CHAPTER VI

ASSESSMENT OF VOLTAGE STABILITY USING PHASOR MEASUREMENT

6.1. INTRODUCTION

As power systems become more complex and heavily loaded, voltage stability coupled with economic and environmental constraints become an increasingly serious problem, resulting in operation of system closer to their operational limits. In spite of being local phenomenon, voltage instability may have wide spread impact which might lead to system failure (black out). In order to monitor the voltage stability status of a system, an appropriate index which would indicate the system operating point would be imperative. An accurate knowledge of how close the actual system's operating point is from the voltage stability limit is crucial to the operators. Therefore, determination of a voltage stability index has become an important task for many voltage stability studies. These indices provide reliable information about proximity of voltage instability in a power system.

Over the years, researchers and engineers have found that monitoring and control of voltage stability is particularly suitable when accomplished through PMUs. This device permits real-time measurements, which also help to overcome the shortfalls of inability to track slow or fast load dynamics associated with many currently available monitoring devices. Many methods have been reported in past for the voltage stability monitoring using PMUs. In this chapter, a voltage stability assessment method using real time Phasor Measurement has been presented. For this, it is assumed that all the buses of the system are fully observable by using the proposed OPP techniques. As the slope of the P-V curve increases, the voltage stability limit of a bus decreases. This observation has been utilized to evaluate an index defined as Voltage Stability Predictor Index (VSPI). The VSPI has been calculated at various loading conditions. The effectiveness of proposed index has been tested on various IEEE test systems.

6.2. CRITICAL VOLTAGE IN TWO BUS SYSTEM

A two bus example is given below to provide the basic concepts for calculation of critical voltage [123]. Consider a generator connected to a load bus through a lossless transmission line as shown in Figure 6.1. The voltage at generator bus is assumed to be $E\angle 0$ and the load bus voltage is $Vr\angle\theta$,

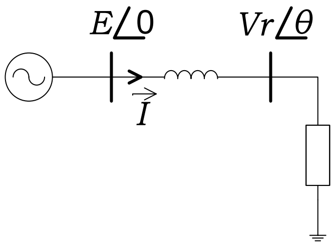

Figure 6.1. Two bus system

$$\vec{V}r = \vec{E} - jX\vec{I} \tag{6.1}$$

Since complex power *S,* is given as,

$$S = P_a + jQ_r = \vec{V}r\ \vec{I}^* \tag{6.2}$$

$$S = \vec{V}r\left(\frac{\vec{E} - \vec{V}r}{jX}\right)^* = \vec{V}r\left(\frac{\vec{E}^* - \vec{V}r^*}{-jX}\right) \tag{6.3}$$

$$S = Vr\angle\theta \frac{\left(E\angle 0 - Vr\angle(-\theta)\right)}{-jX} = -\frac{EVr}{X}\sin\theta + j\left(\frac{EVr}{X}\cos\theta - \frac{Vr^2}{X}\right)$$

Separating real and imaginary parts,

$$P_a = -\frac{EVr}{X}\sin\theta \tag{6.4}$$

$$Q_r = \frac{EVr}{X}\cos\theta - \frac{Vr^2}{X} \tag{6.5}$$

Applying the relation $(\sin\theta)^2 + (\cos\theta)^2 = 1$ and Equations (6.4) and (6.5), following relation can be obtained

$$\left(\frac{-P_a X}{EVr}\right)^2 + \left(\frac{Q_r X + Vr^2}{EVr}\right)^2 = 1$$

The above expression can further be substituted and simplified to,

$$\frac{Vr^4}{E^4} + \frac{Vr^2}{E^4}\left(2QX - E^2\right) + \frac{X^2}{E^4}\left(P^2 + Q^2\right) = 0 \tag{6.6}$$

or

$$v^4 + v^2\left(2p\tan\phi - 1\right) + p^2\left(\sec\phi\right)^2 = 0 \tag{6.7}$$

Where, $v = \dfrac{Vr}{E}$

$$p = \frac{P_a X}{E^2}$$

$$q = p\tan\phi = \frac{Q_r X}{E^2}$$

$$\phi = \tan^{-1}\left(\frac{Q_r}{P_a}\right)$$

The Equation (6.7) would produce four values of voltage, v out of which two would be physically meaningful. The other two solutions correspond to high voltage and low voltage solutions and can be expressed as,

$$v^2 = \frac{-(2p\tan\phi - 1) \pm \sqrt{(2p\tan\phi - 1)^2 - 4p^2(\sec\phi)^2}}{2} \tag{6.8}$$

For example, at $p = 0$, the Equation (6.8) would produce $v = 0$ or 1 as shown in Figure 6.2 below.

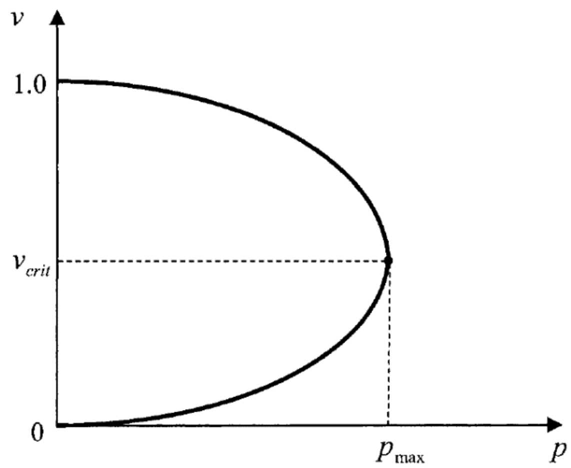

Figure 6.2. Variation of v with respect to p

At the maximum power (p_{max}) point, the term inside the square root in Equation (6.8) would assume zero value. Under this condition,

$$p_{max} = \frac{\cos\phi}{2(1+\sin\phi)} \tag{6.9}$$

and

$$v_{crit} = \frac{1}{\sqrt{2} * \sqrt{(1+\sin\phi)}} \tag{6.10}$$

Studying and controlling voltage collapse occurrences require the use of dynamic and static analysis techniques. A large disturbance, such as a loss in transmission or generation equipment may cause a decrease in reactance, which may cause the network characteristic to shrink so that it no longer crosses the load characteristics. Similarly, as power system networks grow, demand on grid resources increase and contingency impacts on the interconnected grids become more threatening or severe, therefore, a real-time determination of power system operation and control is needed.

6.3. PROPOSED VOLTAGE STABILITY PREDICTOR INDEX

The voltage stability problem is mostly related to the reactive power prevalent in the system. The reactive power deficiency in stressed power system arising either by incapability of voltage source to inject the required reactive power to the system or by inability of transmission line to transfer the demanded reactive power to the weak buses causes voltage instability in power system. If during any one of these conditions, these happens to be occurrence of any disturbance, like increase in load, transmission line outage or outage of generation, then the voltage stability of the system further degrades and may cause decline in voltage at load bus. The successive degradation in system condition may cause voltage collapse, also. So, it is important to monitor voltage of all load buses in real time.

The proposed VSPI has been evaluated using voltage phasor obtained from PMU measurement. In order to demonstrate this method, the voltage phasors have been determined using Continuous Power Flow (CPF) for varying load. Let the load at any bus be changed and because of this the voltage V_{ju} at any load bus j at instant u is changed to $V_{j(u+1)}$ at $(u+1)^{th}$ instant. Therefore, the successive change in voltage with respect to a successive change in load is equal to,

$$s_{j(u+1)} = \frac{V_{j(u+1)} - V_{ju}}{(\delta_{(u+1)} - \delta_u)} \tag{6.11}$$

where $s_{j(u+1)}$ is the successive change in voltages from instant 'u' to '$(u+1)$' at bus 'j' with respect to change in load of the system at these instants. When load is further changed at next instant i.e. at instant $(u+2)$ then $s_{j(u+1)}$ is changed to $s_{j(u+2)}$ due to change in voltage V_j at bus j. Denominator, $(\delta_{(u+1)} - \delta_u)$ is the successive load change. The variation of successive change in slope of the voltage with respect to change in load gives the VSPI for assessment of voltage stability of the system. VSPI should be calculated at all the load buses of the power system and is given by,

$$\mathrm{VSPI}_{j(u+1)} = \frac{\tan^{-1}(s_{j(u+1)})}{-\pi/2} \tag{6.12}$$

In Equation (6.12), numerator is in radian and it's maximum value is ($-\pi/2$). In order to normalize the VSPI within 0 to 1, ($-\pi/2$) has been used in denominator. Therefore, the value of VSPI at the bus varies from 0 to 1. A value approaching unity indicates that the bus is tending to be unstable. However, a value approaching zero is indicator of voltage stable bus. The maximum value of VSPI at instant (u+1) provides the prediction of voltage instability of the network at that instant.

$$\mathrm{VSPI}_{(u+1)} = \max\left(\mathrm{VSPI}_{j(u+1)}\right) \tag{6.13}$$

Thus, this value of $\mathrm{VSPI}_{(u+1)}$ indicates the proximity of voltage collapse. When the value of $\mathrm{VSPI}_{(u+1)}$ is closer to one then the system is nearer to the instability point.

6.4. SOLUTION METHODOLOGY

For 5-bus system shown in Figure 6.3, there are two load buses (bus 4 and bus 5) and three generator buses (bus 1, slack bus and bus 2 and bus 3).

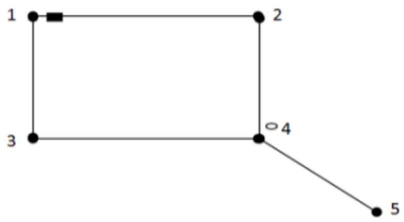

Figure 6.3. 5-bus system

So, for the load bus 4 and bus 5, the values of VSPI have been examined using Equations (6.12) and (6.13) as given below, from Equation (6.11),

$$s_{4(u+1)} = \frac{V_{4(u+1)} - V_{4u}}{\delta_{u+1} - \delta_u} \tag{6.14}$$

and

$$s_{5(u+1)} = \frac{V_{5(u+1)} - V_{5u}}{\delta_{u+1} - \delta_u} \tag{6.15}$$

Equations (6.14) and (6.15) represent the rate of change of voltage at bus 4 and bus 5 with respect to successive change in load. Now from Equation (6.12), VSPI at bus 4 and bus 5 are as follows:

$$\mathrm{VSPI}_4 = \frac{\tan^{-1}(s_{4(u+1)})}{(-\pi / 2)} \tag{6.16}$$

and

$$\mathrm{VSPI}_5 = \frac{\tan^{-1}(s_{5(u+1)})}{(-\pi / 2)} \tag{6.17}$$

From Equation (6.13), most critical bus of the 5-bus system has been calculated, which is as follows:

$$\mathrm{VSPI} = \max\left(VSPI_4, VSPI_5\right) \tag{6.18}$$

Maximum value of VSPI represents the most critical bus in the system which moves towards the instability of the system.

6.5. TEST RESULTS AND DISCUSSION

In this chapter, a voltage stability assessment method using phasor measurement has been presented. Proposed VSPI discussed in section 6.3 is used to check the voltage stability at different load buses. The effect of loading at any load bus is assessed by increasing the load on that bus itself, and compared to its neighboring bus connected to the bus under consideration and to the other weak load buses using VSPI predictor. The nature of change in loads can be of different classifications and could be enumerated as under

- Changing the load at all the load buses keeping the load characteristics constant. (achieved by keeping the load power factor constant)
- Changing the load at the selected critical buses.

It is to be mentioned that the change is assumed to be unidirectional, i.e. only increment is made in the value of load from its base case till the system reaches to its collapse point. The proposed formulation has been tested on IEEE 14-bus, IEEE 30-bus and IEEE 118-bus test systems as case 1, case 2 and case 3 respectively.

6.5.1. Case 1: IEEE 14-bus

IEEE 14-bus test system is taken from [125] and is widely used for illustration and demonstration of different methodologies which are used for assessment and analysis of power system. In this case study, the IEEE 14 bus test system is analyzed and results are presented in this section. It can be observed from Figure 6.4 that the voltage variation at some of the critical buses (4, 5, 9 10, 14) of IEEE 14-bus system due to increase in load (active ad reactive power) at all the load buses. Figure 6.5 shows the proposed VSPI for critical buses of Figure 6.4 with respect to loads. As shown in Figure 6.5, the value of VSPI varies from zero to one. A value approaching unity indicates that the bus is tending to be unstable. However, a value approaching zero is indicator of voltage stable bus. The voltage of bus-5 is approaching to the collapse point, due to continuous increase in load, the value of VSPI changes from 0 to 0.96. Variation in VSPI is slow in the beginning as comparison with the variation at nearer to the collapse point. Figure 6.6 shows the closer view of VSPI of Figure 6.5.

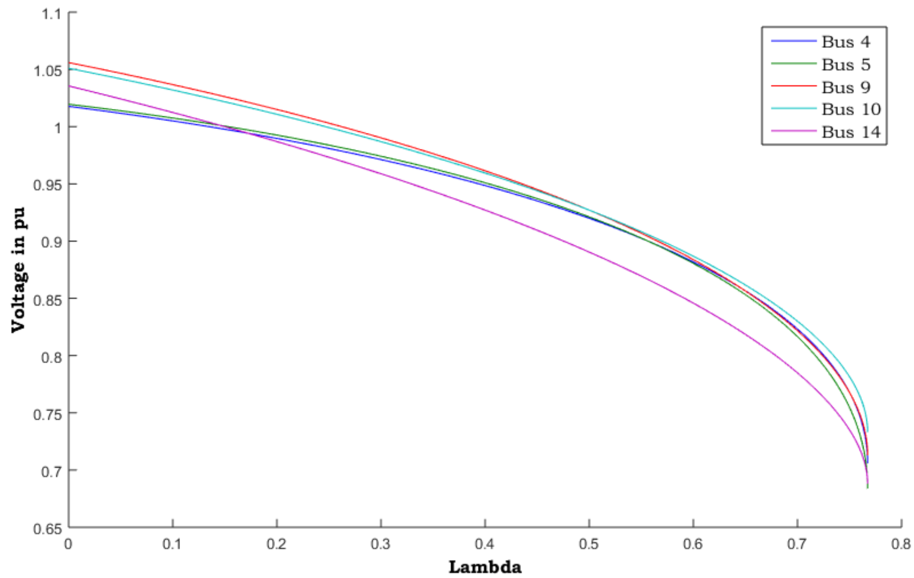

Figure 6.4. Critical bus voltages for load increase of IEEE 14-bus test system

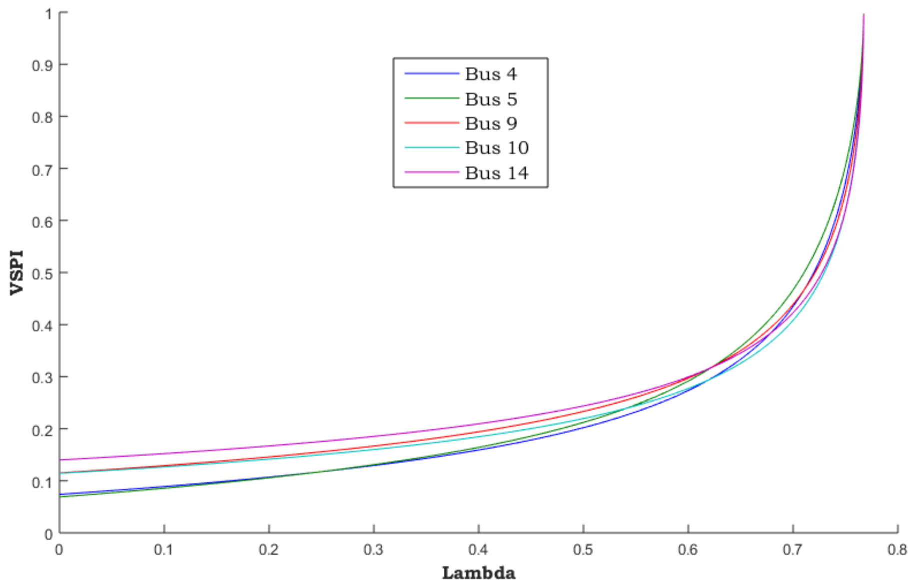

Figure 6.5. VSPI plot for critical buses for load increase of IEEE 14-bus

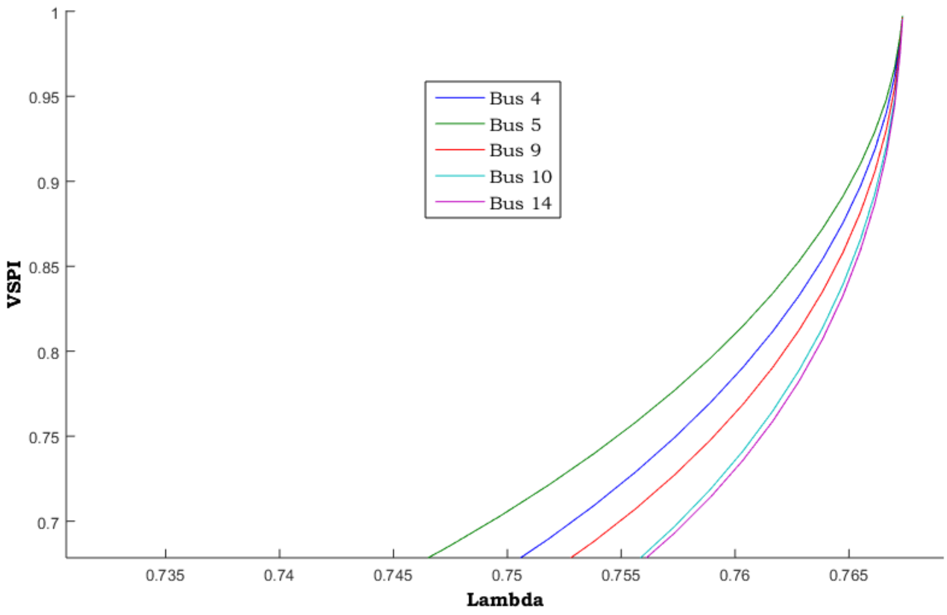

Figure 6.6. Closer view of critical buses for load increase of IEEE 14-bus

6.5.2. Case 2: IEEE 30-bus

The voltage variation of critical buses (4, 6, 7, 8 and 28) of IEEE 30-bus test system [125] due to increase in loads have been shown in Figure 6.7. It is clear from this figure that the rate of change of voltage is maximum at bus 8. Therefore, the value of VSPI at bus 8 approaches to 1 earlier which is shown in Figure 6.8 and Figure 6.9 shows the closer view of variation of VSPI to better understanding of the variation at some of the critical buses.

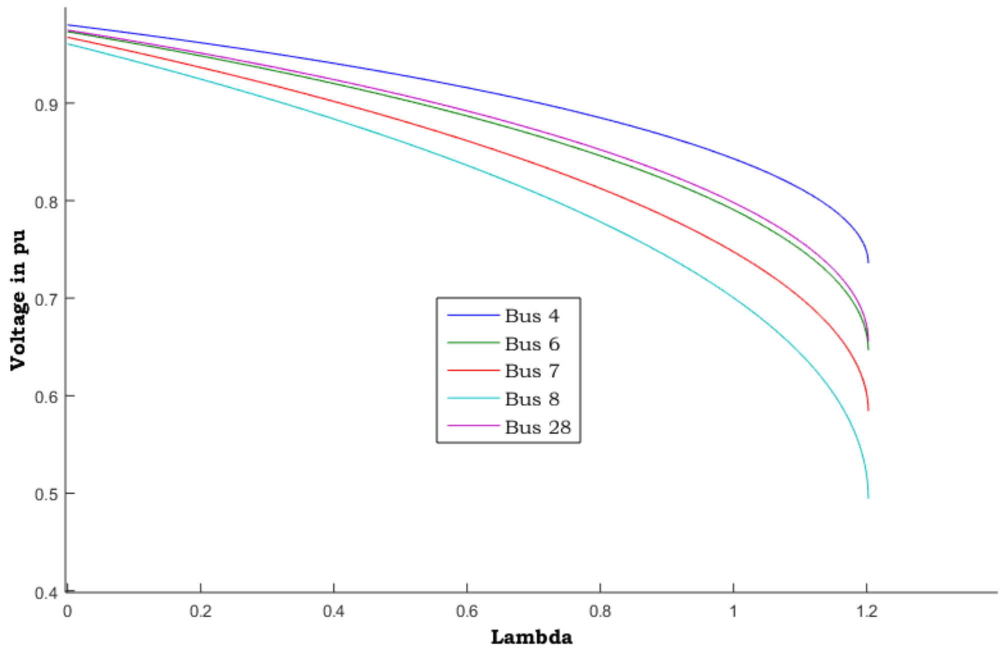

Figure 6.7. Critical bus voltages for load increase of IEEE 30-bus test system

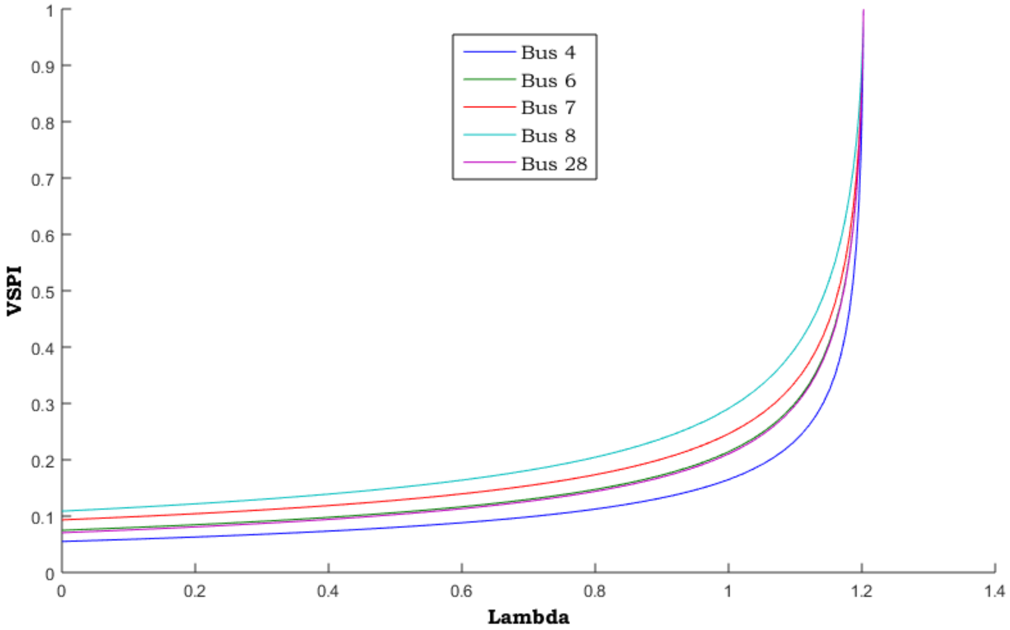

Figure 6.8. VSPI plot for critical buses for load increase of IEEE 30-bus

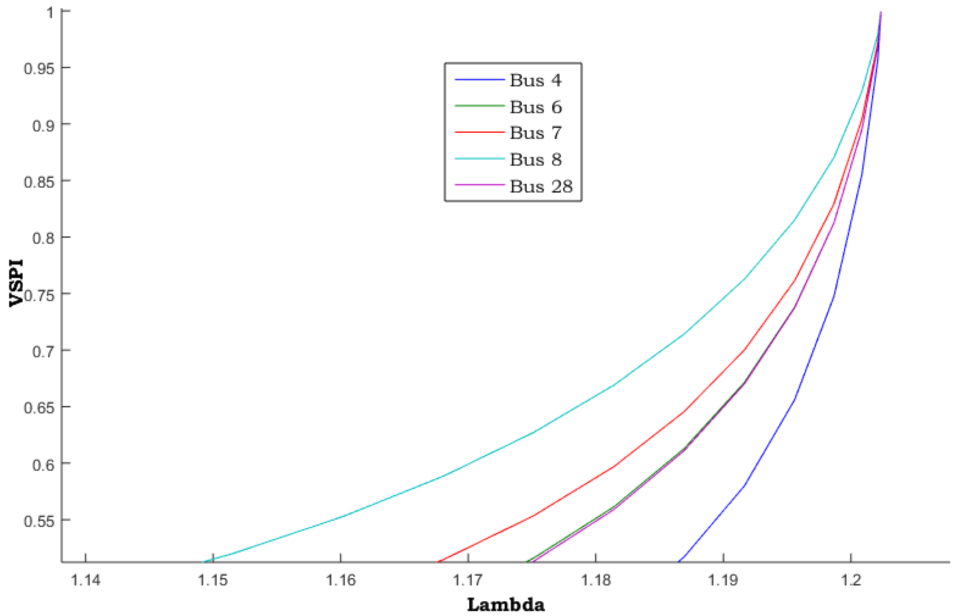

Figure 6.9. Closer view of critical buses for load increase of IEEE 30-bus test system

6.5.3. Case 3: IEEE 118-bus

IEEE 118-bus test system, has also been analyzed on the similar ground as that of IEEE 14-bus and IEEE 30-bus test system. The voltage variation at some of the critical buses i.e. buses 9, 38, 43, 44 and 45 has been shown in Figure 6.10 with respect to change in load. The change in load is done at all the buses and the behavior of VSPI is monitored and shown in the Figure 6.11. It is clear from this figure that the value of VSPI of bus 45 is almost equal to 1, therefore, the most critical bus is bus 45.

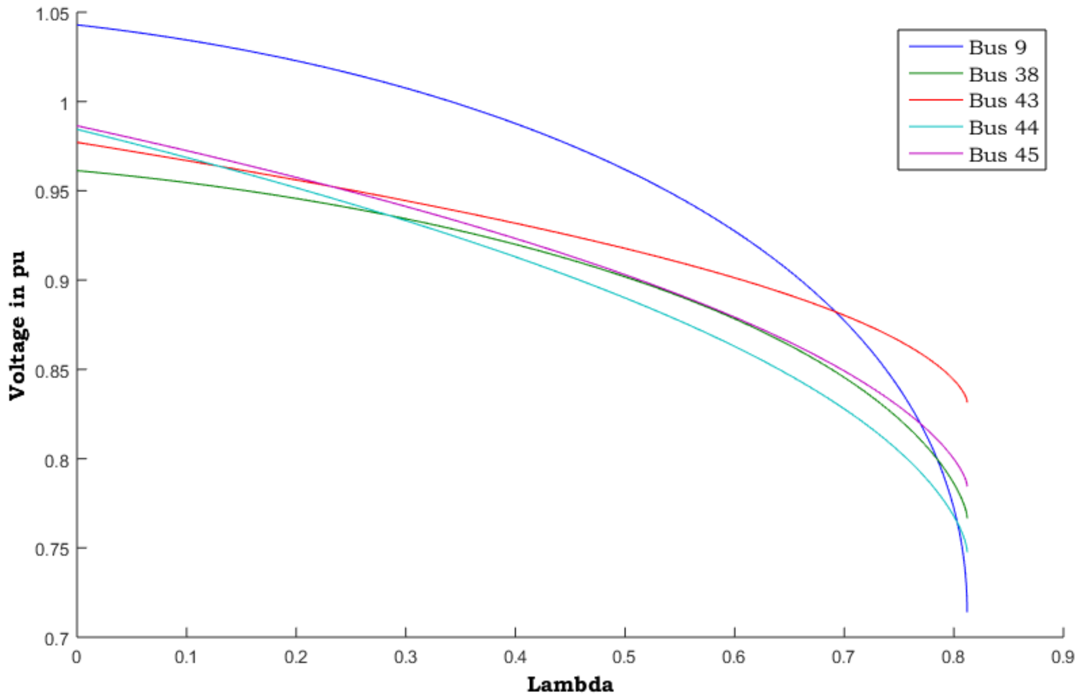

Figure 6.10. Critical bus voltages for load increase of IEEE 118-bus test system

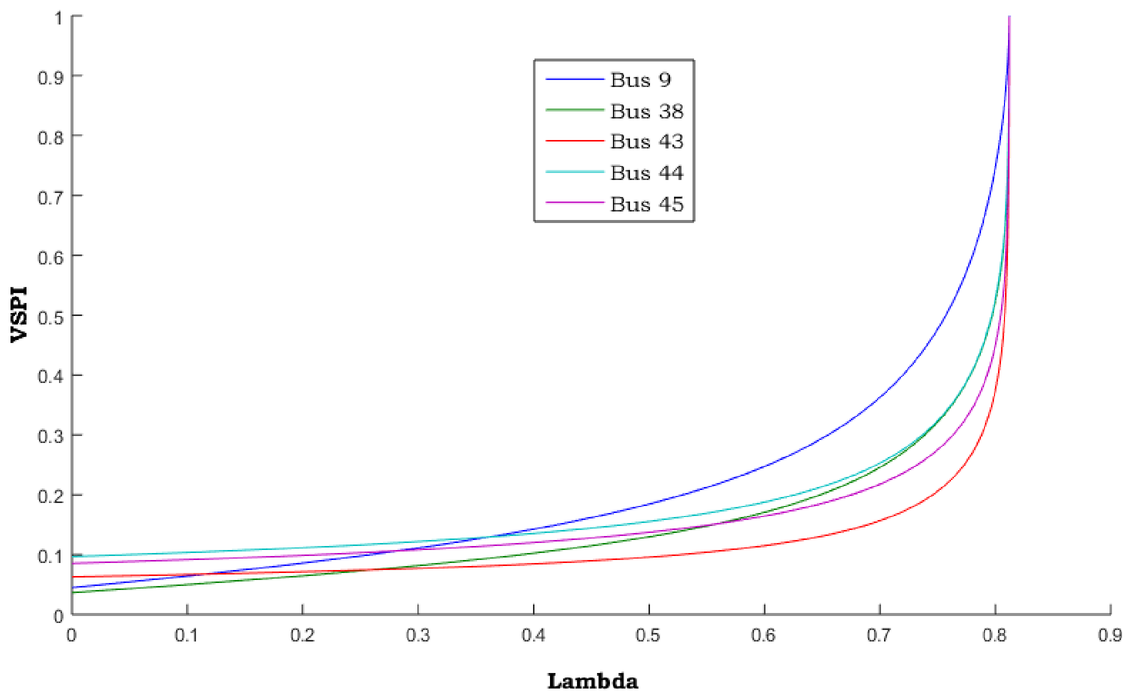

Figure 6.11. VSPI plot for critical buses for load increase of IEEE 118-bus test system

6.6. CONCLUSION

In this chapter, a voltage stability assessment problem using phasor measurement has been formulated and solved using MATLAB programming. Maximum observability of the system has been assumed by using the proposed OPP techniques. The observation has been used to evaluate an index defined as Voltage Stability Predictor Index (VSPI) and its value varies from 0 to 1. The value of VSPI proceed towards unity as the loading is increased and the bus is tending to be unstable. The VSPI correctly predicted the system status at all buses in the purview of voltage stability.