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Possible Steady State Voltage Stability Analysis of Electric Power System Using PV Curve Analysis

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ABSTRACT In recent years, voltage instability and voltage collapse have been observed in power systems of many countries. Such problems have occurred even more often in developed countries because of utility deregulation. Currently, voltage security is of major importance for successful operation of power systems. Assessment of voltage security is needed to utilize power transmission capacity efficiently and to operate the system uninterruptedly. In our research work, we study voltage security of on power system of IEEE20 bus system. We assess voltage security of these systems using P-V curve In other words, we compute margins of real power(P) . To achieve what we promise, we first obtain the power-flow solution for the given data by running the power-flow program that we have coded using MATLAB. The solution is taken as the base case. Second, we choose candidate buses at which we incrementally change real power for plotting P-V curves. The candidate buses are of load buses so that P margins are computed against increase in demand. Third, we run the power-flow program for incremental changes in real power at the candidate bus. The point at which power-flow convergence is no more available is the critical point. Up to the critical point, we obtain voltages at the candidate bus corresponding to changing realpower at the same bus.Fourth, we plot P-V curves using voltages versus P .Finally, the difference between the real power demanded the candidate bus at the critical point and that at the base case gives us the P-margin computed for the candidate bus. This paper proposed that Our investigation of power-flow solutions, P-V curves of the 20 bus IEEE system -shows that we obtain power-flow solution using Newton-Raphson method and compute margins of voltage security with predefined tolerance using MATLAB. Such computations provide us indispensable information for the secure and efficient operation of power systems.

KEYWORD: Voltage stability, Contingency analysis Load shedding, P–V curve–Q–V curve ,Voltage stability margin.

I.INTRODUCTION

In the modern competitive electric energy market, power systems are more heavily loaded than ever before because of the growing demands, maximum economic benefits and efficiency of usage of transmission capacity [1]. The more efficient use of transmission network has already led to a situation in which many power systems are operated more often longer and closer to voltage stability limits resulting in a higher probability of voltage instability or collapse [2, 3]. Thus, voltage stability analysis has become a major concern in power systems planning and operation, and deals with power system adequacy and security. The adequacy of production and transmission capacity is maintained in the long term and is related to the maximum load-ability of a system so that it can be operated with an adequate voltage stability margin to prevent voltage collapse. The security of a power system is related to the remedial actions of pre-/post-contingency that are suitable to secure operational criteria. It is clear that voltage security analysis is commonly based on the detection of a sufficient voltage stability margin in the events of some critical contingencies. Nowadays, a number of methods have been proposed for the purposes of power system adequacy and security analysis [4–9]. The main objectives of these methods have been to accurately quantify stability margins and power transfer limits, identify voltage-weak nodes and areas susceptible to voltage instability, and identifying properly remedial actions to improve voltage stability margins; these are the principal focus of this paper. There are two main methods of accurately assessing voltage stability margins. One is direct measurement; the P–V curve technique is a well-known method, and

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is plotted for a constant power factor under a series of computing load-flow solutions that are based on the continuation method [10, 11] or repeated power flow method.

The P–V curve presents the maximum load-ability (real power) limits of a power system or network maximum power transfer capacity. The Western Electricity Coordinating Council (WECC) proposes a minimum P–V margin requirement of 5% for a single contingency, 2.5% for double contingencies, and larger than zero for multiple contingencies (N≥3) [12]. Many optimal power flow methods for voltage stability analysis are also based on P–V curve margin perspectives [13–17].Steady-state stability is defined as the capability of the network to withstand a small disturbance (fault, small change of parameters, topology modification) in the system without leaving a stable equilibrium point. On the contrary, voltage instability can be described as the system state, when the voltage slowly decreases (due to insufficient reactive reserves) until significant voltage drop appears (voltage collapse).The effect is even lower voltage, repetitive occurrence of stalling and line trippings.For the prevention of voltage collapse, several types of compensation devices are massively used - both shunt capacitors and inductors, series capacitors (TCSCs), SVCs, synchronous condensers, STATCOMs, etc. To reduce the voltage profile (in case of low demand), var consumption must be increased - switching in shunt reactors disconnecting cable lines, reducing MVAR output from generators and synchronous condensers, tap changing, etc. Opposite actions are taken for increasing bus voltages.However, voltage conditions may be even worsened in some cases by massive use of shunt capacitors.

II.ANALYTICAL SOLUTION USING THE THEORY OF LOAD FLOW ANALYSIS

A. Theoretical background to the nose (voltage-power, V-P) curve

Major goal of the steady-state voltage stability analysis is the computation of the V-P curve, also known as the "nose curve" – see Fig. 1. For the chosen PQ bus of the network, this curve shows the dependence of the bus voltage magnitude (vertical axis) on the active power load in the bus when increased from zero to its maximum possible value.

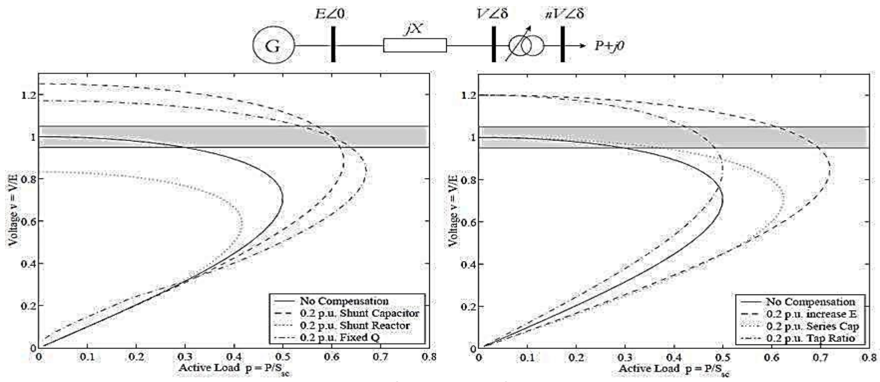
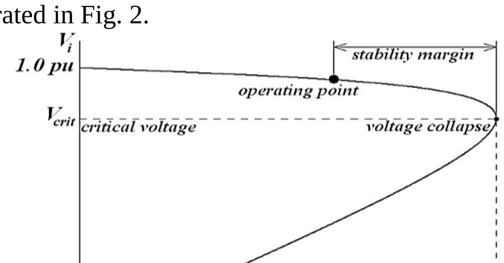


Figure 1 – The P-V curve for bus *i* of a general power system

At the beginning, the voltage starts from the value equal or close to 1.0 per units slowly moving down with gradually increased active power load. In a certain point – so called "saddle node bifurcation point" or "singular point", further load increase would provide no feasible operating voltage magnitude at all and voltage collapse occurs. Therefore, this limited load value is called the "maximum loadability" and corresponding voltage value the "critical voltage". From this point on, only the decrease of power leads to a solution until zero voltage and load are reached. In the practice, only the higher half of bus voltage magnitudes provides a stable operating point.. Among others, level of the reactive power reserve shows the

amount of var compensation available in individual steps of the V-P curve. The impact of various compensation devices on the V-P curve is demonstrated in Fig. 2.



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Vol. 4, Issue 8, August 2015

Figure 2 – Effects of possible compensation devices on the V-P curve

As shown in Fig. 2 above, higher critical voltage value along with higher maximum loadability can be suitably reached using series capacitors, fixed var injections, increased supply voltage and tap ratio switching actions.

B.Analyzed problem I. (3-bus power system)

Although the voltage collapse is a dynamic problem, it can be analyzed using static methods whether the power system parameters move slowly. As the first case study, a 2-bus power system (see Fig. 3) has been considered. The network consists of 3 buses in total, where bus 3 is the consumption point with connected P-Q load. Bus 3 is connected to bus 2 via a long transmission line (R = 8.2 W, X = 89.63 W, B = 1258 mS). The load is supplied from a large part of the country's transmission network, which has been simplied by the Thevenin's theorem into an equivalent power source in slack bus 1. Bus 1 is interconnected with the transmission line 2-3 via relevant system reactance (X = 36 W). The task is to derive the analytical relations between the active power load, voltage magnitude and the phase angle in bus 3.

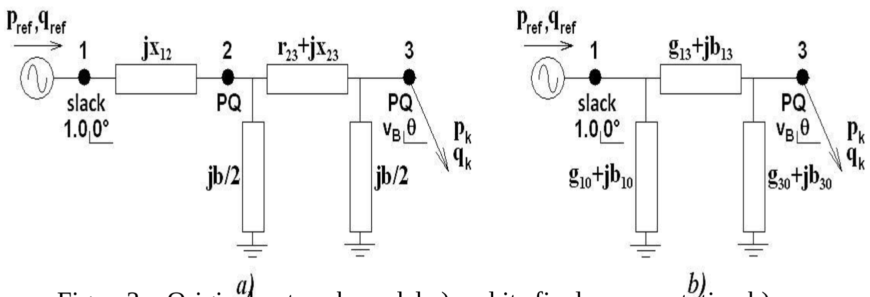

Figure3 – Original network model a) and its final representation b)

For the voltage stability study, calculation in per units (V_{base} = 400 kV, S_{base} = 100 MVA) andconstant power factor for load in bus 3 have been chosen. It was also necessary to recalculate the original network scheme in Fig. 3a) into an equivalent p - element – see Fig. 3b The final 2-bus power system (Fig. 3b)) can be described using the load flow nodal equations – see below.

$$\frac{p_{ref} - jq_{ref}}{1.e^{j0^\circ}} = \left(g_{13} + g_{10} + j(b_{13} + b_{10})\right).1.e^{j0^\circ} - (g_{13} + jb_{13})V_B e^{j\theta}$$

$$\frac{-p_k + jq_k}{V_B e^{-j\theta}} = -(g_{13} + jb_{13}).1.e^{j0^\circ} - \left(g_{13} + g_{30} + j(b_{13} + b_{30})\right)V_B e^{j\theta}$$

For bus 3, active and reactive loads with constant power factor (p.f.) can be expressed as follows:

$$q_k = p_k \tan(\arccos \mathrm{p.f.}) = e.p_k$$

When separating real and imaginary components, the following system of equations can beobtained from the second equation of (2).

$$p_k = g_{13}V_B\cos\theta + b_{13}V_B\sin\theta - (g_{13} + g_{30})V_B^2 \qquad q_k = g_{13}V_B\sin\theta + b_{13}V_B\cos\theta - (b_{13} + b_{30})V_B^2 = e.p_k$$

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Vol. 4, Issue 8, August 2015

Voltage conditions in the network can be examined by solving the above system of equations.Beside the voltage problem, each voltage decrease in bus 3 of the network will result in an increase of voltage phase angle q, which moves state variables close to the static stability limit.Relation between the bus voltage vB and the phase angle q (Eqn. 4) can be simply derived from Eqn. 3.

$$V_B = \frac{(b_{13} + eg_{13})\cos\theta + (eb_{13} - g_{13})\sin\theta}{(b_{13} + b_{30}) + e(g_{13} + g_{30})}$$

When putting Eqn. 18 into the first of Eqn. 3, final formula for static stability p_k = f(□) can beobtained.

$$p_k = \frac{(g_{13}b_{30} - g_{30}b_{13})(b_{13} + eg_{13})}{[(b_{13} + b_{30}) + e(g_{13} + g_{30})]^2}\cos^2\theta + \frac{(b_{13}^2 + b_{13}b_{30} + g_{13}^2 + g_{13}g_{30})(eb_{13} - g_{13})}{[(b_{13} + b_{30}) + e(g_{13} + g_{30})]^2}\sin^2\theta +$$

$$- \frac{\begin{array}{c}2(g_{13} + g_{30})(g_{13}e + b_{13})(b_{13}e - g_{13}) - \\ (b_{13}^2 + 2g_{13}b_{13}e - g_{13}^2)(b_{13} + b_{30} + e(g_{13} + g_{30}))\end{array}}{[(b_{13} + b_{30}) + e(g_{13} + g_{30})]^2}\cos\theta \, . \sin\theta$$

The V-P curve can be found by expressing terms 'cos□ ' and 'sin □ 'separately from Eqn. 4 using the trigonometrically identity formula. By placing them into the first of Eqn. 3, the nose curve is as follows.

$$p_k = \frac{\begin{array}{c}(g_{13}^2 + b_{13}^2)[(b_{13} + b_{30}) + e(g_{13} + g_{30})]eV_B^2 + \\ +(g_{13}^2 + b_{13}^2)\end{array} \\ V_B\sqrt{(g_{13} - eb_{13})^2 + (b_{13} + eg_{13})^2 - [(b_{13} + b_{30}) + e(g_{13} + g_{30})]^2 V_B^2}}{(g_{13} - eb_{13})^2 + (b_{13} + eg_{13})^2} - (g_{13} + g_{30})V_B^2$$

Values of critical voltage vcrit and static stability -qcrit can be found by differentiating Eqns. 5 and6 by V_B and q and setting to zero. The value of maximum loadabilityp_{kmax}can be then simply obtained fromEqn. 6.

$$\left.\begin{array}{l}\dfrac{dp_k}{dV_B} = 0 \rightarrow V_{Bcrit} = 0.669511426\text{pu}(\approx 267.81\text{kV}) \\ \dfrac{dp_k}{d\theta} = 0 \rightarrow -\theta_{crit} = 34°12'32"(\approx 0.59705\text{rad})\end{array}\right\} \rightarrow p_{kmax} \approx 4.9487\text{pu}(494.87\text{MW})$$

As can be seen from the results, the maximum loadability was reached for the phase displacementvalue (-qcrit) lower than 45 degrees which is the maximum theoretical static stability limit value for all simple 2-bus power systems. In comparison, the static stability limit of 90 degrees applies only for the generator and its close adjacent area.Above, the analytical procedure has been introduced for analyzing the voltage stability of simplepower systems. Such approach has been tested on a similar network to the one in Fig. 3, where the transmission line was supplied from two independent power sources modeling two separated parts of the entire transmission power system of the country. Final relations for describing all steady-state processes in this network have been successfully derived. However, these formulas for V-P curve, but also for active and reactive power flows, etc. are not presented in this paper due to limited content of this paper and their complexity.However, both of these methods gain numerical stability problems when approaching the singular point. Especially in the Newton-Raphson method, the Jacobian is becoming singular (det J= 0) when close to the singular point. Due to this reason, the divergence of the Newton-Raphson is inevitable.For the evaluation of formulas analytically derived above for the 3-bus power system, the Gauss-Seidel has been used since it possesses broad range of numerical stability around the singular point. Below (Fig. 4), the V-P curve along with P-θ and V-θ dependencies is transparently shown. Analytical solutions are depicted by cyan colour, while numerical results are drawn by red, blue and green colours, respectively. As can be seen, results from both analytical and numerical methodologies correspond to each other. For transparency reasons, demanded limit values obtained in numerical way are as follows: pmax= 4.948 pu, vcrit = 0.676065 pu, -qcrit =33° 49' 50.16".As already known, the Gauss-Seidel method cannot be practically used for solving the load flowproblems in large electric power systems due to only linear speed of convergence and large number of iterations which are even strongly dependent on the size of the analyzed

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Vol. 4, Issue 8, August 2015

network. Due to these factors, the Newton-Raphson method was massively adopted in the past for becoming more suitable for assessing stable and unstable operations of electric power systems.

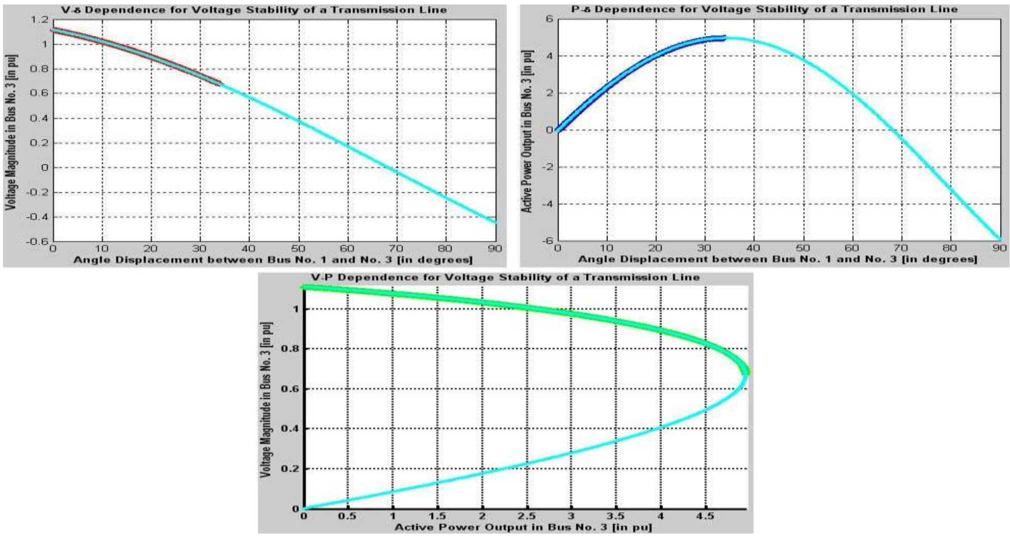

Figure 4 – Final graphical outputs for the 2-bus power system (both analytical and numerical)

III.CONTINUATION LOAD FLOW ANALYSIS

Several static approaches consequential from the traditional load flow programs are being used for theevaluation of the network stability – from the optimal active and reactive power flow (OPF) and eigenvalue analysis through the sensitivity based and path-following methods (such as the continuation load flow) up to modal analysis for transient voltage stability.

Continuation load flow analysis suitably modifies conventional load flow equations to becomestable also in the singular point of the V-P curve and therefore to be capable to calculate both upper and lower part of the V-P curve. For this, it uses the two-step predictor/corrector algorithms along with single new unknown state variable (so-called continuation parameter). The predictor estimates approximate state variable values in the new step (close to the V-P curve) while the corrector makes the corrections of new state variable values to suit the load flow equations – see Fig. 5. As a result, the voltage stability margin for the current operational point can be simply evaluated. Moreover, based on the differential changes of state variables in each predictor step it is possible to locate weak buses and even areas of the system with largest voltage changes with respect to the load increase

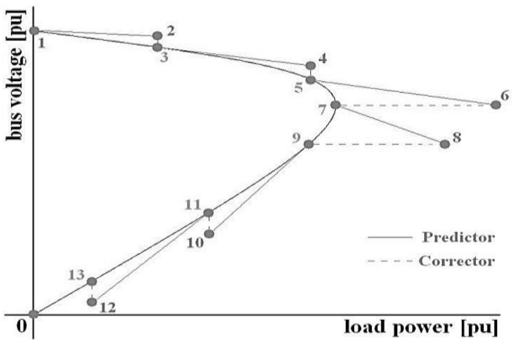

Figure 5 – Continuation load flow analysis (both predictor/corrector steps)

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(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 8, August 2015

Furthermore, the continuation load flow algorithm can be simply formulated for load increase (both active and reactive) in a single bus, in particular network area with more buses or even in the entire network

A.Initial continuation load flow studies

For the first analysis set, the continuation load flow predictor/corrector algorithm has been created in Matlab environment for simulating voltage stability in a chosen PQ bus of the network and relevant responses to the increase of both active and reactive power loads with constant power factor. The Using the numerical approach, maximum load ability of 4.94817 pu and critical voltage of 0.67522 pu have been obtained. When compared to critical values from the analytical solution (4.9784 pu and 0.6695 pu, Eqn. 7), it is obvious that high accuracy of the results has been maintained. In the second study, the IEEE 20-bus power system has been analyzed in terms of the voltage stability. This network (see Fig. 7) contains in total 8 physical PQ buses (No. 4 and 5 in the 132 kV section, No. 9 to 14 in the 33 kV section).The continuation load flow analysis for voltage stability in each PQ bus of the network has been performed separately by increasing both active and reactive power loads with maintained power factor(from the original load connected).

IV.METHODOLOGY OF MARGIN CALCULATION BY PV CURVE

we generate P-V and Q-V curves by series of power-flow solutions. First of all, we run the power-flow program that we code in MATLAB environment using Newton-Raphson method to obtain the power-flow solution. Our program takes into account the reactive power limits of generators in the systems.

Choose a load bus at which the real power P is incrementally increased. The real power output of the generators should remain unchanged during the P-V analysis. The reactive power output of each generator should be allowed to adjust as the P-V analysis progresses. Voltage collapse occurs in the study region after the reactive power capability in the study region is depleted. Increase the real power P by 0.2 p.u. at the candidate bus..Iterate the processes at step 3 until the power flow does no more converge. To reach the collapse point (the nose of the curve) closely, take the last case at which the power flow converges as the base case. Decrease the value of increment to 0.1 p.u. and execute steps 3 and 4..Execute step 5, decreasing the value of increment to 0.05 p.u.Using the methodology for generating P-V curves which we discuss above, we generate P-V curves for load buses 5, 9, and 19 of the 20-bus IEEE system.8Run the program that plots the P-V curve using the calculated voltages corresponding to incrementally changed P values at the candidate bus. Compute the P margin, subtracting P value at the base case from maximum permissible real power Pmax, which is at the collapse point. The approximate P margins for the given buses are easily obtained from the P-V curves in these figures.

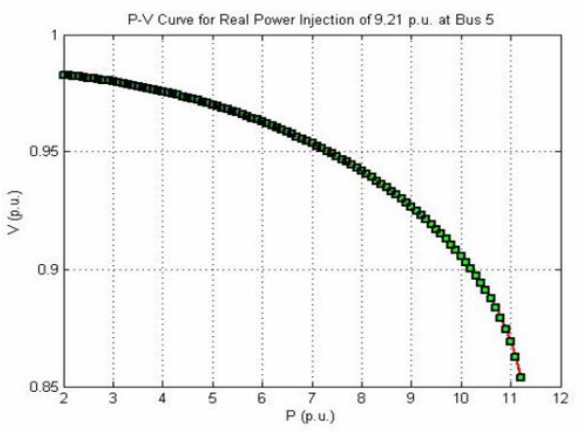

Figure 8 P-V Curve 5 Bus IEEE20

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

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(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 8, August 2015

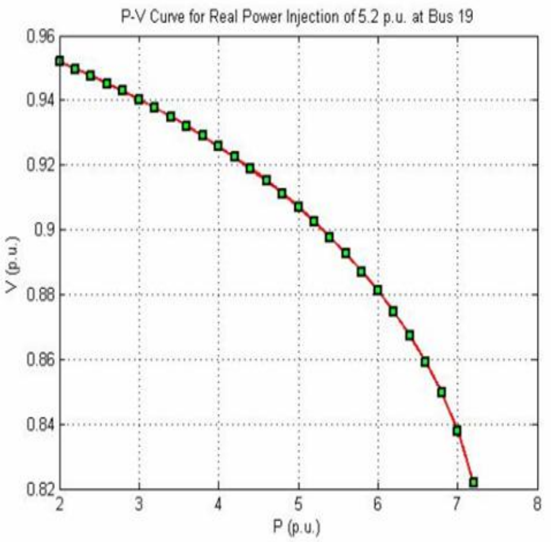

Figure7 P-V Curve 9 Bus IEEE20

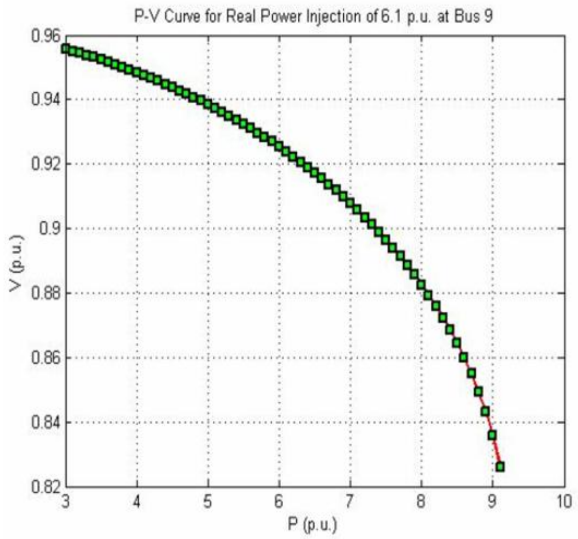

Figure 8 P-V Curve 19 Bus IEEE20

V.CONLUSION

Main aim of this paper was to introduce the voltage stability problem along with possible analytical solution. In the second half, the continuation load flow analysis was presented and used for computing critical values (maximum loadability, critical voltage) and the stability margin for a 3-bus and IEEE 20-bus power systems using the developed programming tool in Matlab environment.

In future work, further development of the program will continue for incorporating the full-scale steady-state voltage stability analysis of even larger power systems. The target will be especially to evaluate stability margin values for all PQ buses concurrently with identifying weak areas of the network with respect to the load increase. Second, load flow analysis of ill- conditioned power systems and networks containing bad input data will be performed using the CLF algorithm for locating the errors in input load data and therefore to enable the load flow calculation using the conventional numerical methods such as the Gauss-Seidel and the Newton-Raphson.

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