Journal of Electrical and Electronics Engineering Research Vol. 2(2), pp. 048-056, March 2010
Available online http://www.academicjournals.org/JEEER

Full Length Research Paper

Estimation of bifurcation point in multi-bus system using generator reactive power limit approach

Nwohu, Mark Ndubuka

Department of Electrical/Computer Engineering, Federal University of Technology, P. M. B. 65, Minna, Niger State, Nigeria. E-mail: mnnwohu@yahoo.com.

Accepted 11 November, 2009

This paper proposes an approach for estimating bifurcation point in multi-bus systems. The approach assumes that the generators would violate their Q-limits before the bifurcation point is reached. The result of this assumption clearly raises the voltages along the PV curve which consequently yield an infinitesimal error. Therefore the final estimated point can be obtained after a number of load flow solutions depending on the complexity of the system and the loading pattern among others. Finally, computer simulations of two system networks are carried out to calculate the bifurcation point at the selected minimum voltage which estimates the bus that violates its Q-limit at a certain load.

Key words: Bifurcation point, PV curves, Q-limit, load flow.

INTRODUCTION

The estimation of the bifurcation point gives a platform for calculating the power margin or extreme loading condition before voltage collapse occurs in a power system at its operating point. This, of course, requires the initialization of the load flow as a basic unit in static and dynamic analysis of the system. The load flow solution can produce the trajectory of the PV curves to a point just before the bifurcation point where the solution starts to diverge. The final estimated point can be obtained after a number of load flow solutions depending on many factors such as system's complexity, the loading pattern, the size of the load step and the required accuracy (Hassan, 1995).

Various approaches have been adopted and applied to large power systems aiming at estimating the bifurcation points and improving the voltage stabilities of these systems.

Semleyen et al. (1991), in their view, discussed the use of the basic nodal equation to obtain the bifurcation point of a large power system. The active and reactive powers of each bus are expressed in terms of its load admittance and voltage. And the secant method is applied to find the zero crossing of the differential of both powers on the admittance-load factor plane.

Semleyen (1991) presents a simple numerical example to show how a proximity index can be calculated from the Jacobian and also depict the relation between the static and dynamic bifurcation using algebraic differential model.

Suzuki et al. (1992) have used the curve fitting technique, after obtaining a good number of lower and upper solutions on the PV curves, to estimate the static bifurcation point. However, the difficulty appears to be in obtaining the lower solution for large systems and the appropriate load increment for a weak system without passing the bifurcation point. The other controversial issue is the suitability of curve fitting techniques close to the bifurcation point when generators Q-limits are considered which tend to give staircase type curves.

Another approach called the Continuation technique which offers a unique approach of obtaining the full trace of nose curves was documented. This formed the basis of Ajjarapu and Christy's work (1992). The same technique has also been used by Canizares and Alvarado (1993) for large AC/DC systems.

The optimization technique (Obadina and Berg, 1998) was one of the early methods of obtaining the exact bifurcation point. An objective function, which is a function of the increase in active and reactive power demand, together with the load flow equations, are used to develop a Lagrange function. A stability margin having a value between 0 and 1 was also defined to serve as a measure of the voltage security of power systems. The same technique was also applied to the Belgian system (Custem, 1991).

However, in this paper, the focus is on the application of the generator reactive power limit technique to systems in order to determine their bifurcation points.

THE CONCEPT OF GENERATOR REACTIVE POWER LIMIT

When the system is complex the computational time can be very long and a technique for fast estimation of the bifurcation point is needed. Generators' Reactive Power Limit technique is one of the techniques used in fast estimation of the bifurcation point. Only reactive power limits of generators' buses can lead to saddle limit induced bifurcation points that associated to a maximum loading condition. It has a direct influence on the voltage profile of electric systems. It limits the computation time and averts the dynamic simulation of many inaccessible parameters in real time. The algorithm of the Generators' Reactive Limit technique is as follows (Lof and Reeve 1993):

Step 1: Set k = 0.
Step 2: Run load flow to obtain base case results or initial state, P_0, Q_0, V_0, θ_0 for each bus.
Step 3: Select a loading and generation scenario.
Step 4: For simplicity assume a uniform load increase of 2% ($d\alpha = 0.02$) on all buses.
Step 5: Obtain another system state using the load flow.
Step 6: Increment k.
Step 7: Evaluate $dQ/d\alpha$ for each generator bus, and $dV/d\alpha$ and $d\theta/d\alpha$ for each bus.
Step 8: Calculate the new load increase $\Delta\alpha_k$ that will cause the first generator, say i, to reach its Q-limit,

$$Q_{imax} = Q_{ik-1} + \Delta\alpha_k(dV_i/d\alpha)$$

Step 9: If all generators have violated their Q-limits, calculate the new load increase $\Delta\alpha$ that will cause the first bus, say i, to reach its critical voltage:

$$V_{icritical} = V_{ik-1} + \Delta\alpha_k(dV_i/d\alpha).$$

Step 10: Assuming that linearity is maintained, obtain a set of voltages and angles for each bus i:

$$V_{ik} = V_{ik-1} + \Delta\alpha(dV_i/d\alpha);\ \theta_{ik} = \theta_{ik-1} + \Delta\alpha_k(d\theta_i/d\alpha).$$

Step 11: Update the Jacobian using the above values and find the new solution:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \left[J_k\right] \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix}.$$

Step 12: Check if the bifurcation point has been passed, that is, if $dV/dQ < 0$ or $dV/dP < 0$.
Step 13: Go to step 4. If the solution is unstable then use the binary or dichotomic search methods until the increment $\Delta\alpha_k$ is within a specified tolerance.

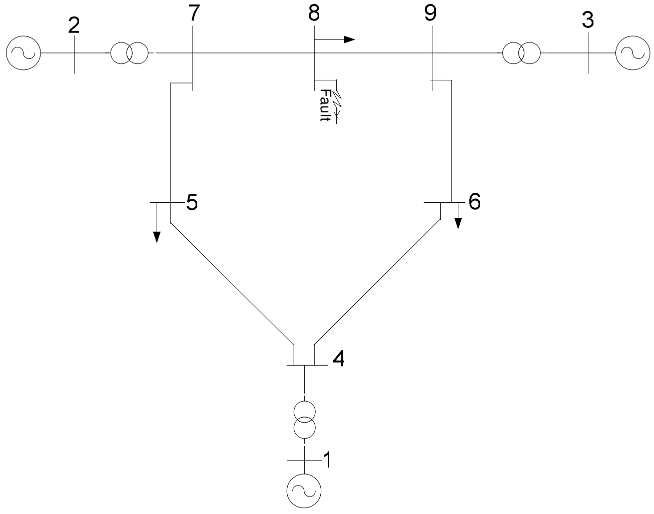

Figure 1. 3-machine 9-bus system.

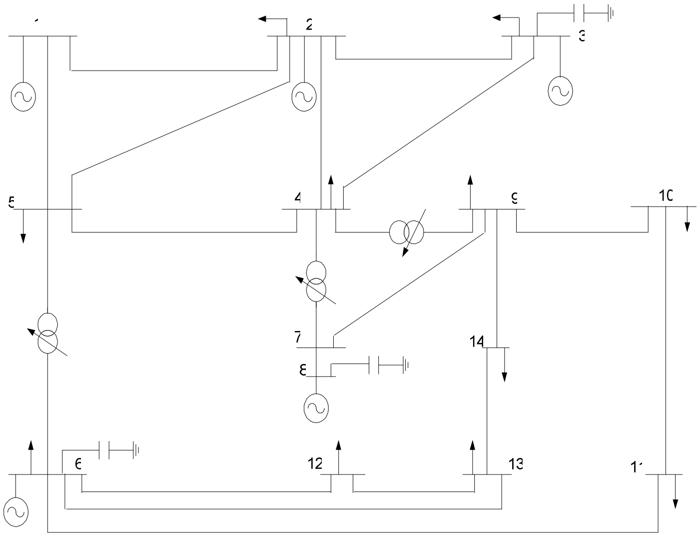

Figure 2. IEEE 14-bus system.

Step 14: Calculate the margin = $\sum_k \Delta\alpha_k$.

DESCRIPTION OF THE TEST SYSTEMS

Two systems have been selected for the application of Generator Reactive Power Limit technique. These systems are 9-bus system and IEEE 14-bus system (Pecas et al., 1993) as shown in Figures 1 and 2. The line and bus data of these systems are given in Appendices A1 and A2.

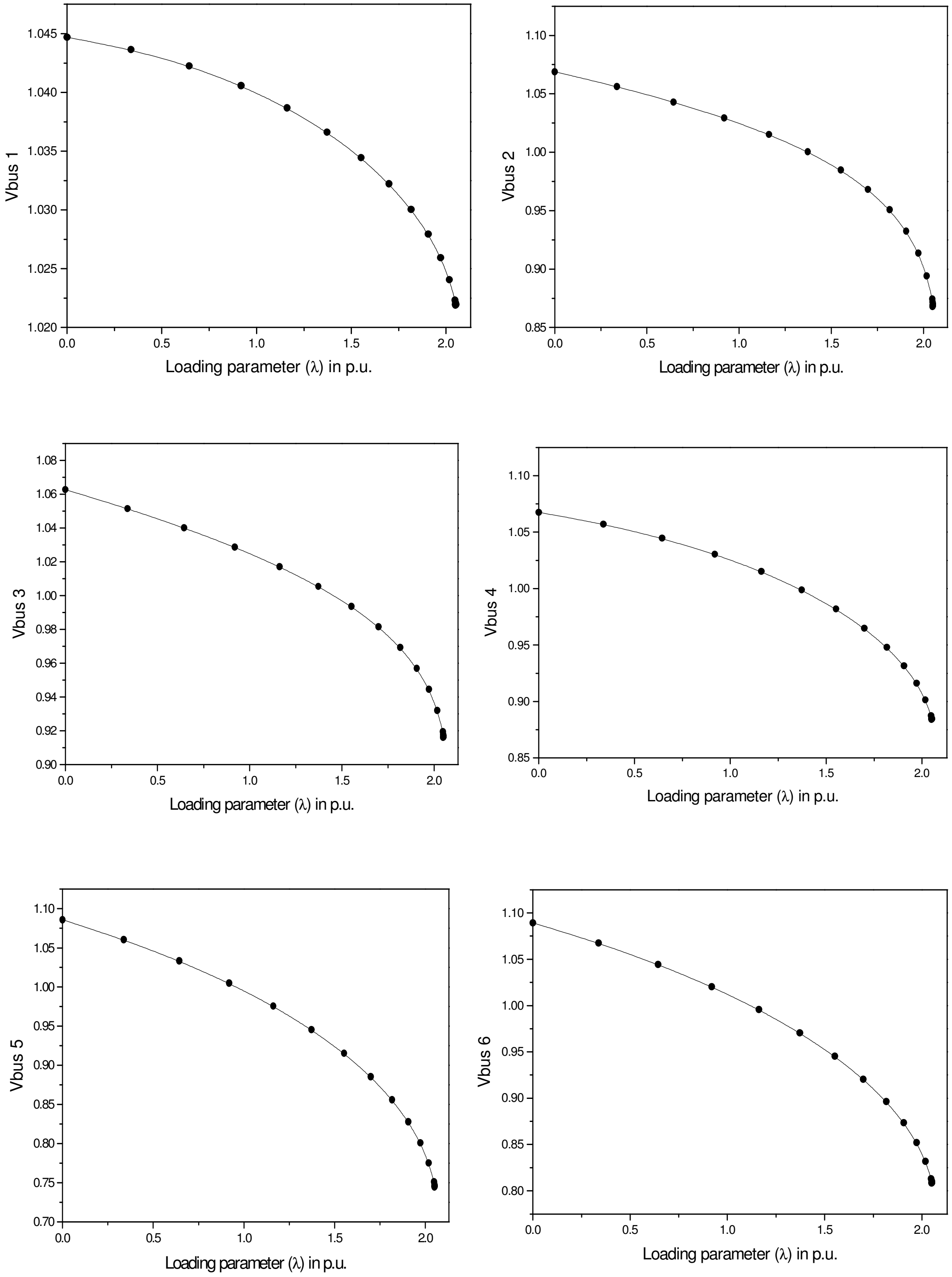

Figure 3a. Simulations for 9-bus systems.

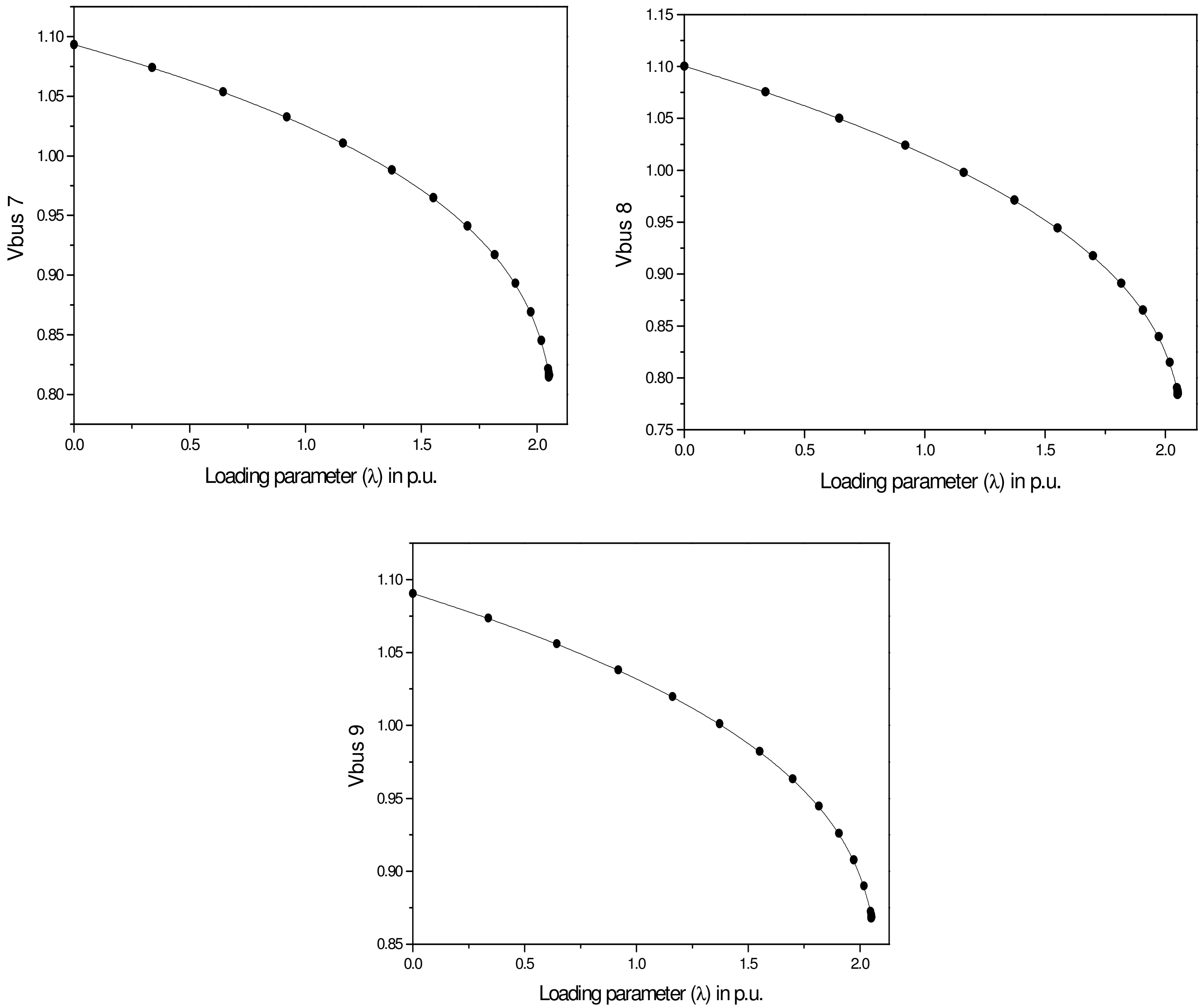

Figure 3a. Contd.

SIMULATIONS

The simulations are carried out with Power System Analysis Toolbox (PSAT). The calculation of the bifurcation point depends on the minimum voltage selected. The calculated step according to the initial slopes will estimate the bus that violates its Q-limit at a certain load (Figures 3a and 3b).

Conclusion

This paper has proposed a technique for estimating the bifurcation point of power systems. It is hoped that this paper would give an insight of the fast approach to estimate bifurcation point for voltage stability of any power network as IEEE 14-bus system has been considered a benchmark for comparative study in the proposed

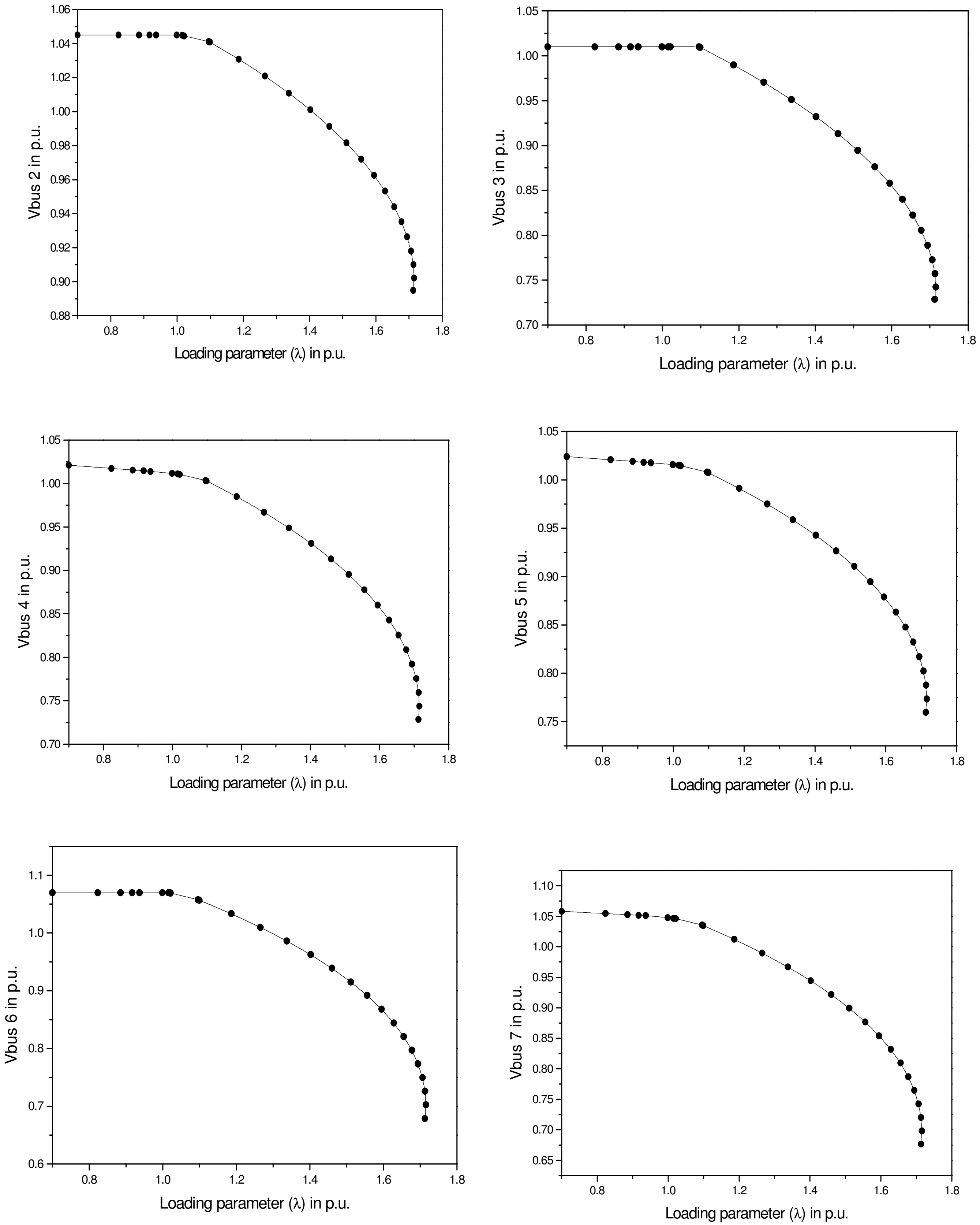

Figure 3b. Simulations for 14 bus systems.

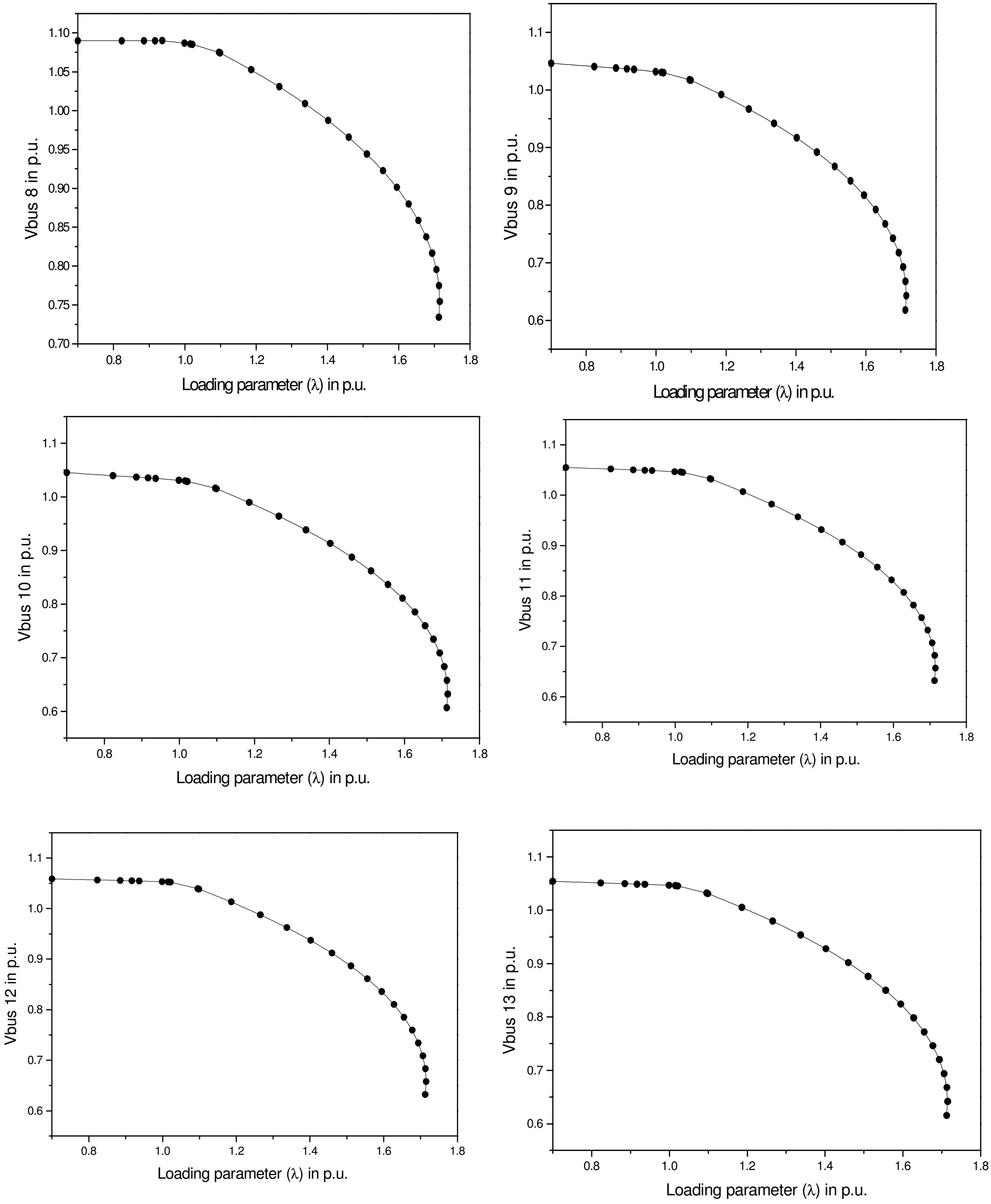

Figure 3b. Contd.

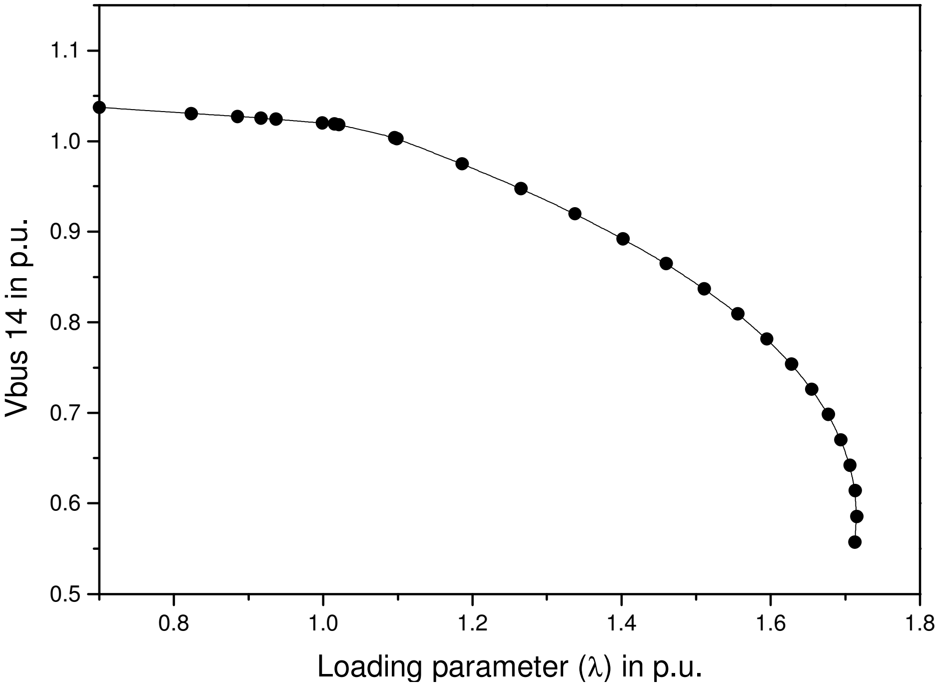

Figure 3. Contd.

technique. Finally, computer simulations of these system networks are carried out to calculate the bifurcation point which, subsequently, evolved pragmatic results that validate the proposed technique.

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Appendix

A1: Study system data (9-bus system).

Line data.

Element no.	From bus	To bus	R	X	Half line charge
1	7	8	0.0085	0.072	0.0745
2	8	9	0.0119	0.1008	0.1045
3	7	5	0.032	0.161	0.153
4	9	6	0.039	0.17	0.179
5	5	4	0.01	0.085	0.088
6	4	6	0.017	0.092	0.079
7	2	7	0	0.0625	1
8	9	3	0	0.0586	1

Values are in per unit and base on 100 MVA.

Bus data.

Bus no.	Bus type	V	Pg	Qg	Pl	Ql	Q_{min}	Q_{max}
1	2	1.04	-	0	0	0	0	0
2	2	1.025	163	0	0	0	-100	130
3	2	1.025	85	0	0	0	-70	50
4	1	1	0	0	0	0	-	-
5	1	1	0	0	125	50	-	-
6	1	1	0	0	90	30	-	-
7	1	1	0	0	0	0	-	-
8	1	1	0	0	0	0	-	-
9	1	1	0	0	0	0	-	-

All power values are in MW and MVAR.

Machine and exciter parameters.

Parameter	Machine 1	Machine 2	Machine 3	Unit
x_d	0.146	0.8958	1.3125	p.u.
x'_d	0.0608	0.1198	0.1813	p.u.
x_q	0.0969	0.8645	1.2578	p.u.
x'_q	0.000969	0.1969	0.25	p.u.
T'_{do}	8.96	6	5.89	sec.
T_{qo}	0.1	0.535	0.6	sec
M	0.0507	0.059	0.0125	p.u.
K_a	50	25	175	p.u.
T_a	0.06	0.2	0.05	sec
K_e	-0.08	-0.05	-0.17	p.u.
T_e	0.405	0.5685	0.952	sec.
K_f	0.0648	0.091	0.03	p.u.
T_f	1	0.35	1	sec

Values are in per unit and sec.

A2: Study System data (IEEE 14-bus system).

Line data.

Element no.	From bus	To bus	R	X	B/2	Transf. ratio
1	1	2	0.01938	0.05917		0.02640
2	2	3	0.04699	0.19797		0.02190
3	2	4	0.05811	0.17632		0.01870
4	1	5	0.05403	0.22304		0.02460
5	2	5	0.05695	0.17388		0.01700
6	3	4	0.06701	0.17103		0.01730
7	4	5	0.01335	0.04211		0.00640
8	5	6	0	0.25202	0.932	
9	4	7	0	0.20912	0.978	
10	7	8	0	0.17615	0	
11	4	9	0	0.55618	0.969	
12	7	9	0	0.11001	0	
13	9	10	0.03181	0.08450		0
14	6	11	0.09498	0.19890		0
15	6	12	0.12291	0.25581		0
16	6	13	0.06615	0.13027		0
17	9	14	0.12711	0.27038	0	
18	10	11	0.08205	0.19207	0	
19	12	13	0.22092	0.19988	0	
20	13	14	0.17093	0.34802	0	

Values are in per unit and base on 100 MVA.

Bus data.

Bus no.	Bus type	V	Pg	Qg	Pl	Ql	Q_{min}	Q_{max}
1	2	1.060	232.4	0	0	0	-	-
2	2	1.045	40.0	0	21.7	12.7	-40	50
3	2	1.010	0	0	94.2	19.0	0	40
4	1	1.000	0	0	47.8	-3.9	0	0
5	1	1.000	0	0	7.6	1.6	0	0
6	1	1.070	0	0	11.2	7.5	-6	24
7	1	1.000	0	0	0	0	0	0
8	1	1.090	0	0	0	0	-6	24
9	1	1.000	0	0	29.5	16.6	0	0
10	1	1.000	0	0	9	5.8	0	0
11	1	1.000	0	0	3.5	1.8	0	0
12	1	1.000	0	0	6.1	1.6	0	0
13	1	1.000	0	0	13.5	5.8	0	0
14	1	1.000	0	0	14.9	5.0	0	0

All power values are in MW and MVAR.