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Checking Loadability Limits and Finding Optimal Location and Size of SVC to Improve Loadability

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Abstract— **Voltage instability is a significant issue that could happen in power systems and sometimes leads to the outage of the system. Voltage instability study is important in power system planning and continual operation. In addition, the maximum loadability ranking process of buses can be performed by computing line stability while increasing the reactive power loads.**

In this paper, by using Power System Analysis Toolbox (PSAT); the IEEE 30 bus system is used to identify the voltage instability by using the Continuation Power Flow (CPF) method. Also, optimal sizing and location of SVC devices to improve the loadability in the system.

Index Terms: **Voltage stability, loadability, optimal size and location, SVC devices, PSAT.**

I. INTRODUCTION

Voltage instability is relatively recent and challenging problem in a power system. Day by day it is gaining importance as the trend of operating power system close to their maximum limits increases. Present day power systems are being operated closer to their stability limits due to economic and environmental constraints.

Power system stability can be stated as the ability of the power system that enables it to maintain in state of equilibrium under normal operating condition and to regain an acceptable state of equilibrium after being subjected to a disturbance. Voltage stability is the ability of the power system to maintain voltage up to their limit, so that when the load admittance is increased, load power will increase, thus both power and voltage are controllable [1].

In power systems, a static voltage stability analysis, the computation of the maximum loading point is important to stability margin determination, the continuation power flow analysis overcomes the convergence problem near the stability limit by reformulating the power flow equations so that they remain well-conditioned at all possible loading conditions. This allows the solution of power-flow problem for stable as well as unstable equilibrium point. The purpose of the continuation power flow was to find a continuum of power flow solution for a given load change scenario. An early success was the ability to find a set of solutions from a base case up to the critical point.

Continuation power flow (CPF) is a well-established technique to calculate loadability limits by producing PV curves, i.e. curves showing a critical voltage as a function of load demand in a power system, or power consumption at a bus. Such curves are usually restricted to positive consumption of active power (P).

In the last decade, several high-level scientific languages, for example Matlab, Mathematica, and Mathcad , have become familiar for research methods. From these languages Matlab proved to be the user best choice; the important features of Matlab are the matrix-oriented programming, with an excellent plotting capabilities. Several Matlab tools in power system have been proposed such as Power System Toolbox (PST), Power Analysis Toolbox (PAT) and Power System Analysis Toolbox (PSAT).

Power System Analysis Toolbox (PSAT) is a Matlab toolbox for both electric power system analysis and control. Power flow, continuation power flow, optimal power flow, small signal stability analysis, and time-domain simulation can be applied in PSAT. The toolbox is also provided with a complete graphical interface and a Simulink based one-line network editor.

In [2], an algorithm is used to determine the optimal placement and size of Static Var Compensator (SVC) in transmission network.

This work uses Matlab based power system analysis tool; Power System Analysis Toolbox (PSAT); which is freely distributed on line; to illustrates some PSAT features for stability analysis and loadability with the case study IEEE 30-bus.

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II. P-V CURVE METHOD

The P-V curve method is widely used method in voltage stability analysis. This involves using a series of power flow solutions for increasing transfers of MW and monitoring its effect on the voltages as a result. This gives the available amount of active power margin before the point of voltage instability. Natakorn Thasnas in [3] said: the inability of the electrical networks to transfer reactive power to load causes voltage instability. Also in [4], Ashwin N. an others said: the PV curve concept can be used to mark the weakest bus in the system. In [5], Pratiksha Molekar and others determined the weak buses of the power system by increasing the reactive load at each load bus slowly with the level of voltage collapse.

As seen in figure (1), the P-V curve starts from voltage at zero load and keeps decreasing the voltage as the load increases till it reaches a particular point where any further increase in the load collapses the voltage to zero. This point is called as the voltage collapse point or the maximum loadability point and the corresponding voltage is referred to as the Critical voltage. The distance of the operating point to the voltage collapse point denotes the stability margin of the system [5-6].

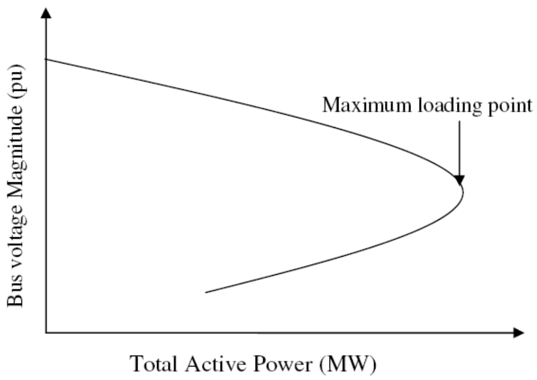

Figure 1. P-V curve

III. CONTINUATION POWER FLOW (CPF) MODEL IN PSAT

Bifurcation analysis requires steady-state equations of power system models, as follows [5-9]:

$$\begin{aligned} \dot{x} = 0 &= f(x, y, \lambda) \\ 0 &= g(x, y, \lambda) \end{aligned} \tag{1}$$

Where x are the state variables, y the algebraic variables (voltage amplitudes and phases) and λ is the loading parameter, i.e. a scalar variable which multiplies generator and load directions, as follows:

$$\begin{aligned} P_G &= P_{G0} + (\lambda + \gamma k_G) P_{S0} \\ P_L &= P_{L0} + \lambda P_{D0} \\ Q_L &= Q_{L0} + \lambda Q_{D0} \end{aligned} \tag{2}$$

Where: (P_{G0} , P_{L0} and Q_{L0}) are the "base case" generator and load powers, whereas (P_{S0} , P_{D0} and Q_{D0}) are the generator and load power directions. If these data are not defined, the base case powers are used [6]. The distributed slack bus variable (k_G) and the generator participation coefficients (γ) are optional.

The continuation power flow method implemented in PSAT consists in a predictor step realized by the computation of the tangent vector and a corrector step that can be obtained either by means of a local parameterization or a perpendicular intersection:

A. Predictor Step

At a generic equilibrium point, the following relation applies:

$$\begin{aligned} & g(y_p, \lambda_p) = 0 \\ & \left.\frac{dg}{d\lambda}\right|_p = 0 \\ & \nabla_y g|_p \left.\frac{dg}{d\lambda}\right|_p + \left.\frac{\partial g}{\partial \lambda}\right|_p = 0 \end{aligned} \tag{3}$$

The tangent vector becomes:

$$\tau_p = \left.\frac{dg}{d\lambda}\right|_p \approx \frac{\Delta y_p}{\Delta \lambda_p} \tag{4}$$

From (3) :

$$\begin{aligned} \tau_p &= -\nabla_y g|_p^{-1} \left.\frac{\partial g}{\partial \lambda}\right|_p \\ \Delta y_p &= \tau_p \Delta \lambda_p \end{aligned} \tag{5}$$

A step size control k has to be chosen for determining the increment Δy_p and $\Delta\lambda_p$, along with a normalization to avoid large step when $|\tau_p|$ is large:

$$\Delta\lambda_p \triangleq \frac{k}{|\tau_p|} \quad \Delta y_p \triangleq \frac{k\tau_p}{|\tau_p|} \tag{6}$$

Where K=±1 , and its sign determines the increase or the decrease of λ. Figure (2) presents a pictorial representation of the predictor step.

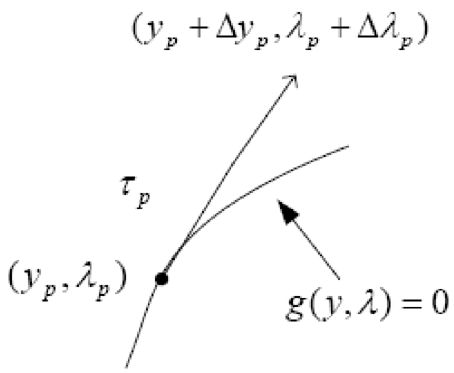

Figure 2. Continuation Power flow: predictor step obtained by means of tangent vector.

B. Corrector Step

In the corrector step, a set of n+1 equations are solved:

$$\begin{aligned} g(y, \lambda) &= 0 \\ \rho(y, \lambda) &= 0 \end{aligned} \tag{7}$$

Where the solution of (g) must be in the bifurcation manifold and is an additional equation to guarantee a non-singular set at the bifurcation point. As for the choice of , there are two options: the perpendicular intersection and the local parameterization.

In case of perpendicular intersection, whose pictorial representation is reported. In figure (3), the expression of becomes:

$$\rho(y,\lambda) = \begin{bmatrix} \Delta y_p \\ \Delta\lambda_p \end{bmatrix}^T \begin{vmatrix} y_c - (y_p + \Delta y_p) \\ \lambda_c - (\lambda y_p + \Delta\lambda y_p) \end{vmatrix} = 0 \qquad (8)$$

Whereas for the local parameterization, either the parameter (λ) or a variable (y_i) is forced to be a fixed value:

$$\rho(y,\lambda) = \lambda_c - \lambda_p - \Delta\lambda_p \qquad (9)$$

Or :

$$\rho(y,\lambda) = \lambda_{ci} - \lambda_{pi} - \Delta\lambda_{pi} \qquad (10)$$

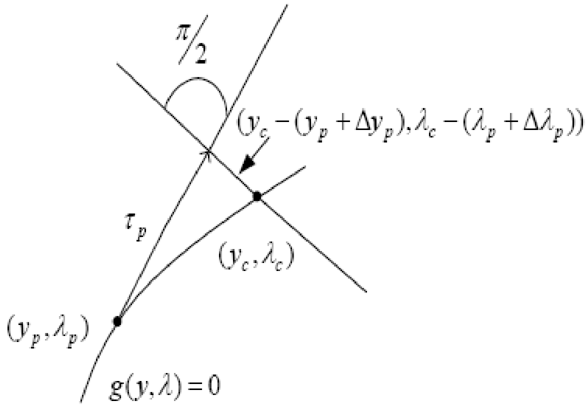

Figure 3. Continuation Power flow: corrector step obtained by means of perpendicular intersection.

IV. RESULTS

This section uses PSAT for voltage stability analysis in case of the IEEE 30-bus system, where this case is one of the widely used test cases available from the power system test case archive. The system has 34 transmission lines, 21 load buses, 6 generation buses, and 4 tap changing transformers. Figure (4) shows the single line diagram of the used system with (S_{base} = 100 MVA) [8].

This work is to find: loadability limit if lambda is equal for all loads in the system, Loadability limits if lambda is associated to each load separately and finally find the optimal location and size of compensating device that increases loadability limit by 5% when lambda is equal for all loads.

A. Lambda is equal for all loads in the system

CPF analysis is handled in IEEE 30-bus. The load flows are calculated at loading condition starting from 100% loading to all buses at the same time where lambda (λ) is equal for all loads. Table (1) gives the values of buses voltages in (pu) voltage, change ratios and the maximum loadability in (pu).

The voltage declines for all the load buses in the system. As seen in table (1), buses numbers (30, 29 and 26) are critical busses and bus 30 is the most critical one compared to the other buses. The maximum Loadability is (λ_{max}= 1.90741).

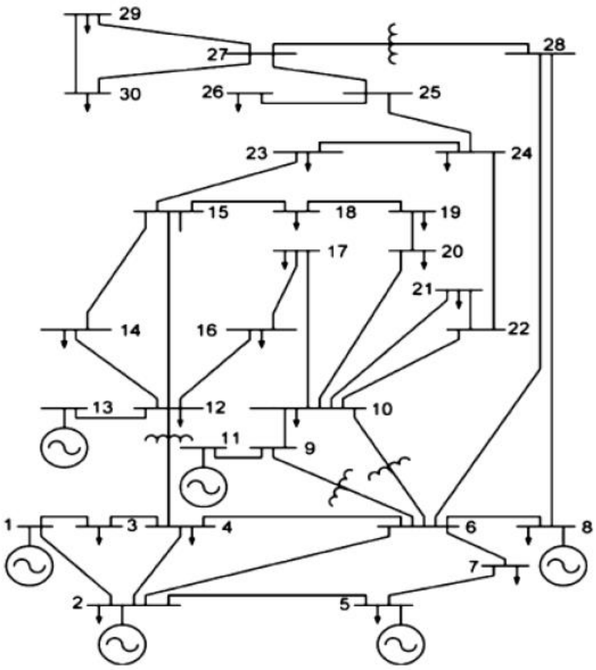

Figure 4. The single line diagram of IEEE 30-bus system

Table 1. Results when lambda is equal for all loads.

Bus number	V (pu)	ΔV (%)
3	0.90110	11.5000
4	0.89293	11.5000
6	0.92406	08.2800
7	0.92992	07.0750
9	0.91026	12.3000
10	0.81884	19.7110
12	0.91121	13.1280
14	0.84542	18.0400
15	0.81769	20.1960
16	0.84389	17.9800
17	0.80770	20.6220
18	0.76876	23.9290
19	0.75252	25.1560
20	0.76552	24.0750
21	0.76508	24.0460
22	0.76570	24.0280
23	0.75302	25.3670
24	0.70056	29.7060
25	0.68083	31.9210
26	**0.59340**	**39.5760**
27	0.71234	29.5370
28	0.90457	09.8610
29	**0.58625**	**40.8330**
30	**0.51228**	**47.6840**
λ_{max}	**1.90741**	

Figures (5, 6 and 7) show the P-V curves for buses 26, 29 and 30 respectively.

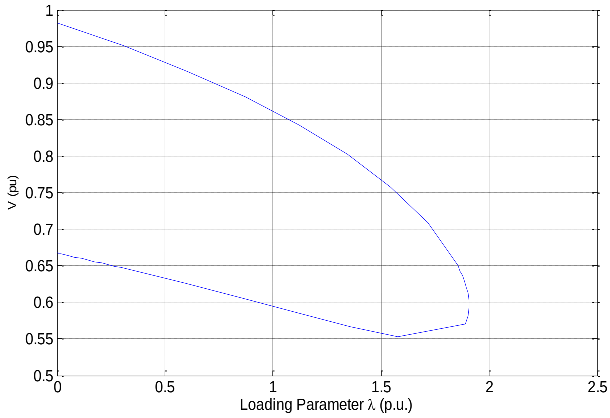

Figure 5. The P-V curve for bus 26 in case A.

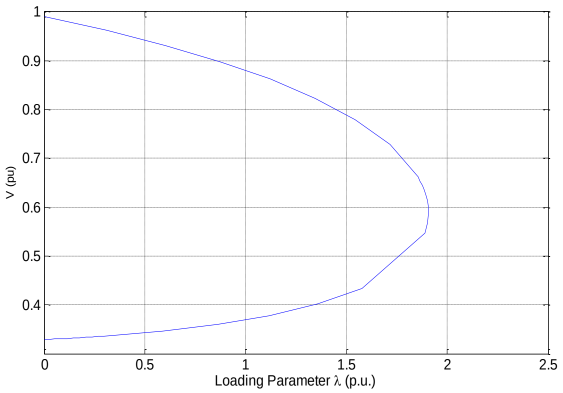

Figure 6. The P-V curve for bus 29 in case A.

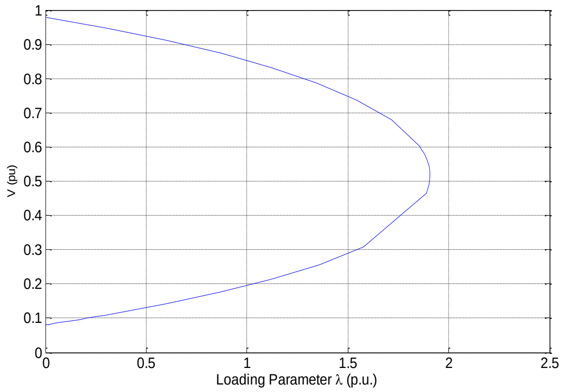

Figure 7. The P-V curve for bus 30 in case A.

B. Lambda is not equal for all loads in the system

The load flows are calculated in IEEE 30-bus where lambda (λ) is not equal for all loads. Table (2) gives the values of buses voltages in (pu) voltage change ratios and the maximum loadability in (pu). As seen in table (2), buses numbers (30, 29 and 26) are critical busses and bus 26 is the most critical compared to the other buses. The maximum loadability is (λ_{max}= 3.19999).

Figures (8, 9 and 10) show the P-V curves for buses 26, 29 and 30 respectively.

Table 2. Results when lambda is not equal for all loads.

Bus number	V (pu)	ΔV (%)
3	0.83465	18.0543
4	0.83398	17.3500
6	0.88814	11.8454
7	0.89358	10.7063
9	0.87646	15.5561
10	0.77317	24.1894
12	0.86025	17.9863
14	0.78312	24.0795
15	0.75267	26.5415
16	0.78446	23.7559
17	0.75125	26.1693
18	0.70802	29.9392
19	0.69813	30.5654
20	0.71119	29.4636
21	0.72150	28.3722
22	0.72187	28.3767
23	0.68910	31.702
24	0.65707	34.0695
25	0.62065	37.9387
26	**0.45333**	**53.8389**
27	0.68337	32.4025
28	0.87665	12.6434
29	**0.58260**	**41.2014**
30	**0.53184**	**45.6868**
λ_{max}	**3.19999**	

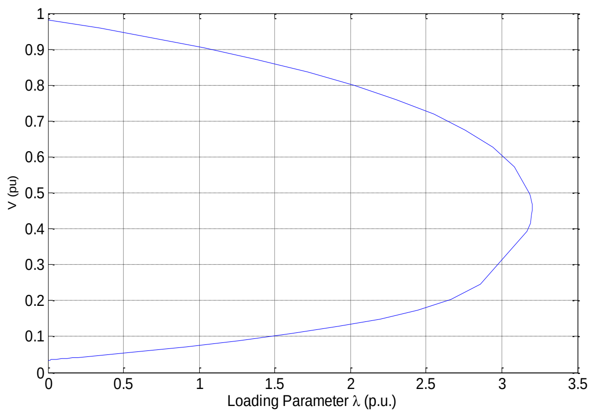

Figure 8. The P-V curve for bus 26 in case B.

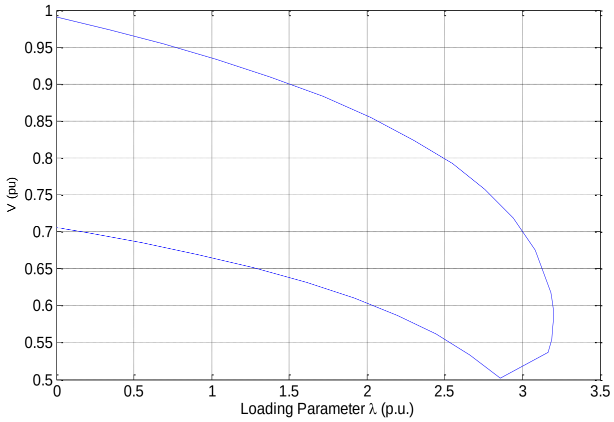

Figure 9. The P-V curve for bus 29 in case B.

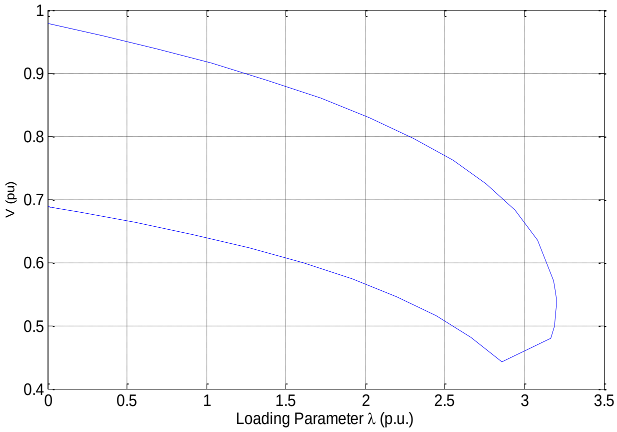

Figure 10. The P-V curve for bus 30 in case B.

C. Optimal location and size of compensating device

Instead of building new substations or transmission lines, proper installation of a SVC device can make the transmission networks accommodate more power transfers with less expansion cost. The goal here is optimally install SVC that rise the maximum loadability by 5 % in previous case (A) when lambda (λ) is equal for all loads. In other words, we look for the location of minimum compensation which makes the loadability be 2.003.

It is clearly from table (3), the best location with minimum compensation when install 0.03786 (pu) at bus 30. Figure (11) shows the same results but in Graphic columns.

Table 3. The required compensation for each bus.

Bus No.	Required Q (pu)	Bus No.	Required Q (pu)
3	1.74822	19	0.39371
4	1.44917	20	0.38764
6	1.37893	21	0.28650
7	2.83149	22	0.27325
9	0.70984	23	0.26276
10	0.37198	24	0.16218
12	0.77026	25	0.08372
14	0.61560	26	0.07409
15	0.44625	27	0.06892
16	0.54831	28	0.54267
17	0.40515	29	0.04542
18	0.41996	30	**0.03786**

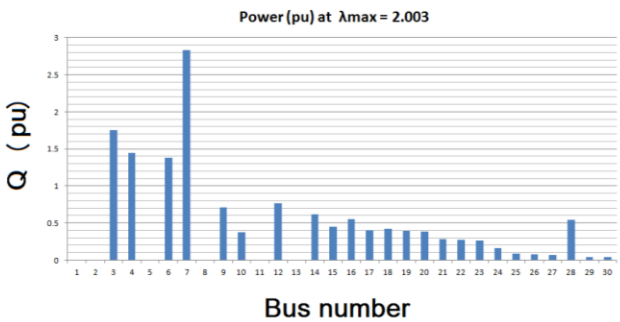

Figure 11. The required compensation for each bus.

V. CONCLUSION

An applications on IEEE30 Bus System using PSAT was presented to identify weak buses for two cases (equal and not equal lambda) and find the optimal location and size of SVC for the first mentioned case.

Based on the results, in the two cases; loadability limits were obtained that the voltage may become unstable. Also, an implementation of finding the optimal location and size of SVC to rise the maximum loadability by 5%. This was done by locating a compensation value of 0.03786 (pu) at bus 30.

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