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Static Voltage Stability Assessment and Critical Loadability Evaluation Using Continuation Power Flow

Chandrakant Dondariya, D.K.Sakravidia

Research Scholar, Department of Electrical Engineering, Ujjain Engineering College, Ujjain, India

Professor, Department of Electrical Engineering, Ujjain Engineering College, Ujjain, India

ABSTRACT: This paper presents a methodology for voltage stability assessment and critical loading evaluation of power system networks using predictor-corrector based continuation power flow. Proximity and mechanism of voltage instability are investigated with FOSS software. IEEE 14 bus and IEEE 25 bus test systems have been selected for investigations based on simulations study. Results obtained are validated with CPF results as obtained by tangent predictor and pseudo arc length parameterization technique.

KEY WORDS: Voltage stability, Critical loading limit, Knee voltage, loading parameter, continuation power flow, weakest bus.

I. INTRODUCTION

Continuation power flow is the most powerful tool for static analysis of voltage stability. It has the ability of tracing the PV curve up to the saddle nose bifurcation point which is also the critical loading point of the system. The problem of having singularity of load flow Jacobean based on static load flow equations at critical loading condition; is a issue and this numerical puzzle can be resolved by continuation power flow algorithm.

PV curves finds wide role in voltage stability analysis. Static load flow equations provide stable and unstable equilibrium solutions. Stable equilibrium solution is considered as practical solution in which an increase in load power causes decrease in voltage. At critical point, however; these two solutions converge in to a single solution. Hence the difference between stable and unstable solution becomes zero at voltage collapse point. This property can be used as an indicator to access proximity to voltage collapse. The slope of PV curve also indicates the closeness of present operating point to voltage collapse point.

PV curve is very helpful in voltage stability studies in many ways:

- (i) It indicates the closeness of present operating state to critical loading state.
- (ii) It is useful to assess distance to voltage collapse under various load increase patterns.
- (iii) It can provide information regarding the mechanism of voltage instability by identification of weak lines and buses that are mainly contribute to voltage collapse.
- (iv) It can be used to adjust margins for compensation and in planning.

Conventional load flow algorithm is not suitable for obtaining critical loading point on PV curve as the Jacobean becomes singular at this point. This difficulty is very well taken care by continuation power flow algorithm proposed by Ajjarappu and Christy [1]. They used a continuation parameter instead of direct bus loadings to trace the PV curve up to the critical loading point. Approximate PV curve by using two pairs of load flow solution was proposed by Suzuki et al [2]. An algorithm based on predictor-corrector has been developed [3] to obtain PV curve. Secant predictor and arc length parameter has been used in the proposed method. Continuous power flow with tangent predictor and pseudo arc length parameter[4] has also been presented. Continuation power flow methods involve four basic elements. These are:

- a. Parameterization
- b. Prediction of next solution (Predictor step)
- c. Applying correction to the predicted solution (Corrector step)
- d. Step increase in continuation parameter.

Continuation power flow traces the complete P - V curves by changing the value of a parameter automatically. In the local parameterization technique [1], a parameter change always occurs close to maximum loadability point. Generally, the loading factor λ is an initially chosen parameter. Near the critical point, it changes to the voltage magnitude that is having the largest variations and after that, it again changes back to λ . The voltage magnitudes and angles may also be chosen as parameters, but, in these cases, the new Jacobian matrix can become singular at the critical point, or in the lower or upper part of the P - V curve [2].

Singularity of load flow jacobian and associated numerical problems can be eliminated by adding parameterized equations [6-12]. Due to robustness provided by these methods in solving nonlinear algebraic equations [8], they have been widely used in the analysis of electric power systems for obtaining multiple solutions, contingency analysis, real power losses reduction, the tracing of loading curves (P - V curves), and the determination of critical loading point [6-8,12]. Although continuation power flow is fundamental tool for static voltage stability assessment; it is time consuming. However It is used as benchmark for many of the indirect methods in which proximity indicator has been used to assess maximum loadability point [13].

In this paper, a systematic approach to voltage stability assessment with power system analysis toolbox (PSAT) has been used for NR flow and CPF based simulation study and the results obtained are validated [4].

II. CONTINUATION POWER FLOW EQUATIONS

Modified power flow equation

In locally parameterized continuation technique [1], a loading parameter λ is incorporated into load flow equations. A constant power load model has been taken for reformulation. A loading parameter λ is assumed to exist such that $0 < \lambda < \lambda_c$

Where; $\lambda = 0$ corresponds to the base load and

$\lambda = \lambda_c$ corresponds to the critical load.

Conventional power flow equations at i^{th} bus can be written as-

$$P_{Gi} - P_{Li} - \sum_{j=1}^n V_i V_j y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \quad (1)$$

$$Q_{Gi} - Q_{Li} - \sum_{j=1}^n V_i V_j y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) = 0 \quad (2)$$

Subscript G and L represent generation and load respectively. y_{ij} is the $(ij)^{\text{th}}$ element of Y_{bus} matrix.

Load real and reactive powers can be expressed in terms of loading parameter as,

$$P_{Li} = P_{Lio} + \lambda k_{Li} S_{\Delta base} \cos \phi_i \quad (3)$$

$$Q_{Li} = Q_{Lio} + \lambda k_{Li} S_{\Delta base} \sin \phi_i \quad (4)$$

Where,

P_{Lio}, Q_{Lio} - Original real and reactive load at i^{th} bus

k_{Li} - multiplier to adjust the rate of load change at i^{th} bus

ϕ_i - Power factor angle of load at i^{th} bus.

$S_{\Delta base}$ - Apparent power which is chosen to provide appropriate scaling of loading parameter λ .

The real power generation at i^{th} bus is also modified as given in equation (5).

$$P_{Gi} = P_{Gio}(1 + \lambda k_{Gi}) \quad (5)$$

Where;

P_{Gio} : the active generation at bus i in the base case

k_{Gi} : A constant to represent rate of change in generation with λ .

By substituting modifications as given in equations (3),(4) and (5) in to conventional load flow equations (1) and (2); following reformulated equations are obtained-

$$P_{Gi} - P_{Lio} - \lambda k_{Li} S_{\Delta base} \cos \phi_i - \sum_{j=1}^n V_i V_j y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \quad (6)$$

$$Q_{Gi} - Q_{Lio} - \lambda k_{Li} S_{\Delta base} \sin \phi_i - \sum_{j=1}^n V_i V_j y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) = 0 \quad (7)$$

A continuation algorithm is applied to reformulated power flow equations (6) and (7).

Let F represents the set of reformulated load flow equations of variables V, δ and λ .

$$F(V, \delta, \lambda) = 0, 0 < \lambda < \lambda_c \quad (8)$$

where; δ represents the vector of voltage angles and V represents the vector of bus voltage magnitudes. In general, the dimension of F is $2m_1 + m_2$, where m_1 and m_2 are the number of PQ and PV buses respectively.

Base case solution $(V_0, \delta_0, \lambda_0)$ of equation (8) can be obtained by conventional power flow. By varying value of loading parameter λ over the range $0 < \lambda < \lambda_c$, the solution path of V - λ can be traced. A predictor-corrector scheme is implemented to find next solution at a different loading condition.

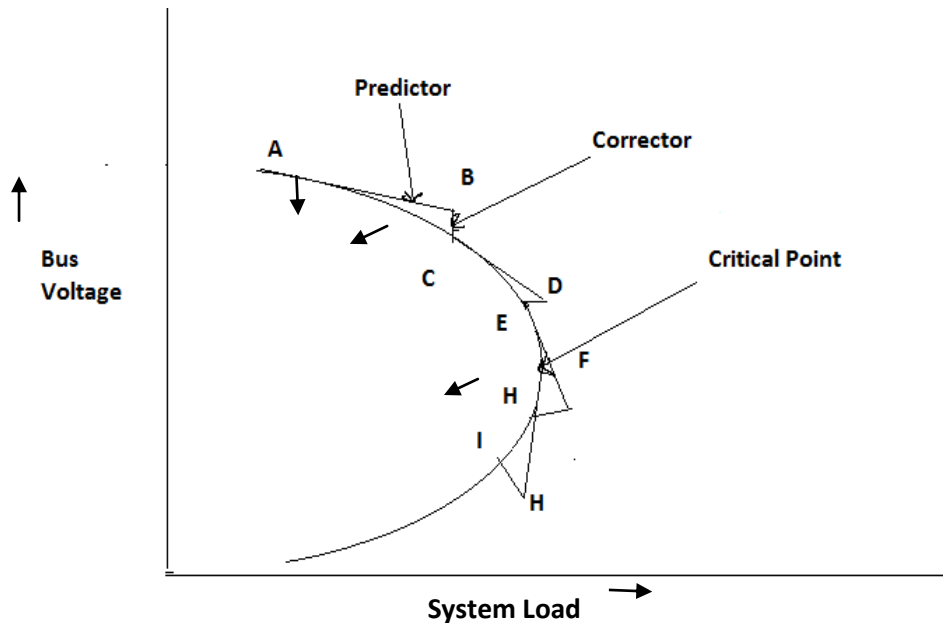


Figure 1: Predictor-corrector process in continuation power flow

1. Predictor step:

In this step, base case solution obtained from NR load flow, is used to take following actions:

- A tangent vector is evaluated at base case operating point which fix the direction as tangent to P-V path.
- Appropriate step size is decided to go towards next operating point.

By taking the derivative of both sides of the power flow equations, we have,

$$\partial[F(\delta, V, \lambda)] = F_{\delta}\partial\delta + F_V\partial V + F_{\lambda}\partial\lambda=0$$

This can be written as

$$\begin{bmatrix} F_{\delta} & F_V & F_{\lambda} \end{bmatrix} \begin{bmatrix} \partial\delta \\ \partial V \\ \partial\lambda \end{bmatrix} = 0 \quad (9)$$

Where,

$\begin{bmatrix} F_{\delta} & F_V & F_{\lambda} \end{bmatrix}$ is conventional load flow jacobian augmented by one column F_{λ} and

$\begin{bmatrix} \partial\delta \\ \partial V \\ \partial\lambda \end{bmatrix}$ is tangent vector.

Since one variable λ is inserted in load flow equations. Hence one more equation is needed for a unique solution for tangent vector. This problem can be solved by choosing ± 1 for one of the components of the tangent vector. In other words, if t is used to denote the tangent vector;

$$t = \begin{bmatrix} \partial\delta \\ \partial V \\ \partial\lambda \end{bmatrix}, \quad t_k = \pm 1$$

$$\begin{bmatrix} F_{\delta} & F_V & F_{\lambda} \\ & t_k & \end{bmatrix} \begin{bmatrix} \partial\delta \\ \partial V \\ \partial\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \quad (10)$$

By solving (10), the prediction can be obtained as follows:

$$\begin{bmatrix} \delta^o \\ V^o \\ \lambda^o \end{bmatrix} = \begin{bmatrix} \delta \\ V \\ \lambda \end{bmatrix} + \sigma \begin{bmatrix} \partial\delta \\ \partial V \\ \partial\lambda \end{bmatrix} \quad (11)$$

where, $\begin{bmatrix} \delta^o \\ V^o \\ \lambda^o \end{bmatrix}$ is the predicted solution for the stepped value of λ (loading); and

σ Represents the step size. The step size should be carefully chosen otherwise corrector step will not converge to a unique solution. It is to be noted that smaller step size would increase computational time.

2. Corrector Step

In this step, correction to predicted solution has been applied. It is done by choosing proper parameterization scheme. . In local parameterization the original set of equations is augmented by one equation that specifies the value of one of the state variables[1].

let

$$x = \begin{bmatrix} \delta \\ V \\ \lambda \end{bmatrix} \quad x \in \mathbb{R}^{2n_1 + n_2 + 1}$$

and let $x_k = \eta$ where η is an appropriate value for the k^{th} element of x . Then the new set of equation would be

$$\begin{bmatrix} F(x) \\ x_k - \eta \end{bmatrix} = [0] \quad (12)$$

By choosing suitable values of k and η , equation (12) can be used to obtain corrector to modify the predicted value.

Selection of continuation parameter is very important in continuation power flow method. It has been selected as the state variable that has the highest rate of change near the solution point. At light loading conditions, loading parameter λ should be chosen as continuation parameter as the voltage magnitude and angle are practically constant. But near the critical operating point, voltage magnitude is a better choice as it has the highest rate of change. Therefore it is necessary to select continuation parameter at each step in the algorithm. The critical point can be identified with $d\lambda$ component of tangent vector. At critical loading point; this component will be zero and it will be negative after this point.

To summarise the procedure of continuation load flow steps; a flowchart has been shown in Figure 2.

A Simulation study has been conducted for IEEE 14 bus and IEEE 25 bus test systems to obtain Critical loadability, knee voltage at weakest bus and load margins based on above and results obtained are validated with [4] .

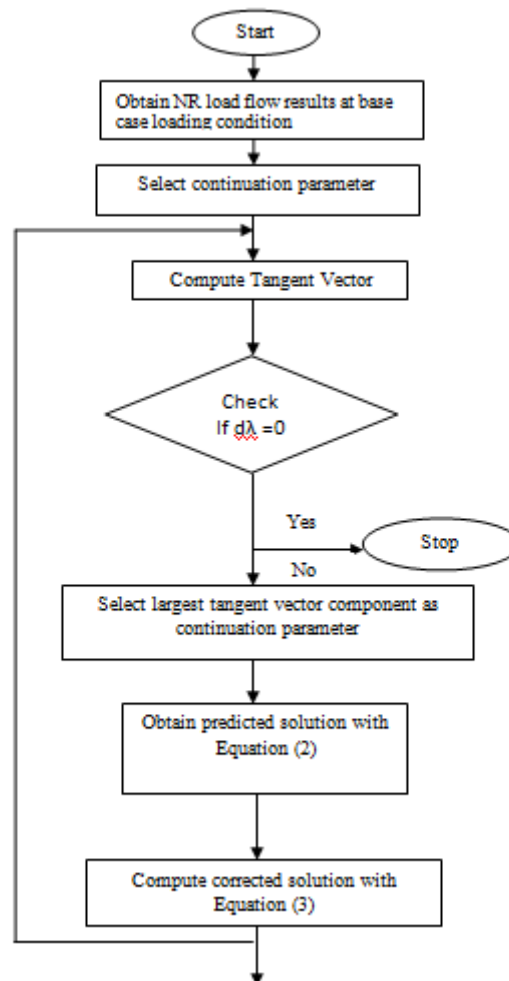


Figure 2 : Flowchart showing steps of Continuation power flow

III. RESULTS AND CONCLUSIONS

To demonstrate the usefulness of continuation power flow in static voltage stability assessment; continuation power flow algorithm as discussed in the previous section has been implemented for IEEE 14 bus and IEEE 25 bus test systems. Power system analysis toolbox 2.1.10, which is free and open source software (FOSS) has been used for simulation and analysis.

1. Simulation study of IEEE 14 bus test system

IEEE 14 bus system [4,15] has been modeled using simulink library as shown in Figure 3.

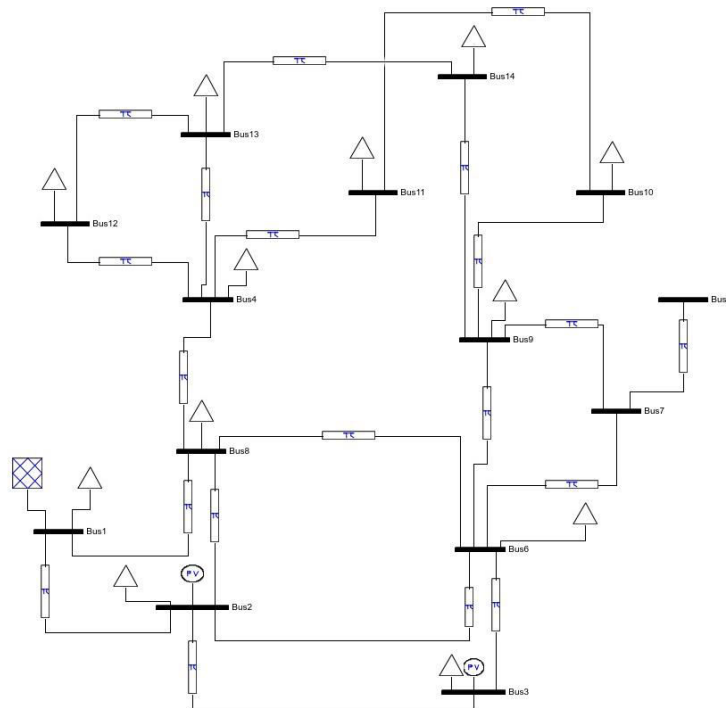


Figure 3 : IEEE 14 bus test system model used in PSAT analysis

NR flow based load flow analysis has been carried out firstly to validate the model and the bus voltages and angles are obtained at real and reactive system loadings of 4.09 pu and 1.375 pu respectively at 100 MVA base. It is also the base case loading condition ($\lambda=1.0$). The results are as shown in Table 1 confirm that the system is correctly modeled.

Table 1: Bus voltages in IEEE 14 Bus System

Bus No.	Base Case Loading ($\lambda=1.0$)		Critical Loading($\lambda=1.7886$)	
	Voltage [pu]	Angle[rad.]	Voltage [pu]	Angle[rad.]
1	1	0	1	0
2	1	-0.040686925	1	-0.127073447
3	1	-0.124673149	1	-0.333106575
4	0.882618412	-0.22681999	0.596852191	-0.624641686
5	0.894208371	-0.20057446	0.645927673	-0.518752175
6	0.941576752	-0.122553792	0.819118766	-0.285622575
7	0.894208371	-0.20057446	0.645927673	-0.518752175
8	0.945529523	-0.104201751	0.827332048	-0.236495127
9	0.876727086	-0.234404635	0.589876438	-0.648747326
10	0.868898376	-0.240445851	0.566666354	-0.674704722
11	0.871632475	-0.237042585	0.570447313	-0.66333794
12	0.864985532	-0.247914093	0.543805854	-0.713849623

13	0.859932322	-0.249273454	0.528317549	-0.719728293
14	0.845895179	-0.265967575	0.506391449	-0.798976104
Total Real Load= 4.09 pu Total Reactive Load=1.375 pu			Total Real Load= 7.3154 pu Total Reactive Load=2.4594 pu	

Load flow analysis of the same model has been carried out with increased real and reactive loadings maintaining constant power factor at all load buses. It was found that at total real system loading of 7.3142 pu, lowest magnitude of bus voltage was 0.5265 at bus 14. After this the LF failed to converge.

Now, CPF tool was used in PSAT to obtain critical loadability point. Tangent predictor and perpendicular intersection based corrector were chosen for the analysis. Step size was selected as 0.05. Voltage limits were not considered and complete nose curve was selected as stop criterion. At critical point, total real and reactive loadings were obtained as 7.3145 pu and 2.4594 pu respectively. The knee voltage magnitude at bus 14 is 0.5064. The completion time of CPF is 3.8547 sec. PV curve for the most critical bus 14 is obtained as shown in Figure 4.

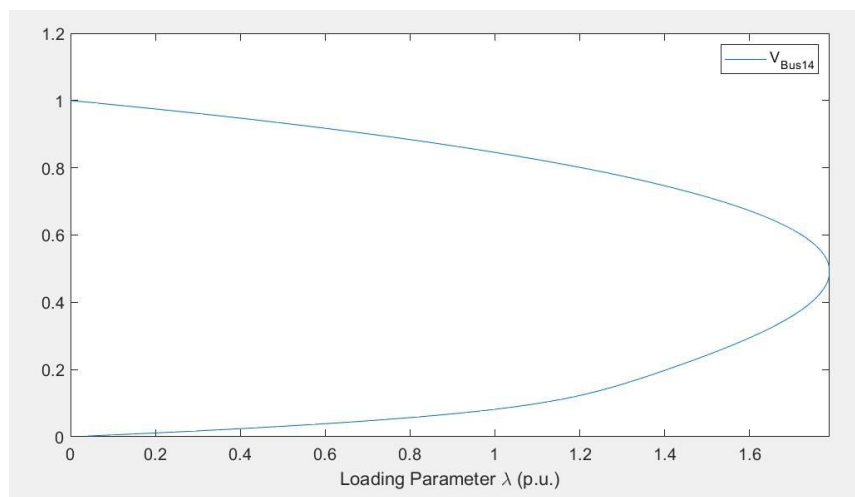


Figure 4 : PV curve of bus 14 in IEEE 14 bus system

Tangent vector and pseudo arc length parameterization based continuation power flow technique[4] was applied to IEEE 14 bus system in which FORTRAN 77 based program was used to determine maximum loadability of the system. The critical real system loading was 7.3029 pu and knee voltage was 0.5145 pu as obtained in [4].

A summary of results obtained are tabulated as shown in Table 2.

Table 2: Simulation results of IEEE 14 bus system

Parameter	C.P.F.[4]	C.P.F. (PSAT 2.1.10)
Method Used	Predictor – Tangent Corrector- Pseudo arc length	Predictor – Tangent Corrector-Perpendicular intersection
Load model used	Constant PQ	Constant PQ
p.f. of load increase	Constant	Constant
Critical real system load (pu)	7.3029	7.3155
Knee voltage at bus 14 (pu)	0.5145	0.5064
Real power margin at base case point	321.29 MW	322.55 MW
Reactive power margin at base case point	130.42 MVar	132.57 MVar

2. IEEE 25 bus test system

Similar analysis were performed on IEEE 25 bus system [4,15]. The system is modeled with the help of simulink library as shown in Figure (5).

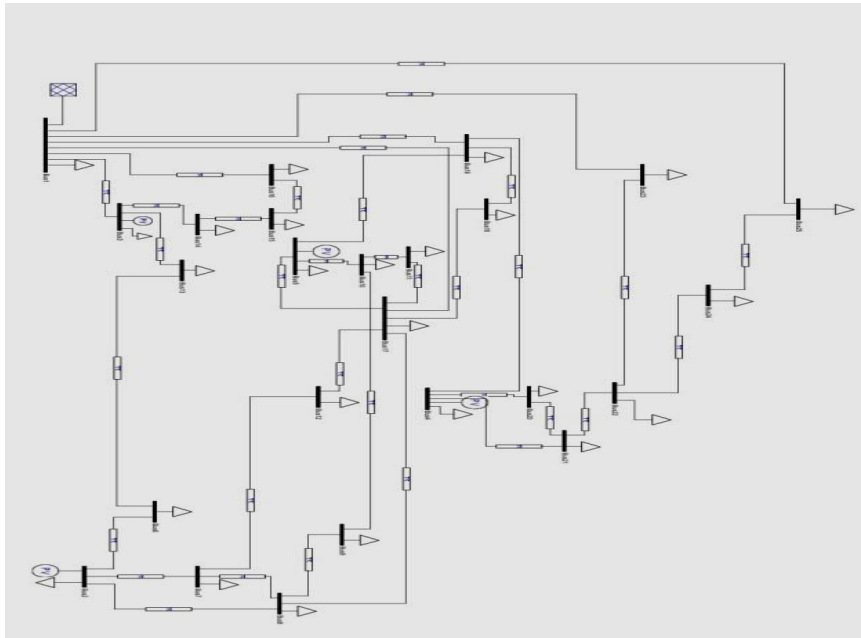


Figure 5: IEEE 25 bus test system model used in PSAT analysis

Conventional NR based load flow was performed on the system model in PSAT at base case load in order to validate the model. The load flow results at base case load are shown in table 3.

Load flow analysis of the same model has been carried out with increased real and reactive loadings maintaining constant power factor at all load buses. It was found that at total real system loading of 20.1116 pu, lowest magnitude of bus voltage was 0.5393 at bus 24. After this load flow failed to converge.

CPF tool was used in PSAT to obtain critical loadability point. Tangent predictor and perpendicular intersection based corrector were chosen for the analysis. Step size was selected as 0.05. Voltage limits were not considered and complete nose curve was selected as stop criterion. At critical point, total real and reactive loadings were obtained as 20.5393 pu and 6.4150 pu respectively. The knee voltage magnitude at bus 24 was 0.5064. The completion time of CPF is 3.4038 sec. PV curve for the most critical bus 24 is obtained as shown in Figure 6.

Table 3: Bus voltages in IEEE 25 bus system

Bus No.	Base Case Loading ($\lambda=1.0$)		Critical Loading($\lambda=2.8137$)	
	Voltage [pu]	Angle[rad.]	Voltage [pu]	Angle[rad.]
1	1	0	1	0
2	1	0.218899	1	0.351834
3	1	0.152806	1	0.283807
4	1	-0.02198	1	-0.378
5	1	0.199349	1	0.270636
6	0.975077	0.144564	0.917531	0.202274
7	0.971161	0.127711	0.884209	0.09381
8	0.968912	0.116451	0.87646	0.057844
9	0.958915	0.103492	0.845954	0.005236
10	0.970827	0.124378	0.887197	0.067371
11	0.968196	0.100346	0.877876	0.012323

12	0.969399	0.099727	0.877316	0.016838
13	0.974449	0.136403	0.917153	0.195958
14	0.932056	-0.01894	0.722418	-0.18484
15	0.931374	-0.04286	0.726612	-0.24624
16	0.946261	-0.0437	0.787426	-0.20939
17	0.972474	0.087674	0.886815	-0.00073
18	0.967454	0.03647	0.868298	-0.17444
19	0.989049	0.013397	0.944779	-0.24707
20	0.968234	-0.05701	0.86657	-0.47751
21	0.947615	-0.07757	0.753465	-0.53585
22	0.929095	-0.09614	0.638425	-0.58411
23	0.956038	-0.0543	0.780646	-0.24216
24	0.914921	-0.12117	0.510337	-0.72387
25	0.923565	-0.11237	0.527331	-0.6186
Total Real Load= 7.3 pu Total Reactive Load=2.28 pu		Total Real Load= 20.5393 pu Total Reactive Load=6.4150 pu		

A summary of results obtained are tabulated as shown in Table 4.

Table 4: Simulation results of IEEE 25 bus system

Parameter	C.P.F. [4]	C.P.F. (PSAT 2.1.10)
Method Used	Predictor – Tangent Corrector- Pseudo arc length	Predictor – Tangent Corrector-Perpendicular intersection
Load model used	Constant PQ	Constant PQ
p.f. of load increase	Constant	Constant
Critical real system load (pu)	7.3029	7.3155
Knee voltage at bus 14 (pu)	0.5145	0.5064
Real power margin at base case point	321.29 MW	322.55 MW
Reactive power margin at base case point	130.42 MVar	132.57 MVar

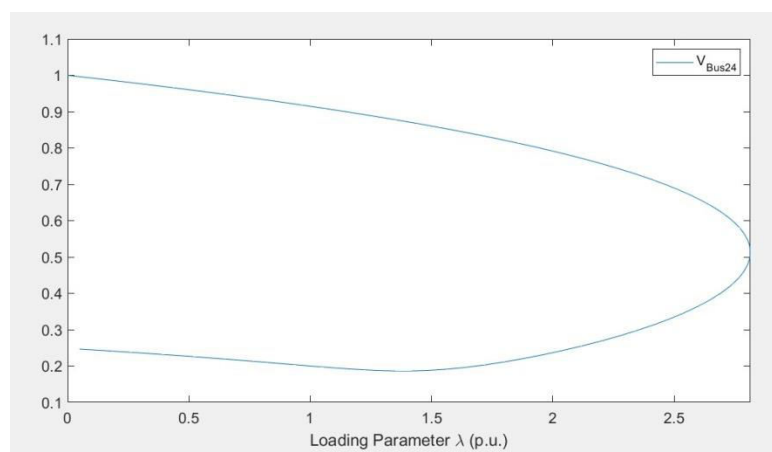


Figure 6: PV curve of bus 24 of IEEE 25 bus system

IV. CONCLUSIONS

In view of results obtained, it is clear that continuation power flow based on predictor-corrector algorithm is the most fundamental tool in static voltage stability analysis and a deep insight to voltage instability can be obtained with this tool. It gives information about proximity to voltage collapse in terms of tangent vector elements and continuation parameter. On the other hand, mechanism of voltage instability can be assessed by weakest bus identification and real

and reactive power margins available at an operating point. Critical loading as obtained with this method can be used as a parameter to assess voltage stability enhancement with compensating devices and distributed generation (DG). The main highlights of the simulation study presented in this paper are-

- (i) Available FOSS software PSAT can be used for voltage stability studies with good accuracy.
- (ii) Continuation load flow and obtaining PV curve is a planning exercise and it can be used for adjusting load margins and extension of existing power system networks.
- (iii) Critical loading limit can be used as parameter to compare various compensation techniques.
- (iv) CPF analysis can be used in distributed generation placement and sizing assessment.

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