assumed a constant value for the first iteration. The maximum value of 'OF' and correspondingly the global best position can be allocated as follows.

If newOF > oldOF

newgbest = pbest

And if newOF <= old OF

newgbest = oldgbest

Step 7

Velocity updation and position updation for different iterations is done as follows.

$$v_j^{(i+1)} = C\{wv_j^{(i)} + c_1 rand_1 (p_{best} - x_j^{(i)}) + c_2 rand_2 (g_{best} - x_j^{(i)})\} \quad (26)$$

Where the values of all the coefficients are given in the table no. (1).

The position of the jth particle for ith iteration is given as follows

$$X_j(i) = X_j(i-1) + v_j(i) \quad (27)$$

If the convergence criteria is not satisfied, updating the iteration counter as i=i+1, and computing the new values of $P_{best,j}$ and G_{best}. The iterative process is continued until all particles converge to the same optimal solution.

Constraints:

Constraints for PF of load buses are as follows.

$$\tan\phi_i . P_i - Q_i = 0 \qquad i = 1, 2, \dots, m \quad (28)$$

Where

ϕ_i=PF angle at i[th] bus.

Constraints for power increase direction are.

$K_{li}.P_l - P_i = 0$ $\quad$ i = 1, 2, … , m and i ≠ l $\quad$ (29)

Where

K_{li}=the factor of active power increase in ith bus with respect to the objective bus.

Constraints for constant active power generation are.

$P_{isch} - P_i = 0$ $\quad$ i = (m+1), (m+2), … , (n-1) $\quad$ (30)

Where

P_{isch}=scheduled active power generation of i[th] bus.

Constraints for reactive power limit of generation and load buses are.

$Q_{imin} \geq Q_i \geq Q_{imax}$ $\quad$ i = (m+1), (m+2), …, n $\quad$ (31)

Constraints for active power limit of generation buses and the slack bus are.

$P_{imin} \geq P_i \geq P_{imax}$ $\quad$ i = (m+1), (m+2), … ,n $\quad$ (32)

Flow chart for the PSO approach is given below[16].

Flow chart:

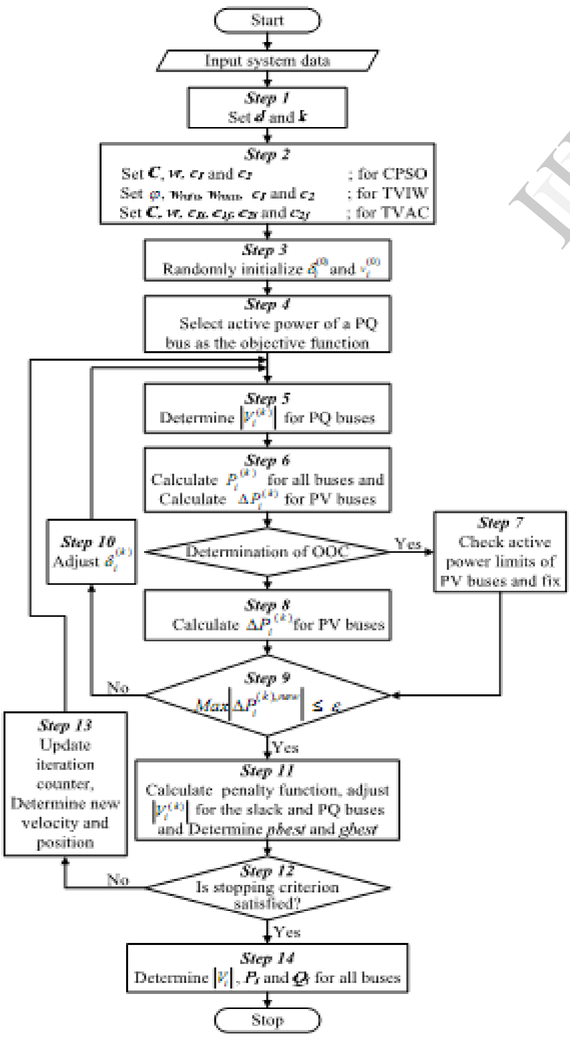

fig.(3)

IV. RESULT AND DISCUSSION

IEEE Six bus test system:

Fig. 4 shows the single line diagram of IEEE six-bus test system with generators at buses 1, 2 and 3, in which bus-1 is taken as slack bus and buses 2, 3 are taken as PV buses respectively. Buses 4, 5 and 6 are taken as PQ buses[15].

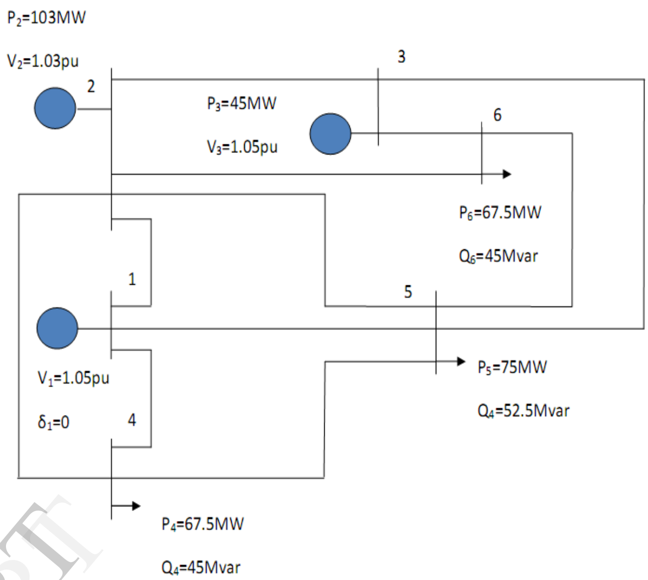

Fig. (4)

CPF method is simply based on solution of power flow equation. After that we apply prediction and correction step to determine voltages at some LF/LM.

Voltages of all buses at some LFs during prediction step are given in the below table

V_1	1.0500	1.0500	1.0500	1.0500	1.0500
V_2	1.0300	1.0300	1.0300	1.0300	1.0300
V_3	1.0500	1.0500	1.0500	1.0500	1.0500
V_4	1.9620	1.5021	1.2000	0.9480	0.9300
V_5	2.1000	1.9780	1.7600	1.1020	0.9521
V_6	1.6500	0.9419	0.9329	0.9230	0.9119
λ	0.1000	0.2000	0.3000	0.4000	0.5000

Table (2)

Voltages of all buses at some LFs during corrector step are given in the below table

V_1	1.0500	1.0500	1.0500	1.0500	1.0500
V_2	1.0300	1.0300	1.0300	1.0300	1.0300
V_3	1.0500	1.0500	1.0500	1.0500	1.0500
V_4	1.7620	1.0021	0.9800	0.9480	0.9300
V_5	1.9800	1.8780	1.6600	0.9981	0.8521
V_6	0.9570	0.9396	0.8532	0.7332	0.6132
λ	0.0000	0.1000	1.3000	1.4000	1.5000

Table (3)

After obtaining this corrector step data we can draw voltage v/s load power curve. These curve shows variation of voltage according to the variation of LM/LF. In fig. (5) the PV curves for all load buses are shown. And signifies that 6th bus is a weakest bus which terminates at VCP/VSL.

PV curves at various LM/LF including VCP for all load buses using CPF method:

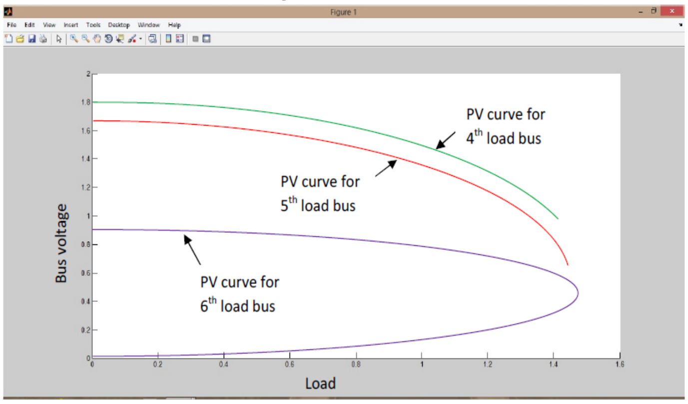

Fig.(5)

Load margin and voltage magnitudes for load buses at the collapse point using PSO method:

V_4	0.8306
V_5	0.7942
V_6	**0.6146**
λ	**1.5197**

Table (4)

Comparison of results using CPF AND PSO method:

Methods	**LF/LM**
CPF	1.5001
PSO	1.5197

Table (5)

The result of CPF method (fig.5) is compared with that of PSO (table 4). It is noticed that PSO provides only single solution, the maximum point. CPF on the other hand, provides a complete PV curve and the voltages at various load margins.

The accuracy of CPF method depends upon the step size taken during the correction step but it is not so in PSO method. So we can say that PSO gives better result than CPF method. Since PSO takes input at random basis so there may be a situation arises that in the first trial it does not give the satisfactory result. But it is very certain that after few trail we achieve the appropriate result.

V. CONCLUSION AND FUTURE SCOPE

PSO is a novel optimization technique which solves the drawbacks of classical methods. This method also considers OOC. PSO determines VCP without several power flow computations and also considers OOC. So this method is very helpful in solving optimization based problems.

In future the power sector will be very large and the power system networks will be more complicated, so accurate voltage stability analysis (i.e. determination of VCP) will be major concern. Further we may consider the other versions of PSO based approach such as adaptive PSO (APSO), passive congregation- based PSO (PC PSO) and self organizing hierarchal PSO (SOH PSO).

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