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Voltage stability index: a review based on analytical method, formulation and comparison in renewable dominated power system

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ABSTRACT

In an interconnected complex power system network voltage stability evaluation is indispensable to guarantee secure power system operation. To further increase the system performance and to make the system safer assessment, the voltage stability improvement is obligatory. In the various literature different voltage security assessment method using the voltage stability index has been presented. Different lists proposed in literature can be utilized to realize the weak buses and weak transmission lines to enacting the countermeasures against issues of voltage insecurity. Additionally, the arrangement and measuring of inexhaustible assets, on the web and disconnected observing of force framework and the measure of load to be shed at whatever point essential. This paper shows a survey on the different voltage stability index from various perspectives. The audit results on various record gives a far and wide logical to perceive the impending works in this field and to choose the best index for variety of applications such as voltage security assessment, renewable energy integration, distributed generation (DG) placement and sizing, online monitoring of the power system, and shedding of load.

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1. INTRODUCTION

Recent definitions of power system stability, including voltage stability definition based on the integration of renewable energy resources into the grid through high-voltage direct current (HVDC) convertors, have been proposed by the IEEE/CIGRE task group [1]. The continuity of proper power flow in the interconnected electrical power systems is maintained by designing the system carefully without any restraint. In earlier beings, voltage instability has been the key reason of several major blackouts in the world in significant part of power systems. Preview study [2]-[13] from 1965 to 2015, many power outages have been pointed out and demonstrating that the voltage variability issues obligated a significant incident in many of the cases. The voltage breakdown term is additionally utilized rather than voltage instability and this is the interaction by which the arrangement of occasions going with voltage insecurity prompts a strangely low voltages or power outage in a huge portion of the power system network [3].

The capacity of a power system to maintain constant voltages at all its buses after being subjected to a disturbance from a specific initial operating condition is the IEEE definition of voltage stability [4]-[8]. The failure of reactive power sources to provide enough reactive power or the failure of power system cables to transmit the required reactive power can both cause voltage instability [9]. The reactive power is generally provided by generators excitation system and reactive power compensators such as shunt capacitors and other compensating devices. The leading instances producing voltage instability issues in the electrical power system network are gradual or sudden increase in the loading condition, maloperation of protective devices, sudden tripping of large rating power system apparatus like generators, transmission lines and power transformers, surpassing some generator units' reactive power limits and issues with on-load tap shifting transformers. Several solutions for the reduction of voltage instability in the power system are already exists. The most important one is as [10]: i) improving faulty buses and lines during the power system expansion phase (by DG units or other voltage-supporting apparatus), ii) shunt capacitor device switching, iii) load shedding, iv) FACTS device implementation to extend the VS margin, and v) the blocking of tap changer. Here the shedding of load is the latter line of shield. Another use of voltage stability indices (VSI) is producing the countermeasures in contradiction of voltage instability [14]-[16].

In these instances, the indices which have been used in real-time application, the data needed is provided by the phasor measurement unit (PMU) who is the measure of wide area measurement system. To measure the voltage instability, a number of indices have been described in the studies [17]-[20]. Only the voltage and current of the buses are required, and very few indices depend on the impedance of the power system. Practically it is impossible to get power system impedance with high accuracy due to the atmospheric effects and deficiency in information. Thus, the performance of indices is most of the time associated with error as they are dependent on power system impedance.

This paper shows the review on various voltage stability indices considering several features and aspects such as method of voltage instability calculation, concept of voltage stability, equations and stability condition. For a variety of applications, including the positioning and capacity findings of distributed generations (DGs), the static and dynamic VS assessment, the ranking of buses and transmission lines contributing to voltage instability issues, and more, the analysis of the review results can be used to understand the upcoming works in voltage stability analysis and to select the best VSI, and the activation of countermeasures for controlling the system prior to voltage collapse.

This paper is systematized in the succeeding manner: in section 2, voltage stability index need for renewable integration has been discussed; section 3 describes voltage stability indices; section 4 explained the classification of voltage stability indices; section 5 describes the review on VSI’s utilizing approaches for cyber physical systems and machine learning approaches; challenges and direction towards future research has been discussed in section 6; and section 7 concludes the discussion.

2. VOLTAGE STABILITY INDEX NEED FOR RENEWABLE INTEGRATION

The trend towards renewable energy integration into the grid is increases and hence following challenges are brought into notice for large renewable energy integration in to the existing grid: i) Rises the ambiguity in the power flow and voltage profile of the system; ii) It may lead to clashes of voltage and var control devices between interconnected power systems of unlike regions; iii) Intensify the needless operation of discrete var and voltage control devices; iv) Decreases the system voltage stability; and v) It constructs difficulties in the reactive power market. Also, distribution generators which are of small power generators (typically from 2 kW to 10 MW range) are integrating to grid to improve conventional electrical power system [21]-[22]. These technologies include wind and solar energy, microturbines, small hydro-power, small gas turbines, fuel cells, and biomass. When distributed generators are integrated to power system network it will benefit existing network by increasing voltage profiles and load factors, by reducing losses and peak operating costs. It also improves system reliability and efficiency [23]. To accomplish benefits, a suitable sizing and placement of distributed generator must need to be selected. The location of generator units has been selected according to voltage stability index. For the sitting and sizing of distributed generation nearly all the indices which has been able to regulate the weak transmission lines and buses can be used.by using appropriate and accurate voltage stability index, better locations for the distributed generator units can be attained. Furthermore, complex index increases the computational time of the problem to be optimize especially in large power systems. Therefore, the best solution for DG sitting and sizing issues is to employ an accurate and simple index. The voltage stability indices are categorized conferring to their forms (e.g., line, bus, and overall voltage stability indices), concepts used, equations, and stability condition in order to give a broad perspective for the proper selection of voltage stability indices. The accuracy of these assumptions is then evaluated in the following sections.

Voltage stability has become more crucial in modern distribution system owing to rising demands and the penetration of DG. Compared to traditional power systems, the ability of renewable energy producing systems to control voltage is constrained [24]-[26]. As inverter-based renewable energy generation systems replace traditional synchronous generators, the stability, frequency, and voltage of the power system are being put to the test [25]. When a power system's ability to control voltage falls below threshold, system behavior deteriorates. For instance, in a double-fed induction generator-based wind energy conversion system (DFIG-WECS), the capacity to modify voltage depends on the rate of wind generation penetration [26]. The classification procedure for voltage stability analysis in the system with renewable energy resources is shown in Figure 1. Analysis and verification have been done in several literature [27]-[47] for voltage stability analysis considering different case studies such as with only PV generation, only wind generation, with hybrid distributed generator. Table 1 summarizes the networks' verification platforms and ways of operation/configuration in brief.

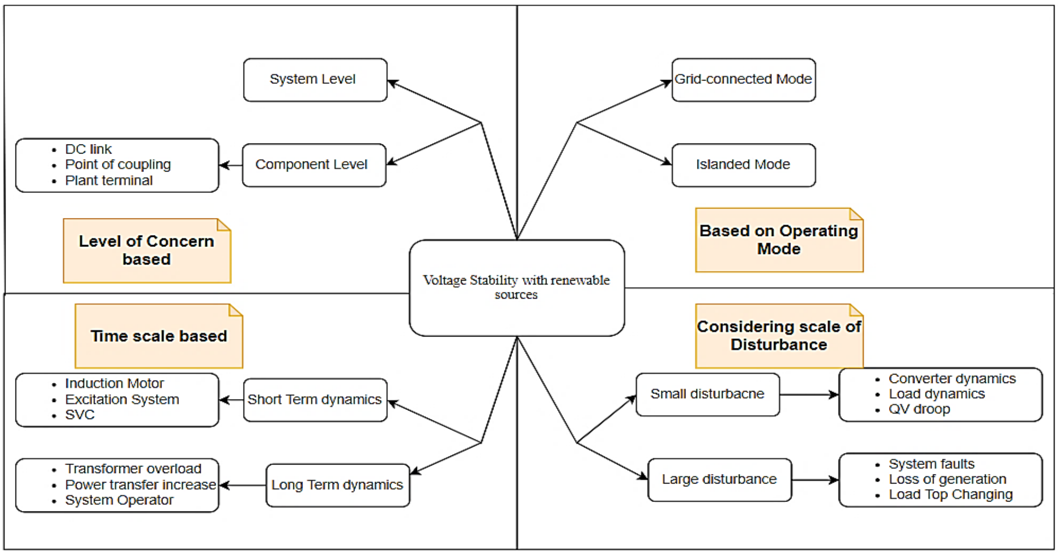

Figure 1. Voltage stability comparison with renewable dominated power system

Table 1. Overview of simulation tools in several operation modes with varied generation

Generator type	References	Ways of operation
Wind generator	[27]-[31]	
Photovoltaic (PV)	[32]-[36]	
Wind and PV	[37]-[41]	Integrated to grid
Hydro and PV	[42]	
Wind, PV, and hydro	[43]	
Wind	[44]	
PV	[45]	Standalone or islanded
Wind and PV	[46] [47]	

3. VOLTAGE COLLAPSE POINT DETECTION

Numerous VSI’s have been reported in different literature. These VSI’s has been classified as [48]-[54]: i) based on singularity of Jacobian matrix, ii) system variables-based voltage stability indices, and iii) bus index, line index, and overall voltage stability indices. The VSI’s based on singularity of Jacobian matrix is mainly used to compute the voltage collapse point and to spot the voltage stability margin. Generally, two bus representation is used by most of the researchers to describe the voltage collapse criterion shown in Figure 2. The fundamental drawback of this approach is the high computing time required for bigger systems, where even minor topologic changes result in changes to the Jacobian matrix and necessitate repeated calculations of the matrix. They are not appropriate for determining the voltage stability in real time.

Moreover, use of indices based on singularity of Jacobian matrix concept can cause a rise in the running time of distributed generation sizing and sitting problems. In contrast, the various indices depend on system variables requires little computation time and are appropriate for real-time applications. The limitation of these indices is that it just shows the critical lines and busses of the system and cannot accurately estimate the stability margin. In many applications voltage stability indices are used to spot the weak buses and weak lines in power system or energizing the countermeasures in contradiction of voltage instability. Consequently, it is very essential to classify the various voltage stability index which have been described in this study and can be very useful to the researchers who will going to work on voltage stability.

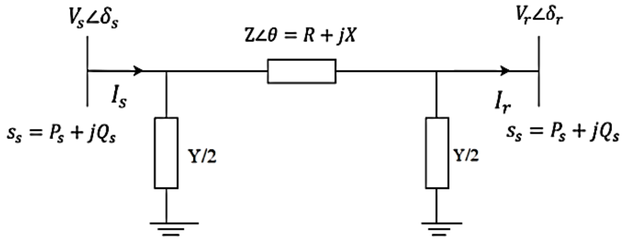

Figure 2. Two bus power system representation

4. COMPARISON OF VSI/CLASSIFICATION

The classification of voltage stability methos is shown in Figure 3. Various conditions for developed VSI's are as: i) power flow using Jacobian singularity, ii) P-V and V-Q curves, iii) based on theorem of maximum power transfer, iv) based on power transfer limit of transmission line, and v) Lyapunov stability theory.

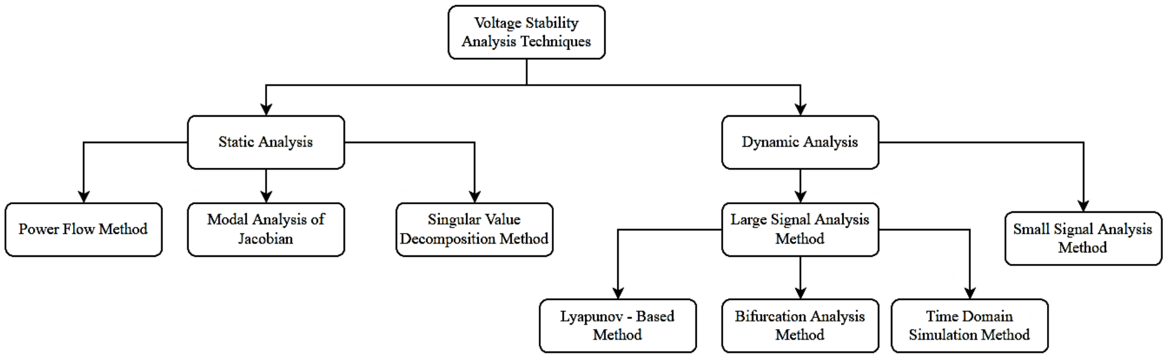

Figure 3. Classification of voltage stability methods

4.1. Load flow using Jacobian singularity

In load flow the steady state limit is directly associated to Jacobian matrix. The voltage instability state can be indicated by the singularity of Jacobian matrix after load flow and as a result, the eigen values of the linearized system matrix may serve as a warning sign of impending voltage collapse. At different buses, the real and reactive power equations can be expressed by non-linear equations as in (1) and (2).

$$\Delta Pi = Pisp - Vi\,Vj\,(Gij\,cos\theta ij + n\,j = 1\,Bij\,sin\theta ij) = 0\Delta Qi = Qisp - Vi\,Vj\,(Gij\,sin\theta ij - n\,j = 1\,Bij\,cos\theta ij) = 0 \quad (2)$$

By using Taylor's series expansion to linearize the equation above the power balance equations and ignoring higher order terms yields (3).

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}\frac{\partial P}{\partial V} & \frac{\partial P}{\partial \theta}\\ \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial \theta}\end{bmatrix}\begin{bmatrix}\Delta V\\ \Delta \theta\end{bmatrix} \text{ or } \begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = [J]\begin{bmatrix}\Delta V\\ \Delta \theta\end{bmatrix} \quad (3)$$

Where ΔP, ΔQ is change in active and reactive powers respectively; ΔV, $\Delta\theta$ is change in voltage and load angle respectively; and J is Jacobian matrix.

4.2. P-V and Q-V curves load margin [55]-[57]

The fundamental and conventional method of observing voltage to proximity of collapse, the P-V and Q-V curve is shown in Figure 4 which displays the stability regions. The amount of additional load required to cause voltage collapse under specific load-increasing assumptions is known as the loading margin at a specific operational condition. It has been heavily utilized in voltage stability research to evaluate other indices' performance. In reality, the loading margin is determined using the direct and continuous power flow methods.

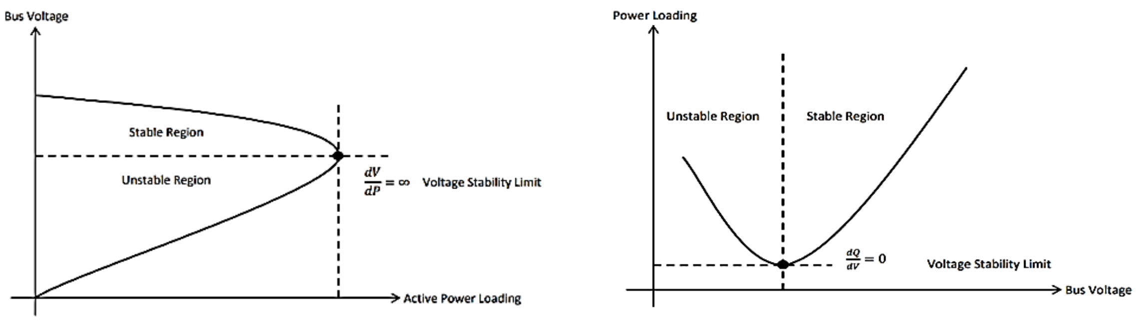

Figure 4. P-V curve and Q-V curve

4.3. Maximum power transfer theorem

This method is the most practical for stability analysis and real-time regulation of power systems since it makes determining equivalents simple. Thevenin's theory had been applied to obtain the network equivalent in the vast majority of cases. A simple technique for estimating the voltage stability of a complex system in global mode is network equivalent at a bus shown in Figure 5.

4.4. Power transferable limit of a transmission line

Majority of the line indices were discovered by studying the capability of power transfer through a transmission line. When there is no practical way to lower the voltage at the receiving end, the maximum power limit is reached. Two bus transmission line model is shown in Figure 6. By condensing the formulas for receiving end active and reactive powers, the receiving end voltage of the line in Figure 6 can be calculated using (4).

$$V_r^4 + (2P_rR + 2Q_rX - V_s^2)V_r^2 + (P_r^2 + Q_r^2)Z^2 = 0 \quad (4)$$

As a result, the standard for determining the critical limits of various line VSI's is to equalize the expression for the discriminant in (4) to zero. Where:
- $Vs\angle\delta s$ & $Vr\angle\delta r$: sending and receiving end bus voltages.
- $(Ps + jQS)$ & (Pr $+jQr$): sending and receiving end real and reactive powers.
- R, X, Y: resistance, inductive reactance and shunt half line charging admittance of transmission line respectively.

A few indices in terms of transmission line parameters i.e., ABCD parameters, have also been derived by using the pie-model of transmission line, as shown in Figure 7.

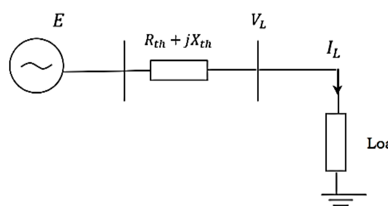

Figure 5. Thevenin's equivalent circuit

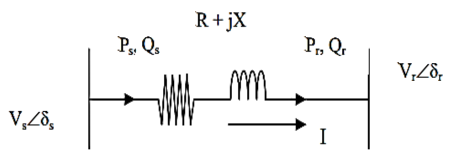

Figure 6. Two bus transmission line model

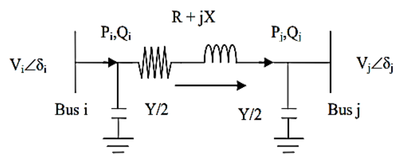

Figure 7. Line model with shunt admittance

4.5. Lyapunov based stability theory

This theory had been originally identified for direct stability studies of power systems. Therefore, the method based on it had been efficiently applied and employed as a VS predictor in [58], [59]. The indices are classified based on calculation and formulation has been shown in Figure 5 and classification criterion for recognize the voltage collapse has been shown in Figure 8.

Both load flow solutions and measurements of the voltages, powers, and currents pumped into several buses can be used to determine power system variables. The power system's weak points are identified by an index derived from these system variables and characteristics, which is used to launch remedial action against voltage collapses. As a result, these are categorized as follows based on the identification of the part susceptible to voltage collapses: i) line indices, ii) bus indices, and iii) overall indices.

The buses that are closest to the voltage stability limits can be found using bus indicators, making them prime candidates for installing shunt FACT's controllers. Similar to this, series correction in weak lines has been achieved using line indices. The overall indices don't just flag poor buses or lines; they also predict the stability level of the entire power system. The results of an extensive survey are presented in this section, where the imperative indices that have been created up to now are stated in sequential order lengthwise with the criteria that directed their development. The voltage stability indices based on Jacobian matrix have been proposed in the literature are listed in Table 2.

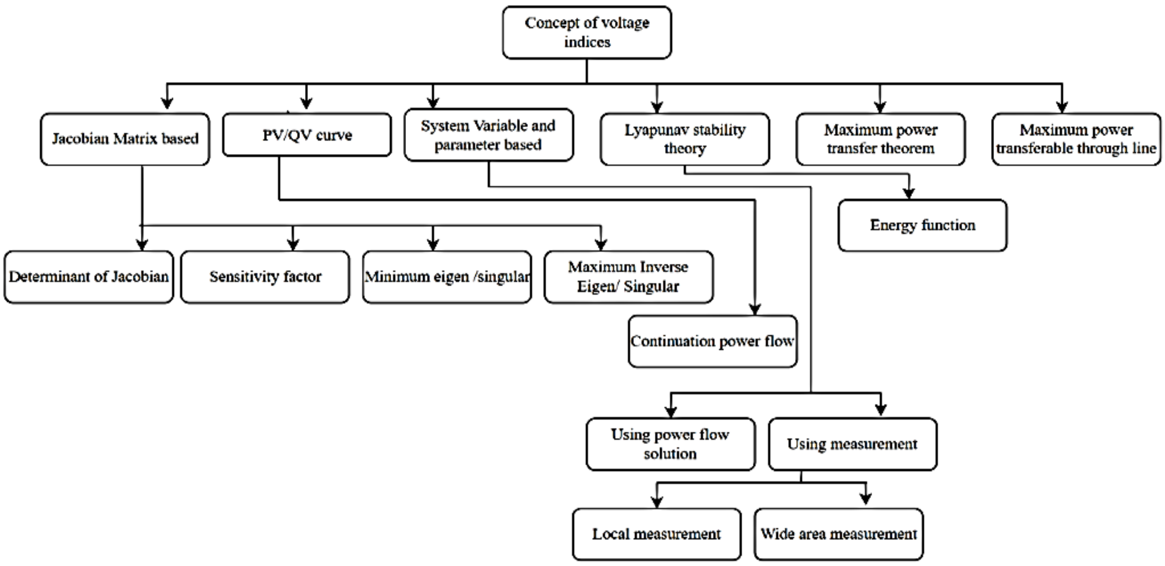

Figure 8. Voltage collapse recognition criterion

Table 2. Voltage stability indices based on Jacobian matrix

Index	Reference	Expression	Concept used	Stability condition
Det J Det J_R	[60]	$\lvert J\rvert = \begin{vmatrix} \frac{\partial P}{\partial V} & \frac{\partial P}{\partial \theta} \\ \frac{\partial Q}{\Delta V} & \frac{\partial Q}{\partial \theta} \end{vmatrix}$ $\lvert J_R\rvert = \lvert J_{QV} - J_{QS} * J_{PS}^{-1} * J_{PV}\rvert$	Power flow	$\lvert J\rvert \neq 0$ $\lvert J_R\rvert \neq 0$
Singular/eigen values/modal analysis	[61]-[62]	Minimum eigen/singular value	power flow	All eigen singular value should be positive
$J^C \in C^{2n\times 2n}$	[63]	$J^C = \begin{bmatrix} -I^n & V^n - Y^b \\ -V^n Y^b & I^n \end{bmatrix}$ $\wedge = (V^n)^{-1} Y\frac{b}{n} V^n$	Jacobian singularity	$\lambda^{cr} = \min_{\lambda i}\lvert\lambda_i - 1\rvert$=0
Sensitivity Factors	[64]	$VSF_1 = max_1\left\{\frac{dV_1}{dQ_1}\right\}$	Singularity of Jacobian	VSF_1 should be small positive
Inverse sensitivity factors (VQ- sensitivities)	[65]	$IVSF$= 1/VSF	Inverse of reduced Jacobian J_R^{-1}	$IVSF \neq 0$
Second order index	[66]	$c=\frac{\sigma_{max}}{c_0\left(\frac{d\sigma_{max}}{d\lambda_{total}}\right)}$	Singularity of Jacobian	c > 0
P and Q angle	[67]	$\alpha_1 = \cos^{-1}\left\{\frac{(\nabla f_1 \cdot T_{ag1})}{(\lVert\nabla f_1\rVert \lVert T_{ag1}\rVert)}\right\}$	Singularity of Jacobian	α_1 < 90°
Tangent Vector Index	[68]	$TVI_1 = \left\lvert\frac{dV_1}{d\lambda}\right\rvert^{-1}$	Inverse sensitivity factors	$TVI_1 \leq \in$
Test function	[69]	$t_{cc} = \lvert e_c^T J J_{cc}^{-1} e_c\rvert$	Singularity of J	$t_{cc} \neq 0$
$S_{\lambda\omega}$	[41]	$S_{\lambda\omega} = \frac{\Delta\lambda}{\Delta\omega} = -\frac{MF\rvert_\omega}{MF\rvert_\lambda}$ $\Delta\lambda_i = \sum_r S_{ir0}\Delta\omega_r$	Jacobian matrix singular point	Loading margin measures by formulation

4.5.1. Line VSI's

These indices are referred to a transmission line which can be used to assess voltage stability. The two-bus representation of a system in Figure 1 provides the foundation for all line indices used for voltage stability analysis. Because of this, most line indices have the same theoretical foundation; the assumptions made by each index may vary. Table 3 [70]-[87] displays the line indices used for voltage stability analysis that have been proposed in the literature.

Table 3. Line voltage stability indices

Index	Reference	Expression	Concept used	Stability condition
Line stability factor	[70]	$LQP = 4\left(\frac{X}{V_S^2}\right)\left(Q_r + \frac{P_s^2 X}{V_S^2}\right)$	Line power transfer capability (LPTC)	$LQP < 1$
Voltage stability load index	[71]	$VLSI = \frac{4[V_s V_r \cos\delta - V_S^2 \cos\delta]}{V_S^2}$	LPTC	$VLSI < 1$
Transmission path stability index	[72]	$TPSI = 0.5V_g - \Delta V_{d'}$	Maximum power transfer theorem	$TPSI > 0$
Line stability index	[73]	$L_{mn} = \frac{4XQ_j}{[V_i \sin(\theta-\delta)]^2}$	LPTC	$L_{mn} < 1$
Line stability index	[74]	$L_p = \frac{4RP_j}{[V_i \cos(\theta-\delta)]^2}$	LPTC	$L_p < 1$
Fast voltage stability index	[75]	$FVSI = \frac{4Z^2 Q_j}{V_i^2 X}$	LPTC	$FVSI < 1$
L_{sr} index	[76]	$L_{sr} = \frac{S_r}{S_{r(max)}}$	LPTC	$L_{sr} < 1$
Voltage load stability bus index	[77]	$VLSBI = \frac{V_r}{\Delta V}$	LPTC	$VLSBI > 1$
Voltage stability margin index	[78]	$VSMI = \frac{\delta_{max} - \delta}{\delta_{max}}$	Maximum power transferable through a transmission line [MPTTTL]	$VSMI > 0$
Power transfer stability index	[79]	$PTSI = \frac{2S_r(1+\cos(\theta-\delta))}{V_s^2}$	[MPTTTL]	$PTSI < 1$
New line stability index	[80]	$NLSI = \frac{P_r R + Q_r X}{\frac{V_s^2}{4}}$	[MPTTTL]	$NLSI < 1$
Line stability index	[81]	$L_{ij} = \frac{4Z^2 Q_r X}{V_s^2 (R\sin\delta - X\cos\delta)^2}$	[MPTTTL]	$L_{ij} < 1$
Line collapse proximity index	[82]	$\text{LCPI} = \frac{4A\cos\alpha\,(P_j B\cos\beta + Q_j B\sin\beta)}{(V_i \cos\delta)^2}$	Voltage quadratic equation solution	LCPI < 1
New voltage stability index	[83]	$\text{NVSI} = \frac{2ZX\sqrt{P_r^2 + Q_r^2}}{2Q_s X - V_s^2}$	[MPTTTL]	NVSI < 1
Critical boundary index	[84]	$\text{CBI}_{\text{ik}} = \sqrt{\Delta P_{ik}^2 + \Delta Q_{ik}^2}$	Voltage quadratic equation solution	$\text{CBI}_{\text{ik}} > 0$
Modified voltage stability indices	[85]	$MVSI_J = \frac{4(Q_j Y_{jj}\sin\varepsilon_{jj})}{\left(\sum_{i=1,i\neq j}^{N} V_i Y_{ij}\right)^2}$	Active and reactive power transfers	$MVSI < 1$
Smoothening reactive power loss-based voltage instability detection index	[86]	$QLVIDI_{(t)} = \frac{CQL_{(t)}}{CQLB_{(t)}} - \frac{CQL_{(t-\tau)}}{CQLB_{(t-\tau)}}$	PMU	Details are in reference
Real-time short-term voltage stability (STVS) assessment	[87]	Details are in reference	PMU	Data collection Inaccuracy (Z)

4.5.2. Bus VSI's

Assess the voltage stability of system buses only but do not give any details regarding weak facilities that could experience voltage related issues in the system. Thus, it is not possible to identify deficient facilities using bus voltage stability indices. This section examines the bus index. Table 4 [88]-[99], [48]-[51] displays the bus voltage stability index that have been suggested in the literature.

Table 4. Bus voltage stability indices

Index	Reference	Expression	Concept used	Stability condition
L-index	[88]	$L_j=\left\|1-\sum_{i\in\alpha_g}\frac{F_{ji}V_i}{V_j}\right\|$	Quadratic voltage equation	$L_j<1$
Voltage index predictor	[89]	$\Delta S=\left(V_j-Z_{th}I_{ij}\right)^2/4Z_{th}$	MPT	$\Delta S>0$
P-Q boundary	[90]	$P_{cr}=-\frac{E^2R_{th}}{2X_{th}^2}+\frac{\|Z_{th}\|E}{2X_{th}^2}$ $Q_{cr}=\frac{P_LX_{th}}{R_{th}}-\frac{E^2}{2R_{th}^2}+\frac{\|Z_{th}\|E\sqrt{E^2-4P_LR_{th}}}{2R_{th}^2}$	Feasible solution of voltage equations	$P_L<P_{cr}$ $Q_L<Q_{cr}$
Voltage collapse prediction index	[91]	$VCPI_k=\left\|1-\sum_{m=1, m\neq 1}^{n}V'_m/V_k\right\|$	Feasible solution of power flow and voltage equations	$VCPI_k<1$
S difference criterion	[92]	$SDC=\left\|1+\frac{\Delta V_rI_r^*}{V_rI_r^*}\right\|$	rise in the line's reactive power losses	$SDC>0$
Impedance stability index	[93]	$ISI=\frac{Z_L-Z_{th}}{Z_L}$	MPT	$ISI>0$
$\frac{Z_L}{Z_S}$ ratio	[94]	$\frac{Z_L}{Z_S}=\frac{M+1}{-M\cos\beta+[(M\cos\beta)^2M^2+1}$ Where: $M=\frac{(S_2-S_1)(Y_2+Y_1)}{(S_2+S_1)(Y_2-Y_1)}$	MPT	$\frac{Z_L}{Z_S}>1$
Voltage stability index	[95]	$VSI_i=\left[1+\left(\frac{I_i}{V_i}\right)\left(\frac{\Delta V_i}{\Delta I_i}\right)\right]^{\alpha}$	Rise in the line's reactive power losses	$VSI_i>0$
Equivalent node voltage collapse index	[96]	$ENVCI=2E_kV_n\cos\theta_{kn}-E_k^2$	Voltage quadratic equation solution	$ENVCI>0$
Linearized motor voltage stability Index	[97]	$LMVSI_i=\frac{MVSI_i}{\left\|d(MVSI_i)/d\lambda_i\right\|}$ Where: $MVSI_i=\|\det(A_i)\|$	Equivalent load state matrix singularity with dynamic induction motor model	$LMVSI_i>0$
DSY (derivative of the load apparent power with respect to its admittance)	[98]	$DSY=\frac{\Delta S_l}{V_l^2\Delta Y_l}$	MPT	$DSY>0$
Voltage stability Risk indices	[99]	$VSRI_i=\frac{1}{N}\left[\frac{\sum_{i=j-N+1}^{j}(d_i+d_{i-1})\Delta t}{2}\right]$	Transient variation of the system voltages	Negative index, highest risk of voltage instability
Simplified voltage stability index	[48]	$SVSI_i=\frac{\Delta V_I}{\beta V_I}$	MPT	$SVSI_i<1$
Linear M- index	[49]	$M_i=1-\frac{\|\bar{V}_i\|\left\|\bar{E}_{effi}-\|\bar{V}_i\|\right\|}{\|\bar{V}_{cri}\|^2}$	Voltage quadratic equation solution	$M_i>0$
dV/dQ index	[50]	$\mathbb{I}_i\triangleq\sum_{k\in\mathcal{L}}\frac{Q_j\delta V_i}{V_i\delta Q_j},i\in\mathcal{L}$		$\mathbb{I}_i\to+\infty\ at\ VC$
dV_L/dV_G index		$\mathbb{J}_i\triangleq\sum_{k\in\mathcal{G}}\frac{\delta V_i}{\delta V_k},i\in\mathcal{L}$	Singularity of Jacobian matrix	$\mathbb{J}_i\to+\infty\ at\ VC$
dQ_L/dQ_G index		$\mathbb{K}_i\triangleq\sum_{k\in\mathcal{G}}\frac{\delta Q_k}{\delta Q_j},i\in\mathcal{L}$		$\mathbb{K}_i\to-\infty\ at\ VC$
P- index	[51]	$P-index_J=\frac{-2\frac{P_{L_j}}{V_j}\frac{dV_j}{dP_{L_j}}}{1--2\frac{P_{L_j}}{V_j}\frac{dV_j}{dP_{L_j}}}$	Load flow Jacobian matrix	$P-index_J<1$

4.5.3. Overall VSI's

The system buses and lines have no bearing on these types of indicators. As a result, the total voltage stability indices can only be used to predict when a system will collapse. They cannot identify weak buses or weak lines. Table 5 (see in Appendix) [52], [100]-[104] lists a few overall indices that have been suggested in the literature.

5. VSI'S UTILISING APPROACHES FOR CYBER-PHYSICAL SYSTEMS AND MACHINE LEARNING APPROACH

Power system stability challenges have recently been addressed using novel monitoring, control, and computation approaches like machine learning (ML) and cyber-physical systems. The works in [105] employed VSI's that were suggested in the works as inputs to an ensemble of machine learning algorithms. Acquiring load ability margin forecasting models. Synchro phasor data can be used to instantly calculate VSIs. In order to deal with instability and facilitate bandwidth allocation, the works in [106] presented an intelligent collaborative balancing mechanism. Occurrences relating to the electricity system. Additionally, it can be used to dynamically define and operate the power system and maintain the best performance of the power system. The method for long-term voltage stability (LTVS) monitoring of the power systems presented in [107] takes advantage of the viability of information of phasor-type to assess the LTVS state.

Li *et al.* [108] provided a more effective approach for stating the ideal composition sites of PMUs, which uses a local index load impedance modulus margin (LIMM) index. The DNN is also used to determine the nonlinear relationship between the operational status of the power system and its corresponding LIMM. As a result, using the state variables for the buses provided by the installed PMUs, the value of the appropriate LIMM may be anticipated. In order to help the system operator, assess the operating environment and take appropriate action, the offered technique increases the LIMM's computation speed and provides real-time estimations of the system voltage stability level [109], [110].

6. CHALLENGES AND DIRECTIONS FOR FUTURE RESEARCH

The operating conditions of the power system are always changing since it is dynamic. System topology, or the linkages between networks, also varies regularly. Uncertainties regarding the sharp increase in electricity demand. The operation of power system components is getting closer to their design limits. Considering the overview of the literature survey on integration of highly penetrated renewable energy resources with the grid, several possible challenges and directions for future research are listed below:

- High penetration of renewable energy sources adds to power quality and control problems.
- Reactive power management in present day power system is assuming great significance in view of the overloading of transmission lines, unacceptable system voltage profile, high transmission and distribution losses and voltage instability/collapse.
- For a system to maintain a desirable voltage profile, to reduce transmission and distribution losses and to prevent voltage instability/collapse, timely reactive power planning and efficient scheduling is necessary.
- Voltage stability analysis with integration of high penetration of renewable energy sources.
- Requirement of Proper mathematical modelling of transmission and distribution networks.
- Voltage stability of specific grid-feeding converter applications, i.e., wind farm, PV solar, and HVDC links.
- In terms of objective function in optimization problem, the objectives considered in most studies are active power loss and voltage magnitude. The voltage stability problem has not been thoroughly studied.
- Monitoring of voltage stability online. Online power system stability evaluation has been implemented using machine learning-based data-driven approaches thanks to the implementation of PMU.
- Most studies have not taken into account the payment for ancillary services related to reactive power, which is not included in deregulated electricity markets with multiple market participants. Designing the reactive power market while taking into account the participation of renewable energy sources is a challenge.
- Identifying long term voltage stability caused by distribution systems vs transmission systems.
- Over-voltages due to large penetration of PVs. This can be solved by coordinated operation of multiple lead–acid battery ESS’s.
- Design of controller for fast reactive power compensation.
- Agent-based identification and control of voltage emergency situations.
- Optimal setting of reactive compensation devices to enhance voltage stability.
- Long term voltage stability with integration of wind energy system.
- Short-term voltage stability in the presence of VSC has been comparatively less investigated.
- Local identification of voltage instability from load tap changer response.
- Impact of electric vehicle fast charging on power system voltage stability.
- Development of a new voltage stability index.
- Event generated var and voltage control method for power grids with connection of large-scale renewable energy resources such as wind and solar.
- Application of big data techniques.
- Design of reactive power market considering participation of renewable energy resources.

7. CONCLUSION

In the paper various voltage stability indices have been reviewed. The maximum power transfer theorem, the existence of solutions to the voltage equation, the Jacobian matrix, the P-V curve, the Lyapunov stability theory, and the existence of solutions to the voltage equation are all these concepts that were taken into consideration when reviewing the voltage stability index in this paper. The majority of voltage stability indices are based on the idea that the voltage equation must have a solution. On the basis of line, bus, and overall indices, another categorization of voltage stability indices was created. It was suggested that the basic line and bus indices can be utilized to raise the precision and shorten the running time of the DG placement and sizing challenges, voltage security assessment, renewable energy integration, online monitoring of the power system and shedding of load. Also, the challenges and directions for future research have been discussed.

APPENDIX

Table 5. Overall voltage stability index

Index	Reference	Expression	Concept used	Stability condition
Voltage instability proximity index	[52]	$VIPI = \cos^{-1}\left\{\frac{y_s^T y(a)}{\|y_s\|\|y(a)\|}\right\}$	Feasible solution of Power flow equations	$VIPI > 0$
Sensitivity matrix	[100]	$S_{Q_g q} = -\varphi_Z^T(\varphi_Z^T)^{-1}\nabla_Z Q_g$	At voltage collapse point Sensitivities turn out to be infinite	$S_{Q_g q} > 0$ At VC $S_{Q_g q}$ changes sign through infinity
Area of voltage stability region	[101]	$AVSR = \int_{P_l}^{P_n}[Q(P) - Q_l]dP$	Possible solution of Power flow equations	$AVSR > 0$
Network sensitivity approach	[102]	$SG_p = \frac{P_{gt}}{P_{dt}}$ $SG_q = \frac{P_{gt}}{Q_{dt}}$	P-V curve	$SG_p \rightarrow \infty\ at\ VC$ $SG_q \rightarrow \infty\ at\ VC$
Voltage instability monitoring index	[103]	$VIMI_k = W_1(k)\frac{DFR_k}{DFR_{max}} + W_2(k)\frac{CVD_k}{CVD_{max}}$	Voltage deviation and consecutive voltage deviation	$VIMI_k < 1$
VSI	[104]	$VSI = \min\left(\frac{P_{max}-P}{P_{max}}, \frac{Q_{max}-Q}{Q_{max}}, \frac{S_{max}-S}{S_{max}}\right)$ $P_{max} = \frac{QR}{X} - \frac{V_S^2 R}{2X^2} + \frac{\|Z_{th}\|V_S\sqrt{V_S^2-4QX}}{2X^2}$ $Q_{max} = \frac{PX}{R} - \frac{V_S^2 X}{2R^2} + \frac{\|Z_{th}\|V_S\sqrt{V_S^2-4PR}}{2R^2}$ $S_{max} = \frac{V_S^2[\|Z_{th}\|-(sin(\theta)X+cos(\theta)R)]}{2\,(cos(\theta)X-sin(\theta)R)^2}$	PMU	System is unstable if the VSI is 0 and 1 when stable

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