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A comprehensive investigation on voltage stability indices for distributed generation placement and sizing

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Abstract
Voltage instability has become the major threat to power system security and a challenge to power system operators to ensure voltages at all buses remain within acceptable limits under highly stressed conditions. Various voltage stability indices (VSI) have been proposed by researchers for fast and accurate assessment of voltage stability. These indices are helpful in taking steps towards voltage stability limit enhancement by placing distributed generation support at proper locations and for providing appropriate MW and MVAr support. This paper presents a comprehensive review of various VSIs proposed for voltage stability assessment. The study can be useful in identifying VSI for specific area of distributed generation placement and sizing for voltage stability enhancement .

Key words: *Voltage instability, Voltage collapse point, distributed generation, Voltage stability index, weak lines .*

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I. Introduction

In today's world with ever increasing electrical power demand, economic considerations and environmental constraints have forced the existing power systems to operate in highly stressed conditions. Extensive utilisation of transmission and generation capabilities and use of shunt capacitors for reactive power management have forced existing matured power networks to operate very close to their security limits[1]. This has led to violations of specially voltage stability limits due to load dependency which result in increasing voltage collapse incidences and subsequent blackouts in India and around the world. Therefore the monitoring of voltage stability and to take countermeasures to mitigate from it, has become a key issue in power system planning and operation.

Voltage collapse phenomenon is undesirable in power systems as it results in partial or complete blackouts. It requires long time for restoration and it is better to avoid it by taking fast actions. In developing countries with growing industrialisation and rapidly increasing load demand, the possibilities of voltage collapse occurrence are more than the developed countries. Countries like USA, France and Japan had suffered voltage collapse in their power systems during 1970's and 1980's as the economy was growing and industrial development was at its peak [1,2] . In the developing countries, the voltage instability has become the major threat to power system security and it becomes a challenge to power system operators to ensure voltages at all buses remain within acceptable limits.

Voltage stability is defined as the ability of a power system to maintain steady acceptable voltage at all buses in the system under normal operating conditions and after being subjected to a disturbance. The main factor causing instability is the inability of the power system to meet the demand for reactive power. The heart of the problem is usually the voltage drop that occurs when active power and reactive power flow through inductive reactance associated with the transmission network. Voltage stability can be defined as the ability to maintain voltage so that when load is increased, load power will increase, and so that both power and voltage are controllable[3]. The problem of voltage instability has attracted major attention of researchers with the increased loading and exploitation of the power transmission network.

One of the primary cause of power system instability is the transmission of real and reactive power over long distances. Reactive power requirement at load buses is supplied through transmission network which itself consumes significant amount of reactive power at heavy loadings. Due to limited reactive power generation capacity of alternators, reactive power compensation (such as shunt capacitors) is provided to meet reactive demand at load ends.Voltage instability is very closely related to reactive power transfer from source to load through transmission lines. System loading, reactive limits of generators, line and generator outage are the main cause of voltage collapse incidences.

Voltage stability assessment of power system network includes :

I. Fast and accurate prediction of real and reactive power margins from the collapse point which can be done indirectly with the use of VSIs

II. Identification of weak buses and lines of the system.

Voltage stability improvement includes countermeasures to avoid voltage instability. It can be done by

I. Placement of distributed generation units at load ends for injecting real and reactive power at appropriate locations.

II. Providing compensation in the transmission network.

III. FACTS devices to extend the voltage stability margin (VSM)

IV. Use of tap changers .

Load shedding is the last step to save the remaining power system from voltage collapse.

In voltage stability studies, VSIs are primarily used to identify weak lines and buses where special attention is required[10-14]. They can be calculated online using data obtained from PMUs or by the data obtained from static analysis. VSIs find manifold applications such as distributed generation placement and sizing, reactive power compensation and planning in power system networks[15-19]. VSIs which are obtained online from the PMUs data, can be used for switching the actions to be taken to avoid voltage instability[20-22].

II. Framework of voltage stability indices

Voltage stability indices are based on the mathematical relationships between load bus voltage, transmission line parameters and real/reactive loadings. These concepts has to be understood to get insight of various VSIs. Considering a transmission line between ith bus and jth bus of the system as shown in Figure 1.

Let ,

Vi, Vj: voltage magnitude at the sending and receiving buses, respectively.

Pi, Qi: active and reactive power at the sending bus.

Pj, Qj: active and reactive power at the receiving bus.

Si, Sj: apparent power at the sending and receiving buses, respectively.

δi, δj: voltage angle at the sending and receiving buses, respectively.

Yij: line shunt admittance.

Rij, Xij, θij: line resistance, line reactance and line impedance angle.

The line impedance amplitude is Zij .

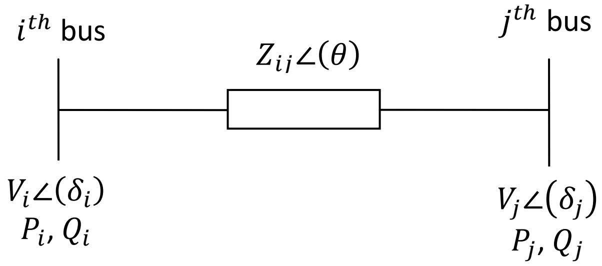

Figure 1 : Line connected between ith bus and jth bus

We have

$$S_j = \frac{V_iV_j}{Z_{ij}}\angle(\theta-\delta_i-\delta_j) - \frac{V_j^2}{Z_{ij}}\angle\theta \qquad (1)$$

The active and reactive power flow equations receiving end can be written as

$$P_j = \frac{V_iV_j}{Z_{ij}}\cos(\theta-\delta_i-\delta_j) - \frac{V_j^2}{Z_{ij}}\cos\theta \qquad (2)$$

$$Q_j = \frac{V_iV_j}{Z_{ij}}\sin(\theta-\delta_i-\delta_j) - \frac{V_j^2}{Z_{ij}}\sin\theta \qquad (3)$$

Let $\delta_{ij} = \delta_i - \delta_j$

Equation (2) and equation (3) rewritten as

$$P_j = \frac{V_i V_j}{Z_{ij}} \cos(\theta - \delta_{ij}) - \frac{V_j^2}{Z_{ij}} \cos\theta \qquad (4)$$

$$Q_j = \frac{V_i V_j}{Z_{ij}} \sin(\theta - \delta_{ij}) - \frac{V_j^2}{Z_{ij}} \sin\theta \qquad (5)$$

By simple mathematical derivation,a forth degree quadratic equation (6) can be obtained.
$Vj^4 + (2Pj\ Rij + 2Qj\ Xij – Vi^2)\ Vj^2 + (Pj^2 + Qj^2)\ Zij = 0$ (6)
At the saddle node bifurcation point, equation (6) has two pairs of real identical roots . At this point, Jacobian matrix becomes singular. If the load is increased beyond this point, the roots become complex . The discriminant of (6) must be greater than or equal to zero [31].
It can also be derived from equations (1) that at collapse point, the complex power received is maximum[5]. As the maximum power transfer takes place, the load impedance becomes equal to the Thevenin's impedance and receiving end voltage becomes exactly half of the sending end voltage . At this condition of maximum reactive power get transferred, any increase in sending end power does not get transferred from the line. The line becomes sink of reactive power and no further support of reactive power is available to receiving end bus[8].
General classification of Voltage Stability Indices (VSIs)
These indices can be classify in to two broad categories-

a. Jacobian based indices
b. System variable based indices

Load flow Jacobian which is available at the end of Newton Rapson power flow convergence, contains many useful information about voltage stability and hence it has been area of interest for many researchers. It is well established that Jacobian becomes singular at collapse point [99] . The minimum magnitude of the eigen values of the power flow jacobian matrix is zero at this point [100] .Accurate prediction of collapse point is not possible with these methods because they show very nonlinear behaviour near the critical point [101]. Some researchers have used test functions based on load flow Jacobian for assessment of voltage stability margin by predicting the voltage collapse point using quadratic model[102,103]. Test functions show more reliability than eigen /singular value of Jacobian matrix [104].

In order to have fast and accurate estimation of voltage collapse point, many researchers have proposed various voltage stability indices. A voltage stability index with inverse Jacobian matrix has been proposed in [105], which can be used to estimate voltage stability margin due to its linear behaviour. Maximum elements of system tangent vector has been used in [105] as voltage stability index. When the system is stressed, inverse of the maximum element of tangent vector becomes zero at collapse point. This index can also be used to estimate maximum loadability point [106]. Jacobian based indices can accurately assess the critical loading point and VSM but they require more computational time.Moreover, any change in the network topology affect the jacobian and requires modifications. Hence jacobian based indices are not suitable for the DG penetration studies.

III. Line voltage stability indices

These indices are used to identify the lines which are prone to voltage instability. Line VSI are based on discriminant of the voltage quadratic equation and the concept of maximum power transfer through the line. According to assumptions made and variables taken in the expression of VSI,many useful indices were proposed by researchers .A brief description is being presented in this section. Table 1 contains key features of various line voltage stability indices that are useful in specific applications.

3.1 Line Stability Index (Lmn)

Line stability index, Lmn is obtained using the concept in which the discriminant of the voltage quadratic equation is set to be greater than or equal to zero [50]. For a typical transmission line, the Lmn calculated by
$Lmn = 4XijQj / [Vi^2 \sin^2 (\theta ij - ðij)]$ (7)
The effects of the active power on the voltage stability as well as the line shunt admittance are neglected. For stable operation, Lmn has value less than unity.

3.2 Fast voltage stability index (FVSI)

Usirin et al. proposed the FVSI based on the concept in which the discriminant of the voltage quadratic equation (6) is set to be greater than or equal to zero [48]. FVSI is calculated by

$$FVSI = 4Zij\ Qj / Vi^2\ Xij \qquad (8)$$

The FVSI must be below 1 for a stable transmission line. If FVSI goes beyond 1.00, one of the buses that is connected to the line will experience a sudden voltage drop leading to system collapse. This index is just an extension of Lmn assuming the load angle across the line is zero.

3.3 Line Stability Factor (LQP)

Mohamed et al. developed the line stability factor, LQP, based on the same concept as two previous line VSIs [51]. The LQP is obtained as follows:

$$LQ\,P = (4\,Xij/ Vi^2)\,(\,Qj + Pj^2 / Xij\,Vi^2\,) \qquad (9)$$

For the transmission line to be stable, it should be LQ P<1. In this index, the lines are assumed to be lossless and the shunt admittance of lines is neglected.

3.4 Novel line stability index (NLSI)

This line stability index is based on the same concept as LQP .Any line in the system whose NLSI is close to unity indicates that the line is approaching its stability limit [53]. This index is given by

$$NLSI = (Pj\,Rij + Qj\,Xij) /0{:}25Vi^2 \qquad (10)$$

δij and shunt admittance are assumed zero in this index.

3.5 Voltage collapse proximity index (VCPI)

Four VCPIs for the line voltage stability has been proposed by Moghavvemi et al based on the concept of maximum power transfer through a line [57]. VCPIs consider the maximum power Pj(max) and QJ(max) transferred through a line and maximum power loss (Pij(max) and Qij(max) in a line. These indices are defined as follows :

$$VCPI1 = Pj/Pj(max) \qquad (11)$$

$$VCPI2 = Qj/Qj(max) \qquad (12)$$

$$VCPI3 = Pij/Pij(max) \qquad (13)$$

$$VCPI4 = Qij/Qij(max) \qquad (14)$$

The power factor is assumed to be constant and the line shunt admittance is neglected.

3.6 Power transfer stability index (PTSI)

The PTSI has been proposed by Nizam et al. as follows [59]:

$$PTSI = 2Sj\ \ Zij\,(1 + \cos(\theta - \varphi)) / Vi^2 \qquad (15)$$

This index is derived based on maximum power transfer through the line and reaches to 1 at critical loading. Line shunt admittance is neglected.

3.7 Voltage Collapse Proximity Index (VCPI-1)

At the collapse point, the voltage drop across the Thevenin impedance is equal to the load voltage. Therefore, to assess the risk of voltage collapse, VCPI [65] has been defined as

$$VCPI\text{-}1 = Vj \cos ð\text{-}\ 0.5Vi \qquad [16]$$

For stable operation, VCPI should be greater than 0. This index uses sending and receiving end voltages only and hence helpful in online voltage stability monitoring.

3.8 Voltage Stability Margin Index (VSMI)

VSMI is based on the relationship between maximum transferable power through a line and the angle difference between sending and receiving buses [68]. Operating at secure and stable conditions requires the value of VSMI to be maintained greater than 0.

$$VSMI = (\delta max - \delta)/\ \delta max \qquad [17]$$

where δmax is the maximum angle difference between sending and receiving ends. Line shunt admittance is neglected .

Table 1: Review of various line voltage stability Indices

S.No.	VSI	Ref.	Assumptions	Expression	Condition for stability
1	Line Stability Index (Lmn)	[50]	Effect of active power neglected, Y= 0	$Lmn = 4XijQj / [Vi^2 \sin^2 (\theta ij\text{-}ðij)]$	Lmn<1
2	Fast voltage stability index (FVSI)	[48]	$\delta ij = 0$	$FVSI = 4Zij\ Qj / Vi^2\ Xij$	FVSI<1
3	Line Stability Factor (LQP)	[51]	R= 0; Y= 0	$LQ\,P = (4\,Xij/ Vi^2)\,(\,Qj + Pj^2 / Xij\,Vi^2\,)$	LQP<1
4	Novel line stability index (NLSI)	[53]	δ= 0, Y= 0	$NLSI = (Pj\,Rij + Qj\,Xij) /0{:}25Vi^2$	NLSI<1
5	Voltage collapse proximity index (VCPI)	[57]	Constant power factor, Y=0	VCPI1 = Pj/Pj(max) VCPI2 = Qj/Qj(max) VCPI3 = Pij/Pij(max) VCPI4 = Qij/Qij(max)	VCPI<1

6	Voltage Collapse Proximity Index (VCPI-1)	[65]	Zth= 0	VCPI-1 = Vj cos ð- 0.5Vi	VCPI>0
7	Power transfer stability index (PTSI)	[59]	Y= 0	PTSI = 2Sj Zij (1 + cos (θ –φ)) / Vi^2	PTSI<1
8	Voltage Stability Margin Index (VSMI)	[68]	Y 0 and R 0 in lossless case	VSMI = (δmax – δ)/ δmax	VSMI<1
9	Voltage Stability Load Bus Index (VSLBI)	[69]		VSLBI=Vj/ΔV	VSLBI>1

IV. Bus voltage stability indices

These VSIs are used for determination of voltage stability of buses of power systems. They can not provide any information about weak lines that are prone to voltage instability. Some useful voltage stability indices have been reviewed in this section. Majority of these indices are based on the behaviour of jacobian near collapse point. Some important bus voltage stability indices as given in Table 2.

Table 2: Some important bus voltage stability indices

S.No.	Ref.	Bus VSI	Expression	Condition for stable operation
1	[78]	Voltage collapse prediction index ($VCPI_{bus}$)	$VCPI_{bus} = Min(VCPI_i)$ $VCPI_i = \left\|1 - \frac{\sum_{m=1, m\neq i}^{N} V'_m}{V_i}\right\|$ $V'_m = \frac{Y_{im}}{\sum_{j=1, j\neq i}^{N} Y_{ij}} V_m$	($VCPI_{bus}$)<1
2	[79]	L-index	$L = \underset{j \in a_L}{max}\{L_j\} = \underset{j \in a_L}{max}\left\|1 - \frac{\sum_{i \in a_G} F_{ji} V_i}{V_j}\right\|$	L-index<1
3	[82]	S difference criterion (SDC)	$SDC = \left\|1 + \frac{\Delta V_r I_r^*}{V_r \Delta I_r^*}\right\|$	SDC>0
4	[83]	Impedance matching Stability Index (ISI)	$ISI = \frac{Z_L - Z_{th}}{Z_L} = 1 - \frac{\|I_r \Delta V_r\|}{\|V_r \Delta I_r\|}$	ISI>0
5	[87]	ZL/ZS ratio	$\frac{M+1}{-M\cos\beta + [(M\cos\beta)^2 - M^2 + 1]^{0.5}}$	Zl/Zs>1

4.1 Voltage collapse prediction index ($VCPI_{bus}$)

This VSI is derived from power flow equation and it varies from 0 to 1[78].It is based on the fact that a stable system must has a solution and determinant of jacobian matrix must not be zero. It can be calculated as

$$VCPI_{bus} = Min(VCPI_i) \quad (18)$$

$$VCPI_i = \left|1 - \frac{\sum_{m=1, m\neq i}^{N} V'_m}{V_i}\right| \quad (19)$$

$$V'_m = \frac{Y_{im}}{\sum_{j=1, j\neq i}^{N} Y_{ij}} V_m \quad (20)$$

4.2. L-index

L-index based on the solution of the power flow equations [79]. This index has been derived as follows:

$$L = \underset{j \in a_L}{max}\{L_j\} = \underset{j \in a_L}{max}\left|1 - \frac{\sum_{i \in a_G} F_{ji} V_i}{V_j}\right| \quad (21)$$

where αL is the set of load buses, αG is the set of generator buses, Vj and Vi are the voltage phasors at bus j and bus i, and Fji is the element in j-th row and i-th column of matrix F whose elements are generated from the admittance matrix [80].

$$F = -Y_{LL}^{-1} Y_{LG} \quad (22)$$

and

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} \mathrm{Y_{LL}} & \mathrm{Y_{LG}} \\ \mathrm{Y_{GL}} & \mathrm{Y_{GG}} \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \quad (23)$$

The values of L-index vary between 0 (no load condition) and 1 (voltage collapse) and the concept of this index is the same as that of VCPIbus. It can be shown that the stability limit is L ¼ 1 when two conditions are fulfilled [79]. The first condition requires that all generator voltages remain unchanged (amplitude and phase angle). The second is related to the nodal currents in which the nodal current at bus j is directly proportional to the current Ii and indirectly proportional to the voltage Vi [76]. In general, these two conditions are satisfied approximately. So, the exact CV is around L ¼ 1. In [78], L-index has been improved to consider the influence of load model. 4 S difference criterion (SDC)

The SDC proposed by Verbic et al. is based on the fact that in the vicinity of voltage collapse point an increase in the apparent power flow at the sending end of the line no longer yields an increase in the received power [8]. The SDC is defined as

$$SDC = \left|1 + \frac{\Delta V_r I_r^*}{V_r \Delta I_r^*}\right| \qquad (24)$$

At the point of the voltage collapse, when ΔSr=0, the SDC equals 0.

Impedance matching Stability Index (ISI)

According to the circuit theory, when the amplitude of load impedance is equal to the magnitude of the Thevenin impedance, the system reaches the maximum transferable power. The ISI which has been proposed by Smon uses the above law to estimate the VSM [83]. This index takes values around 1 in normal conditions and at the voltage-collapse point diminishes to 0. The formulation of ISI is as follows

$$ISI = \frac{Z_L - Z_{th}}{Z_L} = 1 - \frac{|I_r \Delta V_r|}{|V_r \Delta I_r|} \qquad (25) \quad Z_L = \frac{V_r}{I_r^{'}}, Z_{th} = \frac{\Delta V_r}{\Delta I_r} \qquad (26)$$

where ΔVr and ΔIr are the voltage and current differences between two consecutive measurement samples from a PMU at the receiving bus. The ISI is more sensitive to smaller changes in the system voltage and current and determining the threshold for ΔVr and ΔIr requires a lot of tests on the system.

Z_L/Z_S ratio

The index of ZL/ZS ratio is based on the same concept as ISI [87]. In this index, ratio of the load impedance at the load bus (ZL) to the network Thevenin impedance (ZS) at that bus is calculated as follows:

$$\frac{Z_L}{Z_S} = \frac{M+1}{-M\cos\beta + [(M\cos\beta)^2 - M^2 + 1]^{0.5}} \qquad (27)$$

and, ϕS and ϕL are the phase angles of impedances ZS and ZL, respectively. The factor M is calculated by measuring the variation of the load apparent power S and the load admittance Y=1/ZL between the two measurements as .

$$M = \frac{(S_2 - S_1)(Y_2 + Y_1)}{(S_2 + S_1)(Y_2 - Y_1)} \qquad (28)$$

The ZL=ZS ratio index is very sensitive to the small change of the load admittance. So, the time difference between the two measurements ought to be about 500 ms [87]. To maintain a secure condition, the value of this index should be kept above 1.

Table 3: Classification of voltage stability indices

Voltage Stability Indices	Line	Lmn,FVSI,LQP,NLSI,VCPI,VSMI etc.
	Bus	SF, VCPIbus, SDC, ISI, SVSI, P and Q angle, L-index, VSI bus, V/Vo,ZL/Zs ratio etc.
	System wide	Load margin, Singular value, VIPI, SD ,Eigenvalue,etc.

Overall VSIs take the entire system in focus to assess the system stability and accuracy of these indices are set as benchmark for others because of high accuracy .These indices are complex and needs more computations than line or bus indices. Line stability indices are simple and needs less time to compute but they are not so accurate. Hence line VSIs are generally used in weak lines and buses identification. This makes them very suitable for DG placement and sizing problems.

V. Conclusions

Voltage stability indices are based of some fundamental concepts and they can be categories accordingly. Major concepts identified are, solution of voltage equation, maximum power transfer, properties of jacobian matrix and its behaviour near collapse point and PV curves.It is concluded that overall system indices are better in accuracy but takes more computational efforts. On the other hand line VSIs are very easily computed but they can not accurately predict the collapse point. However they are most suitable for line ranking ,identification of weak areas where DG can be placed and their sizing. Contingency analysis also require fast computation of VSI. Bus VSIs have different varieties. They fall in between the extremes of accuracy and fast computation. Many assumptions have been made in deriving VSIs and hence one has to select proper VSI based on system configurations. On line monitoring of power systems can be done by taking two consecutive data obtained from PMUs.

VI. Future direction

Based on the comprehensive review of voltage stability indices and to access the power systems with solar PV integration, authors propose two new voltage stability indices for future Investigations:

A new overall voltage stability proximity indicator based on load flow equations which is given by:

$$S_{\in} = C_{ii} + \sum_{n \neq i} C_{in} x_n \quad (29)$$

$S_{\in}$ is named 'substitution error function' which can be used as proximity indicator for overall system voltage stability assessment. This indicator can predict the collapse point accurately and it can be used to predict maximum loadability and voltage stability margin. For a system to be voltage stable the function $S_{\in}$ should be greater than 0.

For fast and online/offline computation of voltage stability, a new line voltage stability index based on the concept of singularity of load flow Jacobian is proposed.

This index is very easy to compute with local phasor measurement. It is given by:

$$\text{EALI} = \frac{A_2}{A_1} = \frac{V_i - V_j \cos\delta_{ij}}{V_j \cos\delta_{ij}} \quad (30)$$

Where, EALI is the proposed line VSI which is equal to 1 at critical loading and can be computed with voltage phasors of sending and receiving ends of the line.

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