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Voltage Stability Indices: Formulation and Classification Perspectives

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Abstract: Voltage instability had been observed as the foremost cause of blackout incidents worldwide in last three decades. In order to deploy an appropriate countermeasure and enhance voltage stability margin, voltage stability predictor is of utmost importance. Therefore, much research had been focussed to propose voltage stability indices (VSIs) that can identify weak areas and overall condition of power systems. In this paper systematic review covering imperative aspects of formulation theory, expressions, critical values and applicability of VSIs has been presented in chronological order. A broad categorization of VSIs is also addressed. An inclusive review provides a strong foundation for further research in the perspective of voltage stability evaluation for real-time control applications.

Keywords: Voltage instability, Voltage collapse, Voltage stability indices, Indices classification

I. INTRODUCTION

The first major power failure occurred in the U.S. and Canada in 1965 that affected around 30 million people. Great Northeast Blackout in both, making it the single in U.S. history at the time. A significant number of black-outs have been occurred worldwide since then. Some eminent incidents of blackout amongst them are [1- 3]: August 2003-Northeast US and Canada, August 2005- Indonesia, January & February 2008- Central Chinese city of Changzhou, November 2009- Itapúa Paraguay-Brazil, July 2012-Northern grid of India, December-2014 Detroit US, , and. The collapse of Northern grid in India on 30th and 31st July 2012 had been the worst blackout all over the world and affected about 620 million people [4]. The rate of recurrence of these collapses along with their social and economical impacts led to significant research in identifying the cause. The investigations revealed that voltage instability (VI), different from angular stability, led to blackouts in significant part of power systems. The key factors contributing were gradual or sudden increase in load, mal operation of protective devices, limits of reactive power resources and consequence of tap changing transformers action. Therefore, to control the menace of VI vital measures are reactive power compensation, rescheduling of generators, LTC blocking, load reduction, fast capacitor switching, fast load shedding, fault clearing FACTS and HVDC with fast controllers.

Proceeding to abrupt decline in voltages, unusual reactive powers flows in transmission lines were observed. An irrepressible decrease in voltage profiles along with the action of and reactions of power system components leads to partial or overall voltage collapse (VC) [5] - [7].

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These symptoms that identify the system state need to be quantified to initiate protective and corrective control in time. The measure of closeness of the current operating state and system instability state is termed as voltage stability index (VSI).
This quantification should have scalar magnitude that varies smoothly as the system parameters changes. The desirable attributes of these VSIs are predictable shape, computationally inexpensive and sufficiently accurate. Therefore, developing VSIs suitable for different application are of great interest to the power utility engineers, operators and researchers.

The motive of present work is to provide a gist of various indexes developed and widely accepted so far for voltage stability assessment. The various aspects covered are formulation of criterion, derivation of equations and limiting conditions for stability assessment. A straightforward approach has been applied to elaborate the theory of indices development. The crisp review and classification based on the concept, methods and type in chronological order can be of significant importance for in-depth research in the area of voltage stability analysis. Apposite identification of weaker areas with an efficient index may avoid the irrecoverable losses due VC.

Outline of the research work is as follows: Section II of the paper elaborates the various voltage collapse detection criterion. Power flow Jacobian based indices are also presented in tabular form in this section. In Section III the classification based on the method of computation has been shown in pictorial form. Section IV reviews the VSIs that are classified as bus, line and overall indices depending on the part of power system prone to voltage collapse. Section V concludes the discussions.

II. VOLTAGE COLLAPSE DETECTION CRITREON

Various criterions for developing voltage stability indices are:

- Load flow Jacobian
- PV-VQ curves
- Maximum power transfer theorem
- Power transfer limit of a line
- Reactive power consumption of a line
- Lyapunov stability theory

A. Load Flow Jacobian [8-17]

The first criterion was proposed by Venikov et al. [8]. It was shown that the steady state limit is directly related to load flow Jacobian (***J***). Singularity of ***J*** signifies the instability state and hence the Eigen values of the linearized system matrix can be an index of proximity to VC. Since then numerous indices had been derived from the condition of non-solvability of load flow equations and hence singularity ***J***.

The power balance equations at the buses can be represented by non-linear equations as:

$$\begin{cases} \Delta P_i = P_{isp} - V_i \sum_{j=1}^{n} V_j (G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}) = 0 \\ \Delta Q_i = Q_{isp} - V_i \sum_{j=1}^{n} V_j (G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij}) = 0 \end{cases} \quad (1)$$

Linearizing above power balance equations by Taylor's series expansion and neglecting higher order derivatives yields:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \partial P/\partial V & \partial P/\partial \theta \\ \partial Q/\partial V & \partial Q/\partial \theta \end{bmatrix} \begin{bmatrix} \Delta V \\ \Delta \theta \end{bmatrix}$$

Or $$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{PV} & J_{P\theta} \\ J_{QV} & J_{Q\theta} \end{bmatrix} \begin{bmatrix} \Delta V \\ \Delta \theta \end{bmatrix} = J \begin{bmatrix} \Delta V \\ \Delta \theta \end{bmatrix} \quad (2)$$

Where:

$\Delta P,\ \Delta Q$: Active and reactive power errors respectively

$\Delta V, \Delta\theta$: Voltage and angle corrections respectively

J: Jacobian matrix with partial derivative terms

Assuming the loose coupling between active power and voltage magnitudes and setting ΔP = 0:

$$\Delta Q = \left[J_{QV} - J_{Q\theta} * J_{P\theta}^{-1} * J_{PV}\right] * \Delta V \quad (3)$$

$$= [J_R]\Delta V \quad (4)$$

Where: J_R: Reduced Jacobian matrix

The voltage stability limits were derived as the closeness of the determinant of J or J_R near to zero.

Table- I shows the Jacobian matrix based indices.

Table- I: Jacobian Matrix Based Indices

Index	Expression	Stability Condition	Concept Used	Author	Reference
1. Det J Det J_R	$\lvert J\rvert = \begin{vmatrix} \partial P/\partial V & \partial P/\partial\theta \\ \partial Q/\Delta V & \partial Q/\partial\theta \end{vmatrix}$ $\lvert J_R\rvert = \lvert J_{QV} - J_{Q\theta} * J_{P\theta}^{-1} * J_{PV}\rvert$	$\lvert J\rvert \neq 0$ $\lvert J_R\rvert \neq 0$	Solvability of load flow equations	Venikov V. A. et.al., 1975	[8]
2. Singular / Eigen values/Modal analysis	Minimum Eigen/singular Value	All Eigen/ Singular values should be positive	Solvability of load flow equations	Lof P. A. et.al., 1975 Gao B. et.al., 1975	[9] [10]
3. Test functions	$t_{cc} = \lvert e_c^T J J_{cc}^{-1} e_c\rvert$	$t_{cc} \neq 0$	Singularity of J	Chiang H. D. et al., 1995	[11]
4. Sensitivity Factors	$VSF_i = max_i \left\{\frac{dV_i}{dQ_i}\right\}$	VSF_i should be small positve	Singularity of J	Obadina O. O. et al., 1990	[13]
5. Inverse sensitivity factors (VQ-sensitivities)	$IVSF = 1/VSF$	$IVSF \neq 0$	Inverse of reduced Jacobian J_R^{-1}	Flatabo N. et al., 1990	[14]
6. Second order index	$\iota = \frac{\sigma_{max}}{\iota_o (d\sigma_{max}/d\lambda_{total})}$	$\iota > 0$	Singularity of J	A. Berizzi et al., 1998	[15]
7. P and Q angle	$\alpha_i = cos^{-1}\left\{\frac{(\nabla f_i \cdot T_{ag_i})}{(\lVert\nabla f_i\rVert \lVert T_{ag_i}\rVert)}\right\}$	$\alpha_i < 90°$	Singularity of J	Wang L. et al., 1996	[16]
8. Tangent Vector Index	$TVI_i = \left\lvert\frac{dV_i}{d\lambda}\right\rvert^{-1}$	$TVI_i \leq \epsilon$	Inverse Sensitivity factor	De Souza A. C. Z. et al., 1996	[17]

The useful singular and Eigen value orthogonal decomposition techniques to evaluate the smallest Eigen/singular value [9, 10] had been applied in many researches as a measure of VI.

Chiang et al. in [11] had utilized the family of scalar functions discussed in [12] to voltage collapse studies. These test functions have quadratic shape and better than the non-linear indices. Other well known indices are sensitivity factors that are used by utilities all over the world [13]. The sensitivity factors indicate the variation of the generated reactive power with shape. Therefore, inverse sensitivity factors with more predictable loading parameters. Critical generators and critical loads have large sensitivity factors. These indices are of non-linear loads shape and computationally inexpensive are also utilized [14]. Linearization based indices may be inadequate as these

Also the associated right singular / Eigen vectors indicate the most critical buses and the right Eigen/singular value gives the most sensitive direction for power injections changes.

display large discontinuities when generators and transformer taps hit their control limits. To overcome inadequacy of first order indices, a second order index that also includes the effect of sensitivity of index is suggested in [15]. The index P-Q angle had been derived from the geometrical construal of power flow equations in [16]. At VC the angle between the tangent to the curve and the gradient to the surface becomes 90°. Another index similar to sensitivity factors had been explained in [17]. The index TVI becomes zero at VC and can be easily calculated from the Newton-Raphson iteration.

B. PV-QV Curves

Loading margin [18-20] from P-V and V-Q plots of PQ (load) buses is the most fundamental and conventional index predicting proximity to VC. It has been extensively used as benchmark in the voltage stability studies to compare the performance of other indices. Loading margin at a given operating state is the amount of added load that would result in voltage collapse assuming a particular direction of load increase. Loading margins in terms of real power is shown in Fig. 1. Similarly reactive power margin is depicted in Fig. 2. In practice, Direct and continuation power flow methods are utilized to find the loading margin.

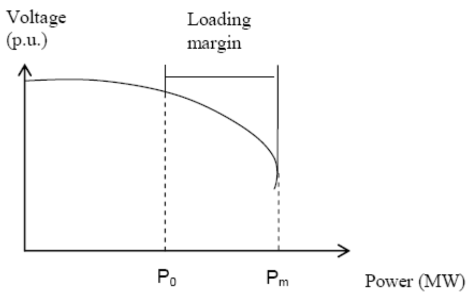

Fig. 1. Typical PV-curve and MW loading margin

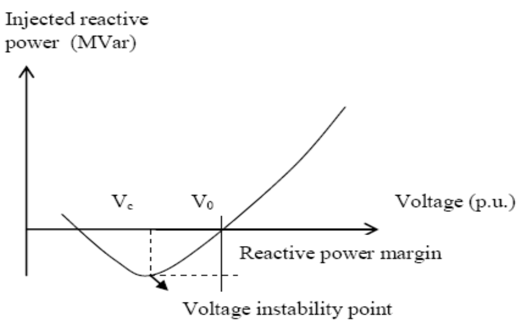

Fig. 2. Typical VQ-curve and MVar loading margin

C. **Maximum Power Transfer Theorem**

Network equivalent at a bus is a straightforward practice for estimation of voltage stability of an intricate system in global mode. Due to ease of determining equivalents, it is most viable way for stability analysis and control power systems in real time. In majority of the cases, network equivalent had been obtained by using Thevenin's theory. In Fig. 3 left part shows Thevenin's equivalent of power grid excluding the bus to be monitored.

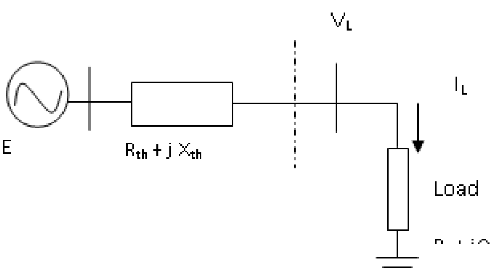

Fig. 3. Thevenin's equivalent model

The two possible solutions of load bus voltage can be determined by solving Equation (5).

$$V_L^4 + 2(R_{th}P_L + X_{th}Q_L)V_L^2 - E^2V_L^2 + (R_{th}^2 + X_{th}^2)(P_L^2 + P_L^2) = 0 \quad (5)$$

As the load increases, two solutions of V_L move towards each other and merge together at the threshold of VI/VC. Therefore, equating discriminant of equation (5) to zero becomes the criterion for detecting the voltage stability margins. In some cases, closeness of load impedance to Thevenin's impedance had been used as proximity indicator.

D. Power Transfer limit of a Line

Most of the line indices have been obtained from the limitation on power transfer through a line. The maximum power limit reaches when no real solution exists for the receiving end voltage.

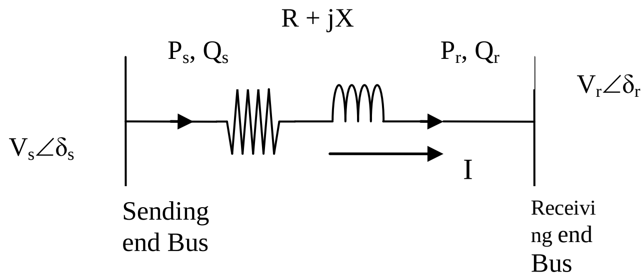

Fig. 4. Single line diagram of a transmission line

The following expression for receiving end voltage of the line shown in Fig. 4 can be obtained by simplifying the expressions for receiving end active and reactive powers.

$$V_r^4 + 2(RP_r + XQ_r)V_r^2 - V_s^2V_r^2 + (R^2 + X^2)(P_r^2 + Q_r^2) = 0 \quad (6)$$

Therefore, equating the expression for the discriminant of equation (6) to zero becomes the criterion for deriving the critical limits of various line VSIs.

Where:

$V_s\angle\delta_s$: Sending end bus voltage
$S_s(P_s + jQ_S)$: Sending end power
$V_r, \angle\delta_r$: Receiving end bus voltage
$S_r(P_r + jQ_r)$: Receiving end power
R, X, Y: line Resistance, reactance and shunt admittance respectively.

Some indices in terms of ABCD parameters have also been derived from the pie model of transmission line as shown in the Fig. 5[49, 52].

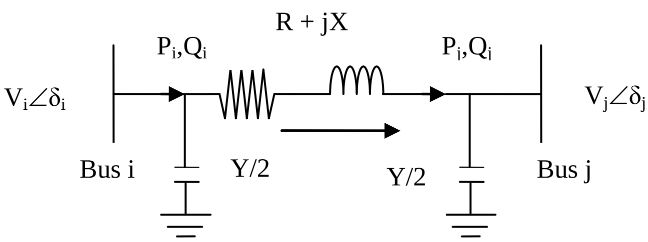

Fig. 5. Transmission line model with shunt admittance

E. **Reactive power consumptions of lines**

An overloaded line consumes high reactive power and consequently restricts transfer of reactive power to receiving end connected loads. Near the point of VC, enhancing the apparent power from the sending end of the line no longer yields an addition to the apparent power delivered to loads. Therefore, increase in reactive power losses is the indicator of voltage instability [25, 28].

F. Lyapunov stability theory

Lyapunov stability theory had been initially established for direct stability investigation of power systems. Hence a technique based on it had been effectively applied and implemented as a voltage stability predictor in [62]. This scalar function had been shown to directly related with the area encircled by the Q- ln V curve or P- α curve assuming PQ loads and thus a measure of VI/VC [63].

A difficulty with this index is that it cannot be readily modified to include more complex system models.

Therefore, in literature using any of the following conditions and simplifying Equations (5)-(6), the indices to predict the voltage stability condition, are derived:

1. Load flow Jacobian matrix
2. Load flow solutions (System variables and parameters)
3. Maximum power transfer theorem
4. Power transfer limit of a Line
5. Feasible voltage solutions of the load buses
6. Reactive power consumption of the line
7. Lyapunov stability theory

III. Classification of Voltage Stability Indices

A. *Based on Criterion/Method used*

Classification of indices based on formulation and calculation methods is shown in the Fig.6.

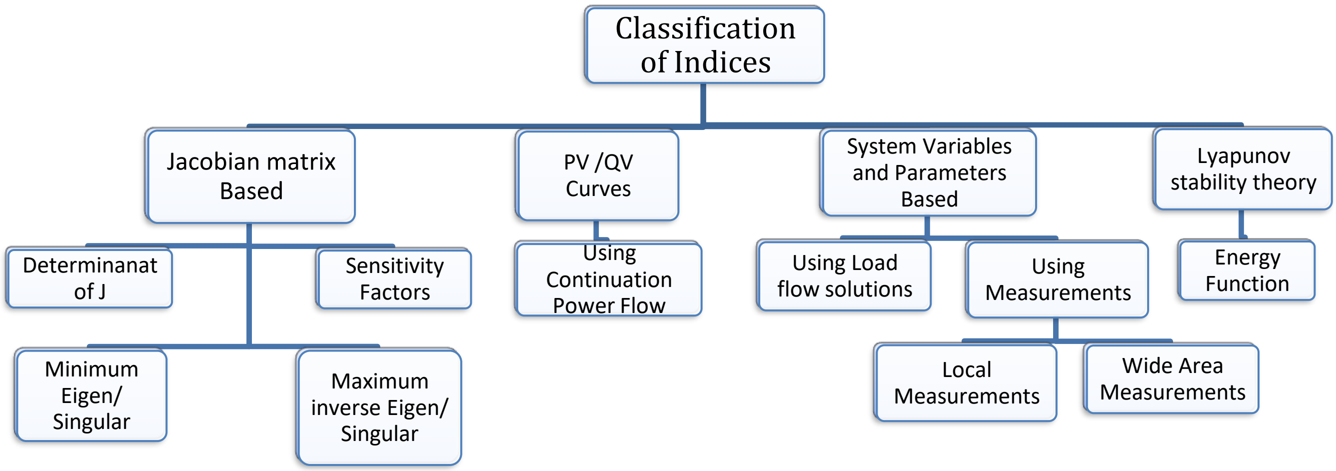

Fig. 6. Classification of Indices based on the criterion/method of calculation

B. Based on Power System Parameters and Variables

Power system variables can be obtained from either load flow solutions or the measurements of voltages, currents and powers injected of various buses. VSIs calculated from these system variable and parameters distinguish the weak parts of power system for initiating the corrective action against VI/VC.

Therefore, from the identification of the part prone to VI/VC, these are classified as:

1. Bus Indices
2. Line Indices
3. Overall Indices

Bus Indices can identify the buses nearest to voltage stability limits and thus the suitable candidate buses for installation of shunt FACTs controllers. Similarly line indices have been utilized for providing series compensation in weak lines. The overall indices anticipate the stability state of the whole power system instead of indicating weak buses or lines.

An inclusive survey has been done and the imperative indices developed so far are reported in the chronological order along with the criterion used for their formulation and presented in section IV.

C. Based on Measurements

With the inception of phasor technology with Phasor Measurement Unit (PMU) and advanced communication technologies, time tagged phasors can be obtained. Analog voltages and currents are converted into phasors and these time tagged phasors are delivered to phasor data concentrators via advanced communication modes with minimum delay. These phasors are converted into useful information predicting the state of power system at the monitoring and control centres. Therefore, many indices had been derived with phasor information for early anticipation of power system instability.

Voltage stability surveillance and controls based on measurement can be classified as follows:

1. Local Measurements [22, 24-29]
2. Wide Area Monitoring [33, 55, 58-61]

Network equivalent at a critical/monitoring bus may be determined from voltage and current phasors measurements with PMUs installed at these buses. Theses buses are analysed independently as no synchronization and information of other buses (Voltages/currents) is required.

The dynamic and wide area tracking of the power system state is quite obvious with the phasor measurement units placed at optimal locations for complete observability.

IV. Bus, Line and Overall Voltage Stability Indices

***A.* Bus Indices:** Bus indices that predict the vulnerable buses are tabulated in Table II.

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Table- II: Bus Indices

Index	Expression	Stability Condition	Concept Used	Author	Reference
1. L-Index	$L_j = \left\|1 - \sum_{i\in\alpha_g} \frac{F_{ji}V_i}{V_j}\right\|$	$L_j < 1$		Kessel P et al, 1986	[21]
2. Voltage Index Predictor	$\Delta S = {(V_j - Z_{th}I_{ij})^2}/{4Z_{th}}$	$\Delta S > 0$	Maximum power transfer theorem	Julian D. E. et al, 2000	[22]
3. P-Q Boundary	$P_{cr} = -\frac{E^2R_{th}}{2X_{th}^2} + \frac{\|Z_{th}\|E}{2X_{th}^2}$ $Q_{cr} = \frac{P_LX_{th}}{R_{th}} - \frac{E^2}{2R_{th}^2} + \frac{\|Z_{th}\|E\sqrt{E^2-4P_LR_{th}}}{2R_{th}^2}$	$P_L < P_{cr}$ $Q_L < Q_{cr}$	Feasible solution of voltage equations	Haque M. H., 2003	[23]
4. Voltage Collapse Prediction Index	$VCPI_k = \left\|1 - \sum_{\substack{m=1\\ m\neq j}}^{n} V'_m/V_k\right\|$	$VCPI_k < 1$	Feasible solution of power flow and voltage equations	Balamourougan V. et al, 2004	[24]
5. S Difference Criterion	$SDC = \left\|1 + \frac{\Delta V_r I_r^*}{V_r \Delta I_r^*}\right\|$	$SDC > 0$	Increase in reactive power losses of the line	Verbic G. et al., 2004	[25]
6. Impedance Stability Index	$ISI = \frac{Z_L - Z_{th}}{Z_L}$	$ISI > 0$	Maximum power transfer theorem	Smon I. et al., 2006	[26]
7. Z_L/Z_S ratio	$\frac{Z_L}{Z_S} = \frac{M+1}{-M\cos\beta + [(M\cos\beta)^2M^2+1]}$ Where: $M = \frac{(S_2 - S_1)(Y_2 + Y_1)}{(S_2 + S_1)(Y_2 - Y_1)}$	$\frac{Z_L}{Z_S} > 1$	Maximum power transfer theorem	Wiszniewski A., 2007	[27]
8. Voltage Stability Index	$VSI_i = \left[1 + \left(\frac{I_i}{V_i}\right)\left(\frac{\Delta V_i}{\Delta I_i}\right)\right]^\alpha$	$VSI_i > 0$	Increase in reactive power losses of the line	Haque M. H., 2007	[28]
9. Equivalent Node Voltage Collapse Index	$ENVCI = 2E_kV_n cos\theta_{kn} - E_k^2$	$ENVCI > 0$	Voltage quadratic equation solution	Wang Y., et al., 2009	[29]
10. Linearized motor voltage stability index	$LMVSI_i = \frac{MVSI_i}{\left\|{d(MVSI_i)}/{d\lambda_i}\right\|}$ Where: $MVSI_i = \|det(A_i)\|$	$LMVSI_i > 0$	Singularity of the equivalent load state matrix with dynamic model of induction motor	Gu W. et al., 2010	[30]

Continued …

11. DSY (Derivative of the load apparent power with respect to its admittance)	$DSY = \frac{\Delta S_l}{V_l^2 \Delta Y_l}$	$DSY > 0$	Maximum power transfer theorem	Parniani M. et al., 2010	[31]
12. Voltage stability Risk indices	$VSRI_j = \frac{1}{N}\left[\frac{\sum_{i=j-N+1}^{j}(d_i + d_{i-1})\Delta t}{2}\right]$ Where d_i is percentage diversity between voltage measurements	Most negative index, shows the highest risk of voltage instability	Transient variation of the system voltages	Seethalekshmi K. et al., 2010	[32]
13. Simplified Voltage Stability Index	$SVSI_i = \frac{\Delta V_i}{\beta V_i}$	$SVSI_i < 1$	Maximum power transfer theorem	Pérez-Londoño S. et al., 2014	[33]
14. Linear M-index	$M_i = 1 - \frac{\lvert \bar{V_i} \rvert \lvert \bar{E}_{eff_i} - \lvert \bar{V_i} \rvert \rvert}{\lvert \bar{V}_{cr_i} \rvert^2}$	$M_i > 0$	Voltage quadratic equation solution	Matavalam A.R.R. et al, 2015	[34]
15. $^{dV}/_{dQ}$ index	$\mathbb{I}_i \triangleq \sum_{j \epsilon \mathcal{L}} \frac{Q_j \delta V_i}{V_i \delta Q_j}$, $i \in \mathcal{L}$	$\mathbb{I}_i \to +\infty$ at VC	Singularity of J	Simpson-Porco J. W. et al, 2016	[35]
16. $^{dV_L}/_{dV_G}$ index	$\mathbb{J}_i \triangleq \sum_{k \epsilon \mathcal{G}} \frac{\delta V_i}{\delta V_k}$, $i \in \mathcal{L}$	$\mathbb{J}_i \to +\infty$ at VC	Singularity of J	Simpson-Porco J. W. et al, 2016	[35]
17. $^{dQ_G}/_{dQ_L}$ index	$\mathbb{K}_i \triangleq \sum_{k \epsilon \mathcal{G}} \frac{\delta Q_k}{\delta Q_i}$, $i \in \mathcal{L}$	$\mathbb{K}_i \to -\infty$ at VC	Singularity of J	Simpson-Porco J. W. et al, 2016	[35]
18. P-index	$P - index_j = \frac{-2\frac{P_{L_j}}{V_j}\frac{dV_j}{dP_{L_j}}}{1 - -2\frac{P_{L_j}}{V_j}\frac{dV_j}{dP_{L_j}}}$	$P - index < 1$	Load flow Jacobian matrix	Kamel M. M. et al, 2017	[36]

B. Line Indices: **Table III shows the imperative line indices.**

Table- III: Line Indices

Index	Expression	Stability Condition	Concept Used	Author	Reference
1. Line Stability Factor	$LQP = 4\left(\frac{X}{V_s^2}\right)\left(Q_{r+}\frac{P_s^2 X}{V_s^2}\right)$	$LQP < 1$	Power transfer limit of a line	Mohamed A. et al, 1989	[37]
2. Voltage Stability Load Index	$VLSI = \frac{4[V_s V_r cos\delta - V_r^2 cos\delta]}{V_s^2}$	$VLSI < 1$	Power transfer limit of a line	Rahman TKA et al., 1995	[38]
3. Transmission Path Stability Index	$TPSI = 0.5Vg - \Delta V_d{}'$	$TPSI > 0$	Maximum power transfer theorem	Gubina F. et al, 1995	[39]
4. Line Stability Index	$L_{mn} = \frac{4X\,Q_j}{[V_i \sin(\theta - \delta)]^2}$	$L_{mn} < 1$	Power transfer limit of a line	Moghavemmi M. et al, 1998	[40]

5. Line Stability Index	$L_P = \frac{4RP_j}{[V_i cos(\theta-\delta)]^2}$	$L_p < 1$	Power transfer limit of a line	Moghavemmi M. et al, 2001	[41]
6. Fast Voltage Stability Index	$FVSI = \frac{4Z^2Q_j}{V_i^2 X}$	$FVSI < 1$	Power transfer limit of a line	Musirin I. et al, 2002	[42]
7. L_{sr} Index	$L_{sr} = \frac{S_r}{S_{r(max)}}$	$L_{sr} < 1$	Power transfer limit of a line	Albuquerque MA et al, 2003	[43]
8. Voltages stability Load Bus Index	$VLSBI = \frac{V_r}{\Delta V}$	$VLSBI > 1$	Power transfer limit of a line	Milosevic B. et al., 2003	[44]
9. Voltage Stability Margin Index	$VSMI = \frac{\delta_{max}-\delta}{\delta_{max}}$	$VSMI > 0$	Maximum power transferable through a line	He T. et al., 2004	[45]
10. Power Transfer Stabilty Index	$PTSI = \frac{2S_r Z(1+cos(\theta-\delta))}{V_s^2}$	$PTSI < 1$	Maximum power transferable through a line	Nizam M. et al, 2006	[46]
11. New Line Stability Index	$NLSI = \frac{P_r R + Q_r X}{V_s^2/4}$	$NLSI < 1$	Maximum power transferable through a line	Yazdanpanah-Goharrizi A. et al, 2007	[47]
12. Line Stability Index	$L_{ij} = \frac{4Z^2 Q_r X}{V_s^2(Rsin\delta - Xcos\delta)^2}$	$L_{ij} < 1$	Maximum power transferable through a line	Subramani C. et al, 2009	[48]
13. Line collapse Proximity Index	$LCPI = \frac{4Acos\alpha(P_j Bcos\beta + Q_j Bsin\beta)}{(V_i cos\delta)^2}$	$LCPI < 1$	Voltage quadratic equation solution	Tiwari R. et al., 2012	[49]
14. New Voltage stability Index	$NVSI = \frac{2ZX\sqrt{P_r^2+Q_r^2}}{2Q_s X - V_s^2}$	$NVSI < 1$	Maximum power transferable through a line	Kanimozhi R. et al, 2013	[50]

Continued …

15. Critical Boundary Index	$CBI_{ik} = \sqrt{\Delta P_{ik}^2 + \Delta Q_{ik}^2}$	$CBI_{ik} > 0$	Voltage quadratic equation solution	Furukakoi, M. et al., 2018	[51]
16. Line Voltages stability Index	$LVSI_j = \frac{2V_{R_j} A_j cos(\beta_j - \alpha_j)}{V_{S_j} cos\left(\beta_j - \delta_{SR_j}\right)}$	$LVSI < 1$	Maximum power transferable through a line	Ratra R. et al., 2018	[52]

C. Overall Indices:

Overall indices are generally Jacobian based and well analyzed in [53]. Overall indices give the measure of the proximity to VC taking into account the whole power system model. Some of these are enumerated in the table IV.

Table IV: Overall Indices

Index	Expression	Stability Condition	Concept Used	Author	Reference
1. Voltage Instability Proximity Index	$VIPI = Cos^{-1}\left\{\frac{y_s^T y(a)}{\lVert y_s\rVert \lVert y(a)\rVert}\right\}$	$VIPI > 0$	Feasible solution of Power flow equations	Tamura Y. et al, 1989	[54]

2. Sensitivity Matrix	$S_{Q_g q} = -\varphi_q^T(\varphi_Z^T)^{-1}\nabla_Z Q_g$	$S_{Q_g q} > 0$ At VC $S_{Q_g q}$ changes sign through infinity	Sensitivities become infinite at voltage collapse point	M. Glavic et al, 2009	[55]
3. Area of Voltage Stability Region	$AVSR = \int_{P_l}^{P_n} [Q(P) - Q_l] dP$	$AVSR > 0$	Feasible solution of Power flow equations	Lee C. Y. et al, 2010	[56]
4. Network sensitivity approach	$SG_p = \frac{P_{gt}}{P_{dt}}$ $SG_q = \frac{P_{gt}}{Q_{dt}}$	$SG_p \to \infty$ at VC $SG_q \to \infty$ at VC	P-V curve	Althowibi et al., 2012	[57]
5. Voltage Instability Monitoring Index	$VIMI_k = W_1(k)\frac{DFR_k}{DFR_{max}} + W_2(k)\frac{CVD_k}{CVD_{max}}$	$VIMI_k < 1$	Voltage Deviation and consecutive voltage deviation	Sodhi R. et al, 2012	[58]

V. CONCLUSIONS

The earlier indices are mainly derived from the conditions of singularity of Jacobian obtained in Newton-Raphson method of load flow analysis. These indices are suitable in offline applications like planning and designing of power grids. The disadvantages of Jacobian based indices are high computational effort and accurate prediction is possible only when extremely close to instability point. Sensitivity factors are well recognized indices and implemented in several utilities all over the world. Sensitivity factors that show the variation of generated reactive powers with the changes in loading parameters involves simple calculations in off-line studies. Loading margin is the bench mark index of voltage collapse. But it requires more computation effort at far away point from the current state.

System variables and parameters based indices have been derived from the concept of maximum power transfer theorem and maximum power flow through a line. These indices can be evaluated using load flow solutions or measurements. Measurement based indices can be determined either using local measurements or global measurements. Thevenin’s equivalent model is obtained and utilised for calculation of local measurement based indices. Although the approach is simple and computationally less expensive, time window frame size poses inaccuracy in Thevenin’s equivalent estimation and hence difficulties in actual implementations.

The comprehensive survey concludes that some indices are more suitable for real time control as these can be calculated easily in spite of less accuracy. On the other hand, some indices involve higher computational costs with more accuracy and hence more suitable for offline studies. All the aforesaid indices have their advantages and limitations. Therefore, to acclaim a specific index is not practical as it depends on the application and viability.

REFERENCES

1. G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, “Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance”, IEEE Transactions on Power System, vol. 20, no.4, pp. 1922-1928, November 2005.
2. C. W. Taylor, Power System Voltage Stability and Control, New York: McGraw-Hill, 1994.
3. W. Lu, Y. Bésanger, E. Zamaï and D. Radu, “Blackouts: Description, Analysis and Classification”, Proceedings of the 6th WSEAS International Conference on Power Systems, Lisbon, Portugal, September 22-24, pp. 429-434, 2006.
4. “India’s Mass Power Failure Worst ever in World History”, Outlook, Press trust of India, July 31, 2012.
5. P. Kundur, Power System Stability and Control , New York : McGraw-Hill, 1994.
6. T. V. Cutsem, and C. Vournas, Voltage Stability of Electric Power Systems, Norwell, MA : Kluwer, 1998
7. A.K Panchal , “Voltage Stability of a Large Grid”, Proc. of 7th International Power Engg Conference , pp 1 - 550, Nov. 29 -Dec. 2 2005.
8. V. A. Venikov, V. A. Stroev, V. I. Idelchik, and V. I. Tarasov, “Estimation of electrical power system steady state stability in load flow calculations”, IEEE Trans. on Power Apparatus and Systems, vol. 94, no. 3, pp. 1034-1041, May/June 1975.
9. P. A. Lof, T. Smecl, G. Anderson, and D. J. Hill, “Fast calculation of a voltage stability index,” IEEE Trans. on Power Systems, vol. 7, pp. 54-64, Feb. 1992.
10. B. Gao, G.K. Morison and P. Kundur, "Voltage Stability Evaluation Using Modal Analysis", IEEE Trans. on Power Systems, Vol. 7, No. 4, pp. 1529- 1542, November 1992.
11. H. D. Chiang and R. J. Jumeau, “Toward a practical performance index for predicting voltage collapse in electric power systems", IEEE Trans. Power Systems, vol. 10, no. 2, pp. 584-592, May 1995.
12. R. Seydel, Practical Bifurcation and Stability Analysis - From Equilibrium to Chaos, New York: Springer- Verlag, second edition, 1994.
13. O. O. Obadina, and G. J. Berg, “Identifying electrically weak and strong segments of power system from a voltage stability view point”, IEE Proc., vol. 137, no. 3, pp. 205-212, May 1990.
14. N. Flatabo, R. Ognedal, and T. Carlsen,“Voltage stability condition in a power transmission system calculated by sensitivity methods”, IEEE Trans. on Power Systems, vol. 5, no. 4, pp. 1286-1293, November 1990.
15. A. Berizzi, P. Finazzi, D. Dosi, P. Marannino, and S. Corsi, “First and second order methods for voltage collapse assessment and security enhancement”, IEEE Trans. on Power Systems, vol. 13, no. 2, pp. 543 – 551, May 1998.
16. L. Wang and A. A. Girgis, “On-line detection of power system small disturbance voltage instability”, IEEE Trans. on Power Systems, vol. 11, no. 3, pp. 1304-1313, August 1996.
17. A. C. Z. de Souza, C. A. Ca~nizares, and V. H. Quintana, \Critical bus and point of collapse determination using tangent vectors," Proc. NAPS, M.I.T., pp. 329-333, November 1996.
18. M. Suzuki, S.Wada, M. Sato, T. Asano, and Y. Kudo, “Newly developed voltage security monitoring system," IEEE Trans. Power Systems, vol. 7, no. 3, pp. 965-973, August 1992.
19. A. Venkataramana, C. Colin, “The continuation power flow a tool for steady state voltage stability analysis”, IEEE Trans. on Power Syst vol. 7(1), February 1992.

20. N. Yorino, S. Harada and H. Cheng, “A Method to approximate a closest loadability limit using multiple load flow solutions”, IEEE Trans. on Power Systems , vol. 12, no. 1, pp. 424-429, February 1997.
21. P. Kessel and H. Glavitch, “Estimating the voltage stability of a power system”, IEEE Trans. Power Delivery, vol. 3, pp. 346-354, July 1986.
22. D. E. Julian, R. P. Schultz, K. T. Vu, W. H. Quaintance, N. B. Bhatt, and D. Novosal,“Quantifying proximity to voltage collapse using the voltage instability predictor (VIP)”, IEEE Power Eng. Soc., vol. 2, pp. 931-936, July 2000.
23. M. H. Haque, “Novel method of assessing voltage stability of a power system using stability boundary in P-Q plane”, Electric Power Systems Research, vol. 64, pp. 35-40, 2003
24. V. Balamourougan, T.S. Sidhu and M.S. Sachdev, “Technique for online prediction of voltage collapse”, IEE Proceedings-Generation, Transmission and Distribution, vol. 151, no. 4, pp. 453-460, July 2004.
25. Verbic G.,Gubina F., “A new concept of voltage-collapse protection based on local phasors”,IEEE Trans on Power Delivery, vol. 19, no. 2, pp. 576–81. April 2004.
26. I. Smon, G. Verbic, F. Gubina, Local voltage-stability index using Tellegen’s theorem, IEEE Trans. on Power Systems, vol. 21, no. 3, pp. 1267–1275, August 2006.
27. A. Wiszniewski, “New criteria of voltage stability margin for the purpose of load shedding”, IEEE Trans. Power System, vol. 22, pp. 1367-1371, July 2007.
28. M.H. Haque, Use of local information to determine the distance to voltage collapse. In Proceedings of the International Power Engineering Conference (IPEC 2007), Singapore, pp. 407–412, 3–6 December 2007.
29. Y. Wan, W. Li and J. Lu, “A New node voltage stability index based on local phasors”, Electric Power Systems Research, vol. 79, no. 1, pp. 265-271, January 2009.
30. W. Gu, Q.Wan, “ Linearized voltage stability index for wide-area voltage monitoring and control”, International Journal Of Electrical Power & Energy Systems, 32(4), 333-36, May 2010.
31. Parniani M, Vanouni M., “ A fast local index for online estimation of closeness to loadability limit”, IEEE Transactions on Power Systems, 25(1):584-85 February 2010.
32. K. Seethalekshmi, S.N. Singh, S.C. Srivastava, “Adaptive scheme for minimal load shedding utilizing synchrophasor measurements to ensure frequency and voltage stability”, Electric Power Components and Systems, 38(11):1211-27, August 2010.
33. S. Pérez-Londoño, L. F. Rodríguez, G. A Olivar, “Simplified voltage stability index (SVSI)”, International Journal of Electrical Power & Energy Systems, 63, 806-13, December 2014.
34. A. R. Matavalam, V. Ajjarapu “Calculating the long term voltage stability margin using a linear index”, In IEEE Power & Energy Society General Meeting, pp. 1-5, July 2015.
35. J. W. Simpson-Porco, F. Bullo., “Distributed monitoring of voltage collapse sensitivity indices”, IEEE Transactions on Smart Grid, 7(4), 1979-88, Juyl 2016.
36. M. M. Kamel, A. A. Karrar, A. H. Eltom, “Development and Application of a New Voltage Stability Index for On-Line Monitoring and Shedding”, IEEE Transactions on Power Systems, vol. 33, no. 2, July 2017.
37. A.Mohamed, G.B.Jasmon, S.Yusoff “A static voltage collapse indicator using Line stability factors”, Journal of Industrial Technology, vol. 7, No. 1, pp. 73-85, 1989.
38. T. A. Rahman, G. B. Jasmon, “A new technique for voltage stability analysis in a power system and improved loadflow algorithm for distribution network”, In IEEE International Conference Proceedings of Energy Management and Power Delivery, Vol. 2, pp. 714-719, November 1995.
39. F. Gubina, B. Strmcnik, “Voltage collapse proximity index determination using voltage phasors approach, IEEE Trans. on Power Systems, vol. 10, no. 2, pp. 788 - 794. May 1995.
40. M. Moghavvemi, and F. M. Omar, “Technique for contingency monitoring and voltage collapse prediction”, IEE Proceedings-
41. Generation Transmission and Distribution, vol. 145, no. 6, pp. 634-640, November 1998.
42. M. Moghavvemi, M. O. Faruque, “Technique for assessment of voltage stability in illconditioned radial distribution network”, IEEE Power Engineering Review, 21(1), pp. 58-60, Jan 2001.
43. I. Musirin, and T. K. A. Rahman, “Novel fast voltage stability index (FVSI) for voltage stability analysis in power systems”, Student Conf. in Research and Development Proc., Malaysia, pp. 265 – 268, July 2002
44. MA Albuquerque, CA Castro, “A contingency ranking method for voltage stability in real time operation of power systems”, In IEEE Power Tech Conference Proceedings, Vol. 1, June 2003.
45. B. Milosevic, M. Begovic, “ Voltage Stability Protection and control using wide- area network of phasor measurements”, IEEE Trans. on Power Systems, vol. 18, no. 1, pp. 121 – 127, February 2003.
46. T. He, S. Kolluri, S. Mandal, F. Galvan, P. Rasigoufard, “Identification of weak locations in bulk transmission systems using voltage stability margin index”, In IEEE Power Engineering Society General Meeting, pp. 1814-1819, June 2004.
47. M. Nizam, A. Mohamed, A. Hussain, “Dynamic voltage collapse prediction in power systems using power transfer stability index”, In IEEE International Power and Energy Conference, pp. 246-250, Nov 2006.
48. A. Yazdanpanah-Goharrizi, R. Asghari, “A novel line stability index (NLSI) for voltage stability assessment of power systems”, In 7th WSEAS International Conference on Power Systems, Beijing, China, pp. 164-167, Sep 2007.
49. C. Subramani, S. Dash, M. A. Bhaskar, M Jagadeeshkumar, K. Sureshkumar, R. Parthipan, “Line outage contingency screening and ranking for voltage stability assessment”, In IEEE International Conference on Power Systems, pp. 1-5, DEC 2009.
50. R. Tiwari, K. R. Niazi, and V. Gupta, “Line collapse proximity index for prediction of voltage collapse in power systems”, IJEPES, vol. 41, no. 1, pp. 105-111, 2012.
51. R. Kanimozhi, K. Selvi, “A novel line stability index for voltage stability analysis and contingency ranking in power system using fuzzy based load flow”, Journal of Electrical Engineering & Technology (JEET), 8(4), pp. 694-703, July 2013.
52. M. Furukakoi, O.B. Adewuyi, M.S.S Danish, A.M Howlader, T. Senjyu, T. Funabashi, “Critical Boundary Index (CBI) based on active and reactive power deviations”, International Journal of Electrical Power & Energy Systems, 100, pp. 50-57, February 2018.
53. S. Ratra, R. Tiwari, K. R. Niazi, “Voltage stability assessment in power systems using line voltage stability index”. Computer and Electrical Engg., pp. 1–13, January 2018.
54. Canizares CA. Voltage stability assessment: concepts, practices and tools. IEEE PES Power System Stability Subcommittee Special Publication; 2002.
55. Y. Tamura, K. Sakamoto, Y.Tayama, “Current issues in the analysis of voltage instability phenomena”, In Bulk power system voltage phenomena voltage stability and security, p.5-39–53, 1989.
56. M. Glavic,.T.V. Cutsem, “Wide-area detection of voltage instability from synchronized measurements. Part 1: Principle”, IEEE Trans. Power Syst., 24(3), pp. 1408–1416, 2009.
57. C. Y. Lee, S. H. Tsai, and Y. K. Wu, “A new approach to the assessment of steady-state voltage stability margins using the P–Q–V curve”, Electrical Power and Energy Systems vol. 32, no. 10, pp. 1091–1098, December 2010.
58. F. A. Althowibi, M.W. Mustafa, “Power system network sensitivity to voltage collapse”, in Proceedings of the international power engineering and optimization conference, pp. 379–83, 2012.
59. R. Sodhi, S C Srivastava and S N Singh, "A simple scheme for wide area detection of impending voltage instability”, IEEE Transactions on Smart Grid, Vol. 3, No. 2, June 2012.
60. L. Mili, T. Baldwin, and R. Adapa, “Phasor measurement placement for voltage stability analysis of power systems”, Proc. IEEE 29th Conf. on
61. Decision and Control, Honolulu, pp. 3033-3038, 1990.
62. B. Genet, J. C. Maun, “Voltage-stability monitoring using wide area measurement systems”, Power Tech., Lausanne, pp. 1712-1717, July 1-5, 2007.
63. S. Corsi, “Wide area voltage regulation & protection”, Proc. IEEE Power Tech. Conf., Bucharest, pp. 1-7, June 28-July 2, 2009.
64. T.J. Overbye, and C.L. DeMarco, “Improved techniques for power system voltage stability assessment using energy methods,” Power Systems, IEEE Transactions on , vol.6, no.4, pp.1446-1452, November 1991.
65. T. J. Overbye, I. Dobson, and C. L. DeMarco, “Q-V curve interpretations of energy measures for voltage security", IEEE Trans. on Power Systems, vol. 9, no. 1, pp. 331-340, February 1994

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