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Voltage stability indices–A comparison and a review

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ABSTRACT

The increasing integration of renewable energy sources (RESs) into the power system, rapid load changes, and increasing power demand create problems for the stability of power systems. Therefore, the voltage stability index (VSI) becomes an important indicator of power system stability. This paper provides a comprehensive overview of most VSIs and a wealth of resources for researchers, students, and employers. For each VSI, list data such as name, abbreviation, calculation method, assumptions, the basic concept, steady-state, threshold, instability, pros, and cons are discussed in detail. Also, the paper describes the relationship between RESs, load changes, and VSI, and it investigates the stability issues of the power system. The significant outcome of this comprehensive review is to provide a good foundation for future work in this field and helps professionals to choose the best VSI that meets their needs for various applications.

1. Introduction

The phenomenon of voltage instability is one of the most important phenomena that negatively impact the electrical network, as it causes a considerable proportion of blackouts in the world. Studies [1,2] pointed out that most of the blackouts occurring between 1965 and 2015 were caused by voltage instability. Voltage stability in a power system can be described by voltage stability indices (VSIs). Voltage stability has several different definitions. According to the IEEE/GIGRE joint working group [3], voltage is stable in a power system that maintains stable voltages at all buses under the given initial operating conditions after disturbance. Meanwhile, in China (DL755–2001) [4], a power system is regarded as stable if the system's voltage remains within the permitted limit or can get back to the acceptable range after a small or large disturbance i.e., no voltage collapse occurs. The IEEE [5] defines voltage stability as the ability of the electrical power network to keep on the voltage within allowed limits by controlling the power and voltage: when the admittance of the load is increased, the power of the load will also be increased. Voltage instability occurs when the power system cannot keep the voltage between limits if demand for reactive power in the loaded system occurs. The main reasons affecting voltage instability are faults in the power system components such as generators, power transformers, and transmission lines. The electrical companies take various countermeasures to avoid voltage instability [6], listed below.

1 System reinforcement: construction of generation stations near the load center and the transmission lines, series compensation, and shunt compensation.
2 Devices and controller: voltage control, control of generator step-up transformers, line drop compensation in automatic voltage regulators (AVRs), and automatic shunt compensation switching.

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3 Real-time operation: voltage security assessment, generation rescheduling, and load shedding protection.
4 Protection systems: modulation of high voltage direct current (HVDC), emergency control for load tap changer (LTC), and contingency of load shedding.
5 Flexible AC transmission system (FACTS) devices.

Voltage stability indices play an important role in exploring and specifying the state of power system operation. Besides that, they help foresee a prospective change in the future and assess the overall long-run progress [7]. Moreover, VSIs have a vital role in identifying the best size and the preferred location of the distributed generations (DGs) [8] and FACTS devices [9] by specifying the weakest bus and the weakest line. Voltage stability indices (VSIs) can be used in three modes. The first one is an online mode: the operator can monitor the value of VSIs and take suitable action to keep the system stable. The second is an offline mode used by the designer for power system stability studies. The third mode is a real-time method in which a phasor measurement unit (PMU) delivers the required information.

Many VSIs have been offered in the literature to estimate the power system voltage stability. Some papers introduced a comparison between the VSIs [10, 11]. However, the following data for each stability index: name, abbreviation, calculating method, assumptions, the main concept, stable condition, critical value, unstable condition, advantages, and disadvantages have not been wholly discussed before. Moreover, it discusses the relationship between renewable energy sources, load changes, and VSIs. In addition to that, the review results can be used to have an overall idea about the utilization of VSIs in different applications. The reader can decide which direction is ok and which dead-end trends are related to his application. Therefore, the main contributions of this paper are as follows.

- It presents the challenges for power system stability.
- It discusses the relationship between renewable energy sources, load changes and VSIs.
- It presents VSIs in distributed energy sources (DESs) placement and sizing.
- It discusses the application of VSIs in the various power system problems.
- It enlists the following data for each VSI: name, abbreviation, calculating method, assumptions, the main concept, stable condition, critical value, unstable condition, advantages, and disadvantages.
- It introduces a comprehensive review of 49 types of VSIs.
- It provides a rich source for researchers, students, and employers regarding VSIs.

This paper is organized as follows: Section II presents the relation between VSIs and the integration of renewable energy sources into the electricity grids. Section III investigates the integration of renewable energy systems and challenges for voltage stability. The relation between load changes and voltage stability is discussed in section IV; section V presents the classification of VSIs, section VI shows different types of VSIs. The comprehensive review of VSIs is listed in section VII. Meanwhile, section VIII shows the relation between VSIs and machine learning and cyber-physical system techniques. Finally, the conclusion is presented in section IX.

2. The relation between VSIs and the integration of renewable energy sources into the electricity grids

The integration of renewable energy sources (RESs), also known as renewable distributed generators (RDGs), continuously increases the electricity grid. This type of electricity production is preferred because of its availability and environmental benefits. However, RESs negatively influence the voltage stability of electrical power systems, especially if penetration is high, due to the variability of the primary resource and the characteristics of a grid connection based on power electronics. The high penetration of RESs and the increase of energy consumption make voltage stability a vital issue to ensure secure planning and operation in the electricity grids. The matching between the energy demand and the generated energy is crucial in power system stability. Voltage stability issues appear when a mismatch occurs between generation and demand. Voltage instability appears by a decrease or an increase in different voltage buses. When the voltage at any bus drops fast, the affected bus reaches the critical point. To exploit the advantages of RESs and avoid their harmful effects on the power system network, the optimal location of the RESs integration into the grid should be achieved. Therefore, the VSIs are very important to identify the weakest lines and buses. Simple and accurate VSIs are very effective, as they avoid complexity and long running time. As in [12], the voltage sensitivity index is used with the wind farm placement index to specify a weak bus.

3. Integration of renewable energy systems and challenges for voltage stability

RESs are becoming the main contributors to our power systems. However, their integration will still lead to considerable technical challenges in the distribution and transmission systems concerning operational aspects and planning. These factors directly affect voltage stability, which is considered a significant side of RESs integration. The integration of RESs was discussed first by [13]. The authors in [14,15] presented a comprehensive review of the integration of RESs into the power system and its influences on stability, the market, and the economy. As [16] point out, distributed resource management executed with VSIs, the dispatch of wind and solar resources, and energy storage could partially alleviate some of these challenges. The most important and widespread RESs are photovoltaic (PV) and wind energy systems, which depend on natural resources and offer green energy. However, as these natural resources are unpredictable and non-controllable, their power generation is intermittent, which leads to fluctuations in the voltage and frequency of the power system. More energy sources are required to ensure the matching between load and supply to mitigate the output power fluctuation. At the same time, reactive power control is responsible for smoothing voltage variation. There are many

methods for voltage control.

i) **The conventional method** relies on the reactive power compensation concept. This solution uses advanced technologies of power electronic and innovative designs, such as the FACTS devices. The FACTS technology includes several devices, including a static synchronous compensator (STATCOM), a dynamic distribution system compensator (DDSC), a power filter compensator (PFC), a distribution static synchronous compensator (D-STATCOM), a thyristor controlled series capacitor (TCSC), a thyristor controlled series reactor (TCSR), a thyristor switched series capacitor (TSSC), a static synchronous series compensator (SSSC), a static VAR compensator (SVC), a thyristor controlled reactor (TCR), a thyristor switched capacitor (TSC), and a thyristor switched reactor (TSR), which are used to enhance the stability issues in the presence of RESs [17,18].
ii) **The virtual synchronous machine method (VSM)**: as the power condition systems play the role of an interface between the RESs and the grid, which are considered as static devices, to overcome this problem, a VSM is proposed to reduce voltage and frequency fluctuations and achieve RES integration, as first proposed by [19].
iii) **Combination of the VSM and reactive power compensation**. The authors of [20] proposed a VSM-based STATCOM with high penetration of RESs, which operates as a variable synchronous condenser based on virtual impedance and virtual inertia. They compared this method and the conventional method (STATCOM based D-q frame) and found the first one is superior.

4. Load changes and voltage stability

The mismatch between load and generation as a result of load changes and the growth of technology leads to instability in the voltage of the power system. The analysis of the PV curve can be utilized to set the actual system load-serving capability, where the voltage values sketch with the increasing load demand to find the maximum margin of real power transfer [21]. The reactive power-voltage (QV) curve analysis can define the reactive power margin. Also, with the increase of the on-load tap changing transformer (OLTC) ratio, the maximum reactive power increases, and the probability of the collapse of the system voltage decreases at the same loading conditions [22]. Moreover, one of the best accurate methods for the evaluation of voltage stability is the continuation power flow (CPF), which includes an efficient power flow equation to overcome the issues of convergence near the stability margins and to connect bus voltage and loadability [23,24].

5. Voltage stability indices in distributed energy sources placement and sizing

Owing to the great integration of the distributed energy sources (DESs) into the modern power system, the DESs become responsible for the security and stability of the power system. Mainly, DESs are used to enhance the traditional power system and face the increase in load demand, which have various types such as solar energy, fuel cells, wind turbines, small hydro-power, and biomass, etc. [25]. DESs have a lot of benefits for the power system like decreasing network losses, enhancing the power factor, minimizing and maintenance operating costs, improving the power system stability and reliability, improving voltage profile [26, 27]. However, the unsuitable selection of the DESs location and sizing leads to unexpected side effects that contrast with their benefits. Therefore, it has become urgent to solve the problems of the DESs integration to avoid its side effects. The DESs issues solution is based on two categories; the first one is related to the optimization-based methods such as ant lion optimization (ALO) algorithm [28], the backtracking search optimization (BSO) algorithm [29], a column and constraint generation (CCG) [30], hybrid particle swarm optimization (HPSO) algorithm [31], and stud krill herd (SKH) algorithm [32]. The second category is related to the analytical methods like loss formula [33], improved analytical (IA) technique [34], power stability index (PSI) [35], VSI [35]. Due to the high accuracy of the VSIs, the DESs can be located and sized in a better solution by taking into consideration the simplicity of the VSIs to reduce the complexity and running time. So, the VSIs have many applications and classifications in power systems that will describe in the VI and VII sections, respectively.

6. Application of VSIs in the various power system problems

The weather variations in the overall world led to high harmful effects on the electrical power systems where most of the RESs depend on the weather, such as wind and PV systems. Moreover, the excessive developments in the world lead to an increase in electricity demand. Therefore, most of the power system network is operating near the total capacity, and consequently, the security and stability of the power system are located in an unsafe region. So, one of the most critical applications of the VSIs is to preserve the stability of the power system to avert the occurrence of major blackouts [36]. Moreover, it provides online monitoring and control power systems to obtain real data. In addition, VSIs are utilized in interconnection power systems and to recognize voltage stability weak buses, coherent load set, and coherent generator set of a weak bus [37]. Also, it is used to reduce transmission line losses, improve the active and reactive power performance [38]. Moreover, section IX presents a comprehensive review of voltage stability indices with the different concepts based on the targeted application.

7. Classification of voltage stability indices

The VSIs can be categorized into two main groups [39]: (i) the system variables-based and (ii) the Jacobian matrix-based types as listed in Table 1.

8. Voltage stability indices

This section will introduce and discuss the various types of VSIs by explaining the main idea, equations, assumptions, and stable and unstable points. In general, most of the VSI calculations are derived from the two bus representation models [40]. Fig. 1 illustrates a two-bus model diagram.

1. Line stability index (Lmn)

Twenty years ago, M. Moghavvemi and F. M. Omar suggested a Line stability index *(Lmn)*. The proposed technique is verified on the system of 24-bus IEEE [41]. The main concept of the *Lmn* relies on the power transfer in the line. Eq. (1) expresses the line stability index.

$$L_{mn} = \frac{4X_{ij}Q_j}{\left[V_i \sin\left(\theta_{ij} - \delta_{ij}\right)\right]^2} \tag{1}$$

The forecasting occurrence of instability in the power system performed can be defined when the *Lmn* is the closest to unity; whenever *Lmn* has a value (>1.0), it's better to maintain the stability condition. *Lmn* is utilized to find the weakest bus in an IEEE 30-bus test system [42]. Then FACT devices with their different types such as hybrid, shunt, and series components are linked to the weakest bus to improve voltage stability.

2. Line stability index (Lp)

The line stability index *(Lp)* was presented by M. Moghavvemi and M. O. Faruque in 2001, and the suggested method is applied on 12-bus and 27-bus radial systems [43]. This technique is used with a radial distribution system by reducing it to two bus systems and representing a π equivalent model. The *Lp* is expressed in Eq. (2).

$$L_p = \frac{4R_{ij}P_j}{\left[V_i \sin\left(\theta_{ij} - \delta_{ij}\right)\right]^2} \tag{2}$$

The value of *Lp* can be between 0 and 1. When the *Lp* is near zero, the system is stable. In contrast, when the *Lp* is near 1, it indicates that the system is in an unstable state.

3. Novel line stability index (NLSI)

In [44], the authors proposed a modification to the *Lp*, which neglects the shunt admittance and assumes that the value of the angle difference between the voltage angle at the sending bus and the voltage angle at the receiving bus is very small ($\delta \approx$ zero). The proposed method was applied to a 30-bus system, and active and reactive powers were considered. Whenever the NLSI value is near 1, the line approaches the stability limit, leading to instability.

$$NLSI = \frac{R_{ij}P_j + X_{ij}Q_j}{0.25V_i^2} \tag{3}$$

4. Stability index (SI)

The authors in [45] deduced stability index *(SI)* relying on the quadratic voltage equation at the sending and receiving ends of the bus, and power at the receiving end of the branch, as shown in Eq. (4). If neglecting shunt admittance, the stability index for radial distribution systems can be deduced as expressed in Eq. (5) [46]. When the value of *SI* equals 0, the power system will reach an instability state.

$$SI = V_i^4 - 4\left\{P_jR_{ij} + Q_jX_{ij}\right\}V_i^2 - 4\left\{P_jX_{ij} - Q_jR_{ij}\right\}^2 \tag{4}$$

$$SI = 2V_i^2V_j^2 - V_j^4 - 2V_j^2\left(P_jR_{ij} + Q_jX_{ij}\right) - Z_{ij}^2\left(P_j^2 + Q_{ij}^2\right) \tag{5}$$

In [47], a probabilistic index is proposed to define the probabilistic distance of each bus to voltage instability. Thus, the VSI in Eq. (4) can be linearized near the expected values of voltage and power of buses. In the first part of the *SI*, the linearized part will become as Eq. (6), where V_{i0} is the predicted voltage value at bus *i*.

$$V_i^4 \cong 4V_iV_{i0}^3 - 3V_{i0}^4 \tag{6}$$

5. Fast voltage stability index (FVSI)

Fast voltage stability index (*FVSI*) is deduced by obtaining the equation of the line current in the two-bus system and taking the following assumptions ($\delta_{ij} \approx 0$; $R_{ij} \sin \delta_{ij} \approx 0$; $X_{ij} \cos \delta_{ij} \approx X_{ij}$). When the value of *FVCI* excesses 1, an unexpected sag in the voltage will

Table 1
Major VSI types.

Jacobian matrix-based	System variables-based
Offline purpose	Online purpose
Used by designer	Used by operator
Based on Jacobian matrix modifications	Based on bus and line elements
High computational requirements	Low computational requirements
Compute the point nearest the voltage collapse margins	Compute the weakest area

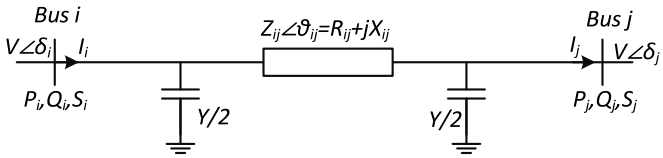


Fig. 1. Two-bus model representation.

occur, which leads to collapse phenomena in the system. Eq. (7) presents the *FVSI* [48,49]. If the assumptions above are not considered as presented in [50], the equation will be extended to (8).

$$FVSI = \frac{4Z_{ij}^2 Q_j}{V_i^2 X_{ij}} \tag{7}$$

$$FVSI = \frac{4Z_{ij}^2 Q_j X_{ij}}{V_i^2 \left(R_{ij}\sin\delta_{ij} + X_{ij}\cos\delta_{ij}\right)^2} \tag{8}$$

FVSI is used to define the weakest bus in the IEEE 30-bus, and the FACT compensators are connected to this bus to improve voltage stability [42].

6. Voltage stability index (VSI)

The voltage stability index *(VSI)* depends on linear extrapolation to evaluate the margin to voltage instability using the information of load current and bus voltage magnitude. The *VSI* formula can be written as (9). The proposed method was verified on the IEEE 30-bus system. The VSI of (7) falls between unity at no load and zero at a collapse event [51].

$$VSI_i = \left[1 + \left(\frac{I_i}{V_i}\right)\left(\frac{\Delta V_i}{\Delta I_i}\right)\right]^{\alpha} \tag{9}$$

The authors in [52] proposed another VSI, which forecasts voltage stability limits at the steady-state. The proposed method begins by calculating three kinds of maximum transferable power by Eqs. (10) to (12) (real, reactive, apparent power) of a single electrical power system source, where φ is the load angle, Q and P are reactive and load active power, respectively. In this index, the VSI_i can be changed to VSI_x to prevent ambiguity. With the expected $Q_{\max}$, $P_{\max}$, and $S_{\max}$, three load margins (P_{margin}, Q_{margin}, and S_{margin}) can be computed with (13) – (15), and the VSI_x by (16), respectively. The line resistance and the shunt admittance of the line are ignored in this index. If the VSI_x value is greater than zero, the system will stabilize.

$$P_{Max} = \sqrt{\frac{V_i^4}{4X_{ij}^2} - Q_j\frac{V_i^2}{X_{ij}}} \tag{10}$$

$$Q_{Max} = \frac{V_i^2}{4X_{ij}} - \frac{P_j^2 X_{ij}}{V_i^2} \tag{11}$$

$$S_{Max} = \frac{(1-\sin\varphi)V_i^2}{2\cos\varphi^2 X_{ij}} \tag{12}$$

$$P_{Margin} = P_{Max} - P \tag{13}$$

$$Q_{Margin} = Q_{Max} - Q \tag{14}$$

$$S_{Margin} = S_{Max} - S \tag{15}$$

$$VSI_x = \min\left(\frac{P_{margin}}{P_{Max}}, \frac{Q_{margin}}{Q_{Max}}, \frac{S_{margin}}{S_{Max}}\right) \tag{16}$$

In [53], the line shunt admittances and the voltage angle are negligibly small so that the VSI_y can be calculated from Eq. (17). The index is distinguished from VSI_x by lower index y. When $VSI \leq 1$, the power system will be stable, but if the value of *VSI* exceeds unity, the system will be unstable.

$$VSI_y = \frac{4Q_j\left[R_{ij} + X_{ij}\right]^2}{X_{ij}\left[V_i^2 + 8R_{ij}Q_j\right]} \tag{17}$$

7. Improved voltage stability index (IVSI)

Relying on the solutions of power flow and variables, the authors in [54] proposed an *IVSI* formula as in Eq. (18) to enhance the stability of the power system. The total voltage stability index $IVSI_T$ is another index for all buses used to evaluate the total stability for the power system with compensation strategies (19). The stability state is achieved when the *IVSI* is close to zero, but when the *IVSI* is

close to unity, the system will be unstable.

$$IVSI = \frac{-4\sum_{j=0}^{n}\left(G_{ij}-B_{ij}\right)\left(P_i+Q_i\right)}{\left[\sum_{j=1}^{n}V_j\left[G_{ij}\left(\cos\delta_{ij}+\sin\delta_{ij}\right)-B_{ij}\left(\cos\delta_{ij}-\sin\delta_{ij}\right)\right]\right]^2} \tag{18}$$

$$IVSI_T = \sum_{i=1}^{N} IVSI_i \tag{19}$$

8. New (Novel) voltage stability index (NVSI)

The new or novel voltage stability index presented in [55] is similar to *Lp,* and neglects resistance and shunt admittance. Eq. (20) shows the *NVSI*. The transmission line will be stable as long as the value of *NVSI* is less than unity.

$$NVSI = \frac{2X_{ij}\sqrt{P_j^2+Q_j^2}}{2Q_jX_{ij}-V_i^2} \tag{20}$$

9. Voltage stability margin (VSMs)

When the permissible system load power rises from the current operating mode to the critical mode is defined as *VSM* [56]. The *VSM* can be defined as the margin of apparent load power (21). When the load power equals the maximum load value (critical point), the formula of *VSM* becomes as in [57]. There are two assumptions: (i) the shunt admittance of the line is ignored, and (ii) the power factor is constant. The system will be unstable when the apparent load power is more than the critical load apparent power; in other words when the *VSM* value is less than zero.

$$VSMs = \frac{S_{cr}-S_l}{S_{cr}} \tag{21}$$

10. Voltage stability margin index (VSMI)

The voltage stability margin index *(VSMI)* relates the reactive and active power transfers, which are represented by P_{Margin} and Q_{Margin}, respectively. These show the ability of the network to transfer the available power without any effect on the stability state. The calculation of *VSMI* is based on the maximum power transfer rates. The *VSMI* is presented in reactive, active, and apparent power expressions and shows the value of loads to avoid voltage instability in the power system [58]. Continuously, the decentralized load shedding strategy is used to calculate the *VSMI* to follow the voltage stability limit at the individual level of the load bus. When the voltage stability conditions are below a threshold, the system will deliver an alarm signal and execute load shedding.

$$P_{Margin} = P_{Max} - P_l \tag{22}$$

$$Q_{Margin} = Q_{Max} - Q_l \tag{23}$$

$$S_{Margin} = \sqrt{P_{Max}^2+Q_{Max}^2} - P_l \tag{24}$$

In another definition for the *VSMI,* [59] relies on the link between line maximum power transfer and δ_{ij}, as expressed in Eq. (25). The shunt admittance is neglected in this reference. For the stable condition, the value of *VSMI* should be larger than zero.

$$VSMI = \frac{\delta_{ij,\,Max}-\delta_{ij}}{\delta_{ij,\,Max}} \tag{25}$$

11. Modified voltage stability indices (MVSI)

The modified voltage stability indices (*MVSI*) are defined by authors in [60], which deal with the load buses in the transmission network. Eq. (26) calculates the *MVSI* where $\sin\delta_{jj}$ is the phase angle of the load bus. When the *MVSI* value equals to or is greater than unity, the load bus will be unstable.

$$MVSI_j = \frac{4\left(Q_jY_{jj}\sin\delta_{jj}\right)}{\left(\sum_{i=1,\ i\neq j}^{N}V_iY_{ij}\right)^2} \tag{26}$$

12. Voltage Collapse Index (VCI)

The *VCI* formula is similar to VSI_i with little difference. It changes the apparent power of the power system by Taylor's theorem [51].

$$VCI_i = \left[1+\left(\frac{I_i\Delta V_i}{V_i\Delta I_i}\right)\right]^{\alpha} \tag{27}$$

The authors in [61] proposed two methods with linear properties of voltage stability. They used a set of line-wise power equations and its line *VCI*. Both modes have a full non-linear formulation of voltage stability, incorporating line-wise optimal power flow (LWOPF). The two models utilize the *VCI* in a different manner. In the first model (Model #1), *VCIs* are expressed as a set of constraints for voltage stability as in Eq. (28), where *l* is the index of branches, and *NT* is the number of branches. The second model (Model #2)

maximizes the voltage collapse indices, so *VCIs* are expressed as an objective function, as in Eq. (29).

$$Min\ (VCI_l) \geq (VCI_{limit})\ \forall\ l \in NT \tag{28}$$

$$Max\ \sum_{l=1}^{NT}(VCI_{il})\ +\left(VCI_{jl}\right) \tag{29}$$

13. Equivalent node voltage collapse index (ENVCI)

The *ENVCI* is based on the equivalent system model (*ESM*) and phasors of local voltage [62]. The *ENVCI* has a lot of merits, such as accuracy in calculations and modeling, and it is suitable for both online and real-time applications. Furthermore, the *ENVCI* can define the weakest bus and voltage collapse point when close to zero.

$$ENVCI\ =\ 2V_iV_j\cos\delta_{ij} - V_j^2 \tag{30}$$

14. Voltage collapse proximity indicator (VCPI)

The main idea of *VCPI* is connected to the concept of maximum power transfer in the line, which is proposed by authors in [63]. The active and reactive powers are defined in the following equations:

$$VCPI_1\ =\ \frac{P_j}{P_{j,\ Max}} \tag{31}$$

$$VCPI_2\ =\ \frac{Q_j}{Q_{j,\ Max}} \tag{32}$$

$$VCPI_3\ =\ \frac{P_l}{P_{l,\ Max}} \tag{33}$$

$$VCPI_4\ =\ \frac{Q_l}{Q_{l,\ Max}} \tag{34}$$

Where the values of P_j, Q_j, and P_l and Q_l are calculated from power flow solutions. The authors conclude that $VCPI_1 = VCPI_2$ and $VCPI_3 = VCPI_4$, so two indicators can be considered.

15. Predicting voltage collapse index (V/Vo)

This index depends on the relation between the voltage magnitude *(V)*, which the load flow can determine at the operation point of the power system, and the no-load voltage *(Vo)*, which can be obtained at no-load condition [64]. The *PVCI* can present an overall picture of the performance of the system stability. When this index has a small value, it indicates the weak bus in the system.

16. Voltage collapse prediction index (VCPI), and voltage collapse prediction index for buses (VCPIbus)

V. Balamourougan and et al. [65] suggested the voltage collapse prediction index *(VCPI)*. This index is based on the information of voltage angle and magnitude of buses and the admittance matrix to expect voltage collapse. This technique is suitable for real-time applications and is computationally efficient. The stable condition will be achieved when the index value equals zero. The unstable condition occurs when the index value equals unity.

$$VCPI_{j,\ bus}\ =\ \left|1 - \frac{\sum_{\substack{i\ =\ 1 \\ i \neq j}}^{n} \dot{V}_i}{V_j}\right| \tag{35}$$

17. Line collapse proximity index (LCPI)

The concept of *LCPI* relies on the transmission line parameters as expressed in (36) [66]. The expression of *LCPI* is as (37), where α is the A part phase angle and β is the B part phase angle. The *LCPI* value lies between zero at no load and unity at instability conditions.

$$\begin{bmatrix} V_i \\ I_i \end{bmatrix}\ =\ \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} V_j \\ I_j \end{bmatrix} \tag{36}$$

$$LCPI\ =\ \frac{4A\cos\alpha\ \left(P_jB\cos\beta + Q_jB\sin\beta\right)}{\left(V_i\cos\alpha\right)^2} \tag{37}$$

18. Voltage instability proximity index (VIPI)

The voltage instability proximity index *(VIPI)* is proposed for predicting voltage instability, based on the association among several load flow solutions and voltage instability, where Y_s and *Y(a)* are the specified value and the critical vector, respectively, and θ is the angle between them [67].

$$VIPI\ =\ \theta\ =\ \cos^{-1}\frac{Y_s^T Y(a)}{\|\ Y_s\ \|\ \|\ Y(a)\ \|} \tag{38}$$

19. Voltage stability load index (VSLI)

The voltage stability load index *(VSLI)* formula is obtained from a two-bus system and the Thevenin equivalent circuit *(TEC)*, which is related to load bus as indicated in Eq. (39) [68]. The *PMU* and Echo State Network *(ESN)* are utilized to estimate the *VSLI* [69]. If the value of *VSLI* is below the unity, the system will be stable; while if the *VSLI* exceeds the unity, the system will be unstable. The IEEE 9 and 24 bus are used to validate this index; the line shunt admittances are neglected.

$$VSLI = \frac{4\left[V_i V_j \cos\delta - V_j^2 \cos\delta\right]}{V_i^2} \tag{39}$$

20. The Voltage Stability Load Bus Index (VSLBI)

The main concept of the voltage stability load bus index (VSLBI) is the value of voltage drop through the transmission line impedance, equal to the load bus's voltage value at maximum power conditions. Eq. (40) expresses the *VSLBI* [70], and this value is more than unity; the stable condition will be achieved and vice versa.

$$VSLBI = \frac{V_j}{\Delta V_{ij}} \tag{40}$$

21. The line stability factor (LQP)

The line stability factor *(LQP)* is offered by [71]. The main idea of *LQ* relies on the voltage quadratic and power flow equations. The stable condition is achieved when the *LQP* value is less than unity, the shunt admittance of the line is neglected, and the line is assumed lossless.

$$LQP = 4\left(\frac{P_i^2 X_{ij}}{V_i^2} + Q_j\right)\left(\frac{X_{ij}}{V_i^2}\right) \tag{41}$$

22. Participation factor (PF)

The participation factor *(PF)* is used as the bus participation factor *(BPF)*, which provides the data on the compensation of reactive power, which is required to adjust the bus voltage [72]. The branch participation factor *(BrPF)* indicates which branches have a strong participation factor behavior over the other branches. This shows which branches demand the largest reactive power for each mode due to a modal increment of the reactive load [73]. In order to compute the support of the critical mode of Jacobian power flow in the system states, the state-in-mode participation factor *(SIMPF)* is used as an index in reference [74].

23. Voltage stability factor (VSF)

The definition of voltage stability factor *(VSF)* is the relation between incremental change in the AC voltage as per unit and the incremental change in reactive power as per unit at constant DC power (42)[75]. The sign of the *VSF* indicates the operating mode, where the positive sign refers to stable mode, while the negative sign refers to the unstable mode.

$$VSF = \frac{\Delta V}{\Delta Q}\Big|_{P_d} \tag{42}$$

From the above equation, the authors improved the *VSF* to the extended voltage stability factor *(EVSF)*, which needs the relation among the voltage and reactive power of dynamic reactive sources. Also, it needs to multi-infeed *HVDC* [76]. *VSF* for the system of single-infeed *VSC—HVDC* is proposed in reference [77].

$$EVSF_i = \frac{\Delta V_i}{\Delta Q_i}\Big|_{\Delta Q_j = 0 (j \neq i)} \tag{43}$$

24. Voltage active/reactive power index (VPI/VQI)

The voltage active power index *(VPI)* and the voltage reactive power index *(VQI)* are proposed in reference [78]. Some assumptions are made, such as that (i) the power factor and the load at the receiving end are constant; (ii) the voltage angle of the receiving end is relatively small and can be ignored. The values of *VPI* and *VQI* vary between zero and unity. When the value is below unity, the system is stable. However, if its value is above unity, the system is unstable.

$$VPI = \frac{4P_j}{G_{ij} V_i^2} \tag{44}$$

$$VQI = \frac{4Q_j}{B_{ij} V_i^2} \tag{45}$$

25. Voltage deviation index (VDI)

The difference value between the one per unit and bus voltage as a function of per-unit value is known as voltage deviation index *(VDI)* [79]. Eq. (46) calculates each bus separately in the system, but Eq. (47) calculates the overall system buses (*N*).

$$VDI_j = \left|1 - V_j\right| \tag{46}$$

$$VDI_T = \sum_{j=1}^{N} \left|1 - V_j\right| \tag{47}$$

26. Power transfer stability index (PTSI)

The theory of limiting the maximum transferable power in a line is the main idea for the power transfer stability index *(PTSI)* similar to *VCPI*. So the achievement of the *PTSI* in predicting voltage collapse is assessed by comparing it with the *VCPI* [80]. The authors in [81] proposed a *PTSI* based on the Radial Basis Function Neural Network *(RBFNN)*. The stability mode is reached as long as the *PTSI* is less than unity and vice versa.

$$PTSI = \frac{2S_jZ(1+\cos(\Theta-\varphi)}{V_i^2} \tag{48}$$

27. Power stability index (PSI)

The authors suggest the power stability index (PSI) in reference [82] for setting the optimal location of the DG associated with the closest bus from the stability margin, which leads to instability mode as the load increases above the defined limit. This index is based on the two-bus systems as in Eq. (49). During stable operation, the index value will be less than one. Meanwhile, the system will be more stable if this value is closer to zero.

$$PSI = \frac{4R_{ij}(P_L-P_G)}{\left[V_i\cos\left(\theta-\varepsilon_{ij}\right)\right]^2} \tag{49}$$

28. L-index

The L-index concept depends on the power flow solution and two-bus systems with analytical analysis as in Eq. (50) [83]. The L-index value is between 0 (stable condition) and 1 (unstable condition). The F_{ij}expresses the matrix F: i th column and j-th row. Its elements are created from the Y matrix method, α_L and α_G are a set of buses of consumer and generator, respectively. In reference [84], the improvement has been made on L-index to examine the effect of the load model. The L-index is used with the AC/DC power system by considering the accurate equivalent model of the converter [85]. The L-index is used to limit the voltage of buses and incorporated with the Transmission network expansion planning problem *(TNEP)* [86]. The impacts of STATCOM and load tap changing transformer *(LTCT)* are validated on the values of the L-index of the load nodes and the minimum acceptable load of each node of the electrical system [87].

$$L = \underset{j\in\alpha_L}{MAX}\left|1-\frac{\sum_{i\in\alpha_G}F_{ij}V_i}{V_j}\right| \tag{50}$$

29. S difference criterion (SDC)

The algorithm of *SDC* uses the local phasors' magnitudes and angles. The main idea of *SDC* is based on the variation in *S* through a time interval; it is used for calculating the value of the voltage-collapse [88]. This concept is based on the losses amount of the line, which increases faster than the speed of sending the apparent power amount in the nearest location from voltage collapse. Moreover, the increased power is consumed by the losses at the voltage collapse point.

$$SDC = \left|1+\frac{\Delta V_jI_{ij}^*}{V_j\Delta I_{ij}^*}\right| \tag{51}$$

30. Impedance matching stability index (ISI)

Based on Tellegen's rule, the impedance matching stability index is proposed by authors in [89], making the calculation of Thevenin's parameters simple. Therefore, at normal operation load, the values of ISI are around unity; meanwhile, at the point of voltage-collapse, the ISI value diminishes to zero. The real-time voltage stability assessment technique based on measurements of PMU in distribution systems is introduced in [90] with *ISI*.

$$ISI = \frac{Z_L-Z_{th}}{Z_l} \tag{52}$$

Where $Z_L = \frac{V_j}{I_j}$, $Z_{th} = \frac{\Delta V_j}{\Delta I_j}$, ΔIr and ΔVr are the current and voltage changes between the two sequential samples computed by PMU at the receiving bus.

31. Impedance ration indicator

The impedance ration indicator measures system stability issues using the Thevenin theorem for two bus models. The index equation is applied as (53) [91]. For secure operation, the index should be less than unity.

$$Impedance\ Ration\ Indicator = \frac{Z_{th}}{Z_L} \tag{53}$$

32. $Z_L = Z_S$ ratio

This index is based on the fact that the electrical network has the maximum power when the impedance of Thevenin (Z_S) is equal to the impedance of the load. It can be computed as in Eq. (54). The voltage stability margin control has various cases [92]. When the level of the stability margin is low in the normal operation case, the alarm should be operated. If this level continues to drop and becomes equal to 2–2.5, the tap-transformer should be stopped. Load shedding should be set if this level still decreases and drops to 1.5–2. So the index should be kept more than one for stable mode.

$$\frac{Z_L}{Z_S} = \frac{M+1}{-M\cos(\phi_S-\phi_L)+\left[(M\cos(\phi_S-\phi_L))^2-M^2+1\right]^{0.5}} \tag{54}$$

Where φ_S,φ_L are the phase angles of Z_S and Z_L, respectively, and M is the relation between S and ZL changes.

33. Simplified Voltage Stability Index (SVSI)

The main idea of this index is based on Thevenin model assumptions and voltage measurements. The main concept used with the *SVSI* is a Relative Electrical Distance *(RED)*. The SVSI is utilized to choose the nearest generator to the load bus and enhance the performance of the electrical factors [39]. *SVSI* at bus *j* is defined as (55), where ΔV_j is the difference between voltage phasors at the specified generator and the load bus, β is the correction factor. The instability state occurs when the value of *SVSI* is equal to one at the specific bus.

$$SVSI_j = \frac{\Delta V_j}{\beta * V_j} \tag{55}$$

34. Network sensitivity approach (SG)

In [93], the authors proposed the network sensitivity approach *(SG)*, whose calculations depend on total active power, reactive power demand, and total active power generation as in Eqs. (56) and (57) and the *P-V* curve. The system reaches its instability point when (56) and (57) increase gradually, which leads to a severe high in the infinite values.

$$SG_p = \frac{P_{gt}}{P_{dt}} \tag{56}$$

$$SG_q = \frac{P_{gt}}{Q_{dt}} \tag{57}$$

35. Sensitivity Analysis (SA)

The sensitivity analysis *(SA)* is used with various indices, and trajectory sensitivities are used in [94]. In the reference [95], the authors derived the L-index sensitivity considering the nodal active and reactive power injections. Then the index can define the amount of emergency load shedding and reactive power compensation to achieve voltage stability. This index is considered a profitable tool for determining the weak nodes and the penetration level of PV systems in the distribution systems, taking into account the capacity of the loads [96,97].

36. Integral steady-state margin (ISSM)

The integral steady-state margin (*ISSM*) is proposed by [98] to recognize the state of the electrical network at a steady-state operation point. Thus, it is used for planning and online security. In the formula below, J_o and J_c are the Jacobian of the system fictitious state and the steady-state, respectively. The margin of stability is between zero and one.

$$ISSm = \left|\frac{J_c}{J_o}\right| \tag{58}$$

37. Critical voltage (Vcr)

Using the eigenvalue theorem and the load flow equations, a critical voltage *(Vcr)* is presented in [99] as given in Eq. (59) and the simplified one in (60).

$$Vcr = \frac{E}{\sqrt{2(1+\cos(\Theta-\phi))}} \tag{59}$$

$$Vcr = \frac{E}{2\cos\delta} \tag{60}$$

Where *Vcr* is the receiving end critical voltage; *E* is the voltage of infinite bus; Θ is the angle of line impedance; δ is the angle of receiving end voltage; φ is the angle of power factor.

38. Line voltage stability index (LVSI)

The quadratic voltage equation is used to derive this index based on *ABCD* parameters, which consider the line's resistance and charging capacitance. So, the *LVSI* estimates exactly the sensitive voltage at any operating conditions and defines the nearest point that will have a voltage collapse [100]. At no load, the value of *LVSI* is equal to 2 (most stable condition), while at the maximum load condition, it is equal to one (voltage collapse state). So, for the system to be in stable condition, the *LVSI* should be more than unity.

$$LVSI_l = \frac{2V_{jl}A_l\cos(\beta_l-\alpha_l)}{V_{il}\cos(\beta_l-\varepsilon_{ijl})} \;\forall\; l = 1,2,3,\ldots N \tag{61}$$

$$LVSI = \max(LVSI_l) \;\forall\; l = 1,2,3,\ldots N \tag{62}$$

39. Minimum eigenvalue and right eigenvector (RE) method

B. Gao and others [101] proposed a technique for the analysis of voltage stability in large electrical networks relying on the particular number of the smallest eigenvalues and the linked eigenvectors of a reduced Jacobian matrix, where these eigenvalues are associated with an approach of voltage/reactive power variation as indicated in Eq. (63). Where ΔV shows voltage magnitudes

deviation; ΔQ is the supplied reactive power deviation; ξ_i is the eigenvector of the ith column to the right; η_i is the eigenvector of the ith row to the left in the reduced Jacobian matrix; λ is the diagonal eigenvalue in the reduced Jacobian matrix. So, the stability of the ith approach depends on the eigenvalue magnitude. When the eigenvalue magnitude is large, minor deviations of the modal voltage for the reactive power variation, the voltage will be stable when the Jacobian eigenvalues are positive. Consequently, the smallest magnitude of the eigenvalue is selected as a fitness function, which requires to be maximized to enhance voltage stability [102].

$$\Delta V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q \tag{63}$$

40. Singular value indicator

The singular value indicator is used with the Jacobian matrix. This index can identify the critical buses and provide information about voltage instability margins. The matrix equations are given in [103]. Three important points for the minimum singular value and the corresponding right and left singular vectors can be considered.

1. The smallest singular value can be used as an index of the closeness to the stability margins.
2. The right singular vector is related to sensitive angles and voltages.
3. The left singular vector is related to the most sensitive direction for the supplied reactive and active power changes.

41. Test Function

The test function index expresses a direct relationship between its value and the load demand value that the system can resist before the occurrence unstable state. The main concept is the quadratic shape. It is more reliable than the other techniques based on the Jacobian matrix as given by the equation in reference [104]. Furthermore, it can estimate the voltage collapse point in the electrical system.

42. Tangent vector index (TVIi)

The tangent vector index *(TVIi)* is proposed by [105], which depends on the system load changes and the tangent vector concept and is used to compute the changes of the load effect on the elements of the vector such as voltages and angles. In this formula dV_i is the change in the voltage at bus *i; dL* is the change in the load. The value of *TVIi* is equal to zero if the derivative value approaches infinity.

$$TVI_i = \left| \frac{dV_i}{dL} \right|^{-1} \tag{64}$$

43. Critical boundary index (CBI)

The critical boundary index *(CBI)* is proposed by [106]. This is based on reactive and active power changes in an electrical network and uses a computational method to compute the critical boundaries. The worst-case for the transmission lines arises when the *CBI* value reaches zero. The high accuracy of prediction is the main advantage for this index, given in (65), where $\Delta P_{ij} = X - P_o$ and $\Delta Q_{ij} = Y - Q_o$

$$CBI_{ij} = \sqrt{\Delta P_{ij}^2 + \Delta Q_{ij}^2} \tag{65}$$

44. Second-order index (i Index)

The main concept of the second-order index *(i)* is based on the maximum singular value of the inverse load flow of the Jacobian matrix and its sensitivity to the system's parameters [107]. At the base case, the value of $i_o = \frac{\sigma_{max}}{d\sigma_{max}/dL_{total}}$, so the index value equals one (stable condition). But when the index value equals zero, the power system will be unstable. Where σ_{max} is the maximum singular value; L_{total} is the total load of the power system.

$$i = \frac{1}{i_o} \frac{\sigma_{max}}{d\sigma_{max}/dL_{total}} \tag{66}$$

45. Integrated transmission line transfer index (ITLTI)

This index is suggested to define the weak line in the system based on transmission line parameters *(ABCD)*, the receiving end power factor, and the power angle between the sending and the receiving end [108].

$$P_R = -\frac{AV_j^2}{B}\cos(\beta - \alpha) + \frac{V_i V_j}{B}\cos(\beta - \alpha) \tag{67}$$

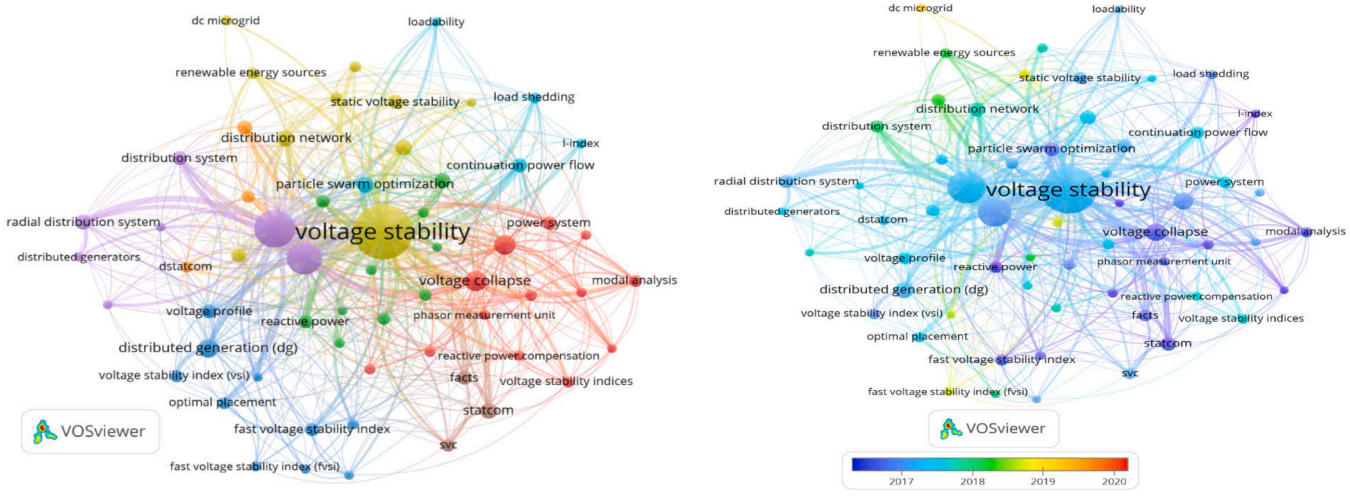
46. VQVI margin vulnerability index

The *VQVI* margin vulnerability index is utilized to specify the weak areas in the electrical network. It is defined as the relation between the changes in the *Q* margin after and before the contingency, as in Eq. (68) [109]. Therefore, the area or bus with a low reactive power margin can be defined as a reactive power vulnerable place near the instability margin.

$$VQVI = \frac{post - contingency\ Q\ margin}{pre - contingency\ Q\ margin} \tag{68}$$

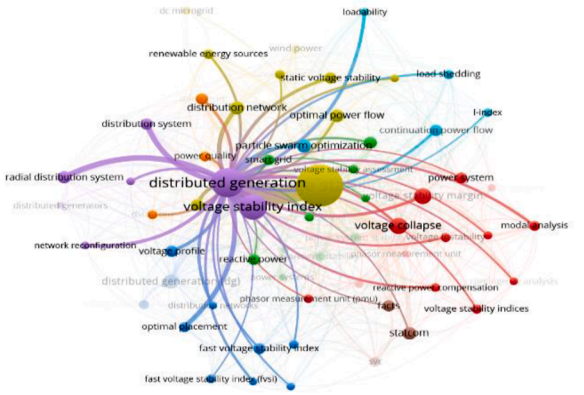
47. Smoothening reactive power loss based voltage instability detection index (SQLVIDI)

In [110], the novel voltage instability detection index *(SQLVIDI)* is suggested for voltage stability monitoring in real-time, which helps to decide at the right time. The concept of this index is based on the losses of reactive power computed from synchrophasor measurements. *SQLVIDI* considers the reactive power limits of generators, the switching of capacitor banks, and the effect of OLTC. Eq.

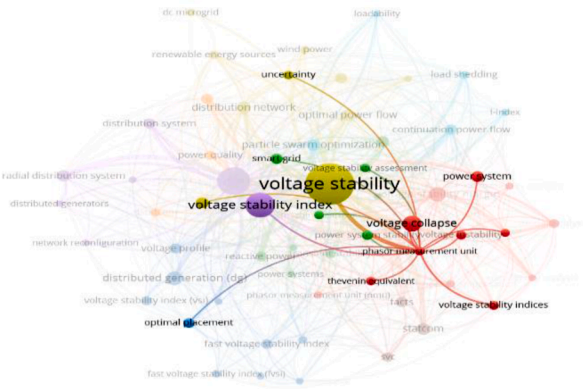


(a) (b)

Fig. 2. Author keywords co-occurrences in the publications related to VSIs research between 2013 and 2021 (a) network visualization, (b) overlay visualization.



(a)



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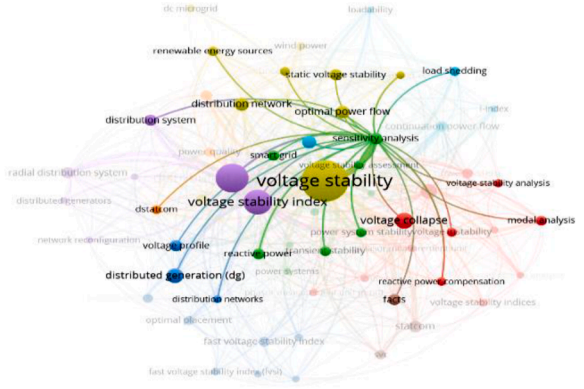

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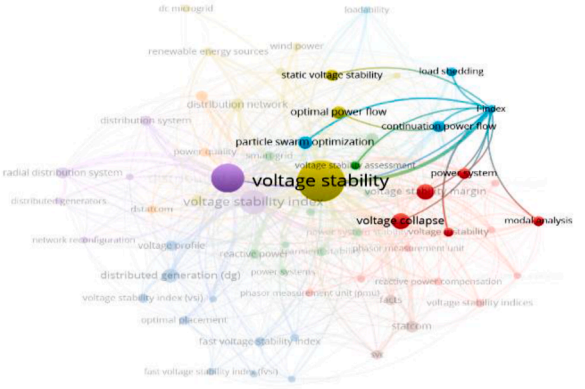

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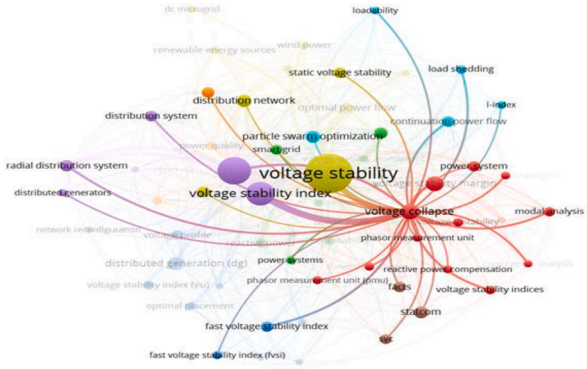

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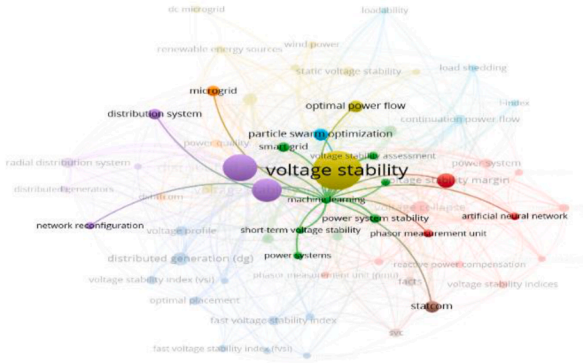

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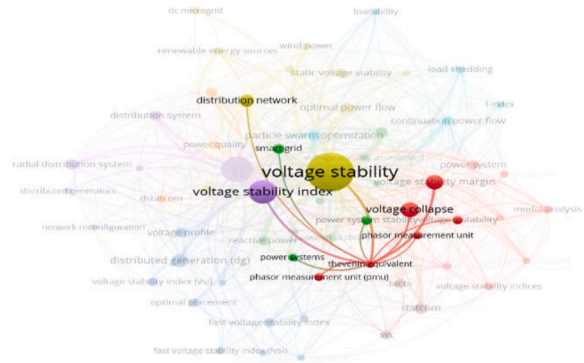
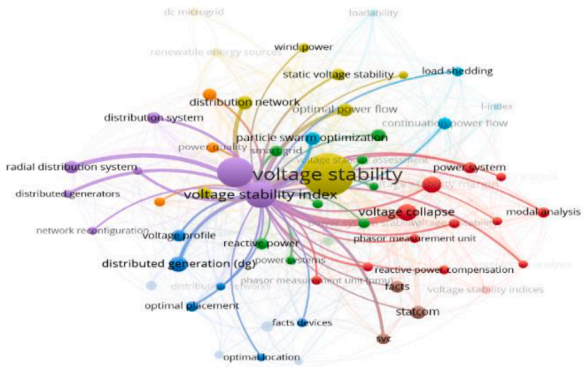


(j)



(h)

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Fig. 3. Author keywords co-occurrences in the publications related to VSIs research between 2013 and 2021 (a) distributed generation, (b) phasor measurement unit, (c) sensitivity analysis, (d) i-index, (e) voltage collapse, (f) machine learning, (j) Thevenin equivalent, and (h) voltage stability index.

(69) presents the *SQLVIDI* where Ψ is a smoothening function, *QLVIDI* is loss of reactive power-based voltage instability detection index, *CQL* is the deviation of consecutive reactive power loss, and *CQLB* is the deviation of baseload reactive power loss. If the index has a positive value, this indicates a warning for the instability case.

$$SQLVIDI = \Psi * QLVIDI \tag{69}$$

$$QLVIDI(t) = \frac{CQL(t)}{CQLB(t)} - \frac{CQL(t-\tau)}{CQLB(t-\tau)} \tag{70}$$

48. Real-time short-term voltage stability (STVS) assessment

In reference [111], the proposed technique is based on a self-adaptive hierarchical and data analytics method utilized for real-time short-term voltage stability *(STVS)* assessment. This technique covers the event of fault-induced delayed voltage recovery (FIDVR) and voltage instability. Based on a strategically designed ensemble-based randomized learning model, the *STVS* assessment is done sequentially and self-adaptively [111].

49. Thevenin equivalent (TE) parameters

In this reference [112], a robust *TE* parameter estimation technique for online voltage stability evaluation is presented.

9. A comprehensive review of voltage stability indices

Furthermore, to the above discussion and the detailed analysis for each VSI included in the proposed work and for providing a comprehensive overview of authors concerns in the relevant field. In addition, to construct and visualize bibliometric networks in this study, the VOSviewer software is used to extract the data for keywords with at least fifteen occurrences were collected from the Scopus database and individual clusters, which included both a network visualization (Fig. 2(a)) and overlay visualization (Fig. 2(b)) were merged. Also, the occurrences average year is emphasized by the soft green, yellow and red colors in the overlay visualization shown in Fig. 2(b). These clusters suggest publications with relative use of keywords in their publications. Among a total of 4087 observed keywords, 75 meet up the level of 15 occurrences. Figs. 3(a) show that the keyword "distributed generation" is interrelated with voltage stability, voltage stability index, optimal placement, FVSI, reactive power compensation, PMU, voltage stability indices, etc., signifying how the distributed generation is considered an attractive solution with VSIs as a robust power system with high power quality. Besides, Fig. 3(b) validate that the keyword "phasor measurement unit" is integrated with the voltage stability, voltage stability index, voltage collapse, Thevenin equivalent, uncertainty, voltage stability indices, optimal placement, power system, and smart grid, which notified that there are very few correlations between the integration of PMU with the others relevant keywords. In addition, Fig. 3(c) validates that the keyword "sensitivity analysis" is combined with the voltage stability, voltage stability index, voltage collapse, load shedding, optimal power flow, etc., as evident in Fig. 3(c).

Meanwhile, the "i-index" is related to voltage stability, PSO, voltage collapse, power system, modal analysis, continuation power flow, load shedding, and optimal power flow is presented in Fig. 3(d). Moreover, the "voltage collapse" keyword strongly connects with the relevant keywords, especially the voltage stability and voltage stability index, as shown in Fig. 3(e). Also, Fig. 3(f) confirm that the keyword "machine learning" is unified with the voltage stability, artificial neural network, power system stability, PMU, short-term voltage stability, voltage stability index, PSO, microgrid, smart grid, and optimal power flow, which informed that the machine learning had become an essential field in the power system stability. Another important keyword in the VSIs field is the "Thevenin equivalent" displayed in Fig. 3(j). It is connected with the voltage stability, voltage stability index, voltage collapse, PMU, power systems, smart grid, and distribution networks. One of the most keywords connected with all keywords used in the study is the "voltage stability index" because it is considered the main keyword in the current study, Fig. 3(h) show this connection with other keywords in the sane topic such as voltage stability, voltage collapse, distributed generation, power system, PMU, FACTS, optimal placement, optimal location, etc., as evident in Fig. 3(h). This intense exploration was validated by the dense connections and proximity between the keywords.

Regarding, VSI based on the jacobian matrix assessments requires collecting the whole data of the power system network components to define the voltage collapse point such as executed with singular value indicator [103]. When the jacobian matrix of the power system network requires the solution for the non-linear system, the particularity point maybe drop. So, the complexity of the VSI based on the jacobian matrix came from this point. Moreover, the inverse of the jacobian matrix is used with an i-index [107]. Meanwhile, the Jacobian diagonal elements are presented with minimum eigenvalue and the right eigenvector method [102]. Also, the VSLI is utilized by using the data collected from PMU to define the power system voltage collapse as listed in [69]. The tangent vector formula is used to deliver the information. Consequently, the TVI is computed based on the load flow calculations [105]; however, the TVI is not suitable for online monitoring, and the dynamic components of the power systems network are not considered. The SDC based on the line approach [88] has main cons related to checking the line's loading; if it is below the rated load value. In [110], the SQLVIDI is used by two elements, the CQL and CQLB are validated by checking the voltage under complex conditions based on the reactive power generator limits.

There are VSIs based on the TE technique as presented in [112]. The VSLI [68] and VSLBI [70] are based on the TE method. The

Table 2
A comprehensive review of VSIs.

Method depends on		SI Name	SI Abbreviation	Equation	Assumptions	The main concept	SC	CV	USC	Advantages	Disadvantages	Reference
System variables	Line	*Line stability index*	*Lmn*	$L_{mn} = \frac{4X_{ij}Q_j}{[V_i \sin(\theta_{ij} - \varepsilon_{ij})]^2}$	The impact of P and Y are ignored	Power transmission in the line and quadratic voltage equation	< 1.0	= 1	> 1.0	- It can define the weak area and the area near voltage collapse.- It can accurately detect instability.	- Definition of the critical load is inaccurate because there are some assumptions in deriving equations.- Neglects the active power effects.- The elative voltage stability results are incorrect in certain cases.	[41]
		Line stability index	*Lp*	$L_p = \frac{4R_{ij}P_j}{[V_i \sin(\theta_{ij} - \varepsilon_{ij})]^2}$	The impacts of Q and Y are ignored.	voltage quadratic equation	< 1.0	= 1	> 1.0	- It can evaluate the state of voltage collapse in the radial networks.- The simplicity of the computation method used and implementation.- A high degree of accuracy.	- Neglects reactive power effects.	[43]
		Novel Line Stability Index	*NLSI*	$NLSI = \frac{R_{ij}P_j + X_{ij}Q_j}{0.25{V_i}^2}$	The impacts of δ and Y are ignored.	voltage quadratic equation	< 1.0	= 1	> 1.0	- The active and reactive power are. taken into account- It gives quite accurate results.		[44]
		Stability Index	*SI*	$S = 2V_i^2V_j^2 - V_j^4 - 2V_j^2(P_jR_{ij} + Q_jX_{ij}) - Z_{ij}^2(P_j^2 + Q_{ij}^2)$	The impact of Y is ignored.	voltage quadratic equation	>0	= 0	< 0	- High sensitivity to voltage collapse.- Depends on the active and reactive power transfer.- Reliable.- Utilized with radial systems.- Need to load flow solution method.		[45]
		Fast voltage stability index	*FVSI*	$FVSI = \frac{4Z_{ij}^2Q_j}{{V_i}^2X_{ij}}$	Y is ignored, sin δ and R sin δ are equal to zero; X cos δ is equal to X.	voltage quadratic equation	< 1.0	= 1	> 1.0	- It can predict the event of voltage collapse and define the line which leads to collapse and evaluate the maximum allowable load	- Neglects the active power effects,- Disagreement may appear at defining the critical load because of some assumptions in deriving equations.- In certain cases, it	[48]

(*continued on next page*)

Table 2 (*continued*)

									cannot provide correct information about voltage stability.	
Voltage stability index	VSI_y	$VSI_y = \frac{4Q_j[R_{ij}+X_{ij}]^2}{X_{ij}[V_i^2+8R_{ij}Q_j]}$	Line shunt admittances and the voltage angle are negligibly small.	voltage quadratic equation	<1.0	$=1$	>1.0	- It can be utilized with DG and without DG for composite loads.- Low computational time and robustness.	- Used with radial distribution networks.	[53]
Voltage stability index	VSI_x	$VSI_x = \min\left(\frac{P_{margin}}{P_{Max}}, \frac{Q_{margin}}{Q_{Max}}, \frac{S_{margin}}{S_{Max}}\right)$	The line resistance and line shunt admittance are neglected.	maximum power transfer theorem	>0	$=0$	<0	- Forecasts the stability limits of steady-state voltage stability.- Applicable for online applications. - For large power systems.		[52]
Novel (New) Voltage Stability Index	*NVSI*	$NVSI = \frac{2X_{ij}\sqrt{P_j^2+Q_j^2}}{2Q_jX_{ij}-V_i^2}$	Neglects the resistance and shunt admittance of the line.	voltage quadratic equation	<1.0	$=1$	>1.0	- Considers the receiving end. - Real power equation.		[55]
Voltage stability margins	*VSMs*	$VSMs = \frac{S_{cr}-S_l}{S_{cr}}$	The power factor is constant, Y is ignored.	maximum power transfer theorem	>0	$=0$	<0	- It can be used in research and practice.- Distribution network with high/medium voltage		[56]
Voltage Stability Margin Index	*VSMI*	$VSMI = \frac{\varepsilon_{ij,Max}-\varepsilon_{ij}}{\varepsilon_{ij,Max}}$	The shunt admittance is neglected.	maximum power transfer theorem	>0	$=0$	<0	- It can define the weakest area in large-scale systems.- It can estimate the limits of voltage stability from the collapse point.- It is suitable for real-time applications.		[59]
modified Voltage Stability Indices	*MVSI*	$MVSI_j = \frac{4(Q_jY_{jj}\sin\varepsilon_{jj})}{\left(\sum_{i=1,\ i\neq j}^{N} V_iY_{ij}\right)^2}$		the reactive and active power transfers	<1.0	$=1$	>1.0	- It deals with the load buses in the transmission network.- In meshed power networks, it is efficient in ordering the load buses.		[60]
Voltage Collapse Proximity Indicator	*VCPI*	$VCPI_1 = \frac{P_j}{P_{j,\ Max}}, VCPI_2 = \frac{Q_j}{Q_{j,\ Max}}, VCPI_3 = \frac{P_l}{P_{l,\ Max}}, VCPI_4 = \frac{Q_l}{Q_{l,\ Max}}$	Constant power factor, $Y=0$	maximum power transfer theorem	<1.0	$=1$	>1.0	- Active and reactive power are calculated.- It is used with online power system applications.- Simple, and High	- The time required for computation depends on system topologies.	[63]

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Table 2 (*continued*)

								reliability and accuracy.		
Line Collapse Proximity Index	*LCPI*	$LCPI = \frac{4A\cos\alpha\ (P_jB\cos\beta + Q_jB\sin\beta)}{(V_i\cos\alpha)^2}$	Π is used to model the line	voltage quadratic equation	< 1.0	= 1	> 1.0	- The line shunt admittance is considered.- The impact set of magnitudes and directions of the active and reactive power are considered to forecast voltage collapse.- It is capable of providing more accurate results.- It can be used to study the influence of the transformer on voltage stability.		[66]
Voltage Instability Proximity Index	*VIPI*	$VIPI = \theta = \cos^{-1}\frac{Y_s^T Y(a)}{\parallel Y_s \parallel \parallel Y(a) \parallel}$		P-V curve	The critical point estimated depends on the exact solution.					[67]
Voltage Stability Load Index	*VSLI*	$VSLI = \frac{4[V_iV_j\cos\delta - V_j^2\cos\delta]}{V_i^2}$	The shunt admittance is neglected.	voltage quadratic equation	< 1.0	= 1	> 1.0	- It does not need the matrix and its inversion, so the requirements of the storage system are low.- High accuracy in all modes of operation.- Receives the data by PMU, which is very suitable for wide-area measurement systems (WAMS).		[68]
Voltage Stability Load Bus Index	*VSLBI*	$VSLBI = \frac{V_j}{\Delta V_{ij}}$	$Z_{th} = 0$	maximum power transfer theorem with PMU & local measurements	>1.0	= 1	< 1.0	- Simple.- Receives the data by PMU, so it is very suitable for WAMS.	- Low accuracy.- Ignores the Thévenin impedance at the sending node.	[70]
Line Stability Factor	*LQP*	$LQP = 4\left(\frac{P_i^2X_{ij}}{V_i^2} + Q_j\right)\left(\frac{X_{ij}}{V_i^2}\right)$	$R = 0$; $Y = 0$	voltage quadratic equation	< 1.0	= 1	> 1.0	- Simple.	- Low accuracy.	[71]
Power transfer stability index	*PTSI*	$PTSI = \frac{2S_jZ1 + \cos(\theta - \varphi)}{V_i^2}$	Line shunt admittance (Y) is neglected	maximum power flow	< 1.0	= 1	> 1.0	- It can forecast the voltage collapse in the practical electrical network with high accuracy.- It is used with an		[80]

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								online bus to evaluate the voltage stability and weakest bus when the line is lost, or the load is added.		
	Network sensitivity approach	*SG*	$SG_p = \frac{P_{gt}}{P_{dt}}, SG_q = \frac{P_{gt}}{Q_{dt}}$	The efficiency of the electrical network is constant.	P-V curve	a sharp rise to infinite values		- Receives the data by PMU, which is very suitable for WAMS.		[93]
	Line Voltage Stability Index	*LVSI*	$LVSI_l = \frac{2V_{jl}A_l\cos(\beta_l - \alpha_l)}{V_{il}\cos(\beta_l - \varepsilon_{ij_l})}$			>1.0	= 1	< 1.0	- It is used to evaluate the stressed lines and the voltage stability condition.- It takes into consideration the line charging capacitances and resistances.- To evaluate the state of voltage stability for various lines, just the data of bus voltage phasors are required.- It can define the MVA limits under different loading conditions.	[100]
	Critical Boundary Index	*CBI*	$CBI_{ij} = \sqrt{\Delta P_{ij}^2 + \Delta Q_{ij}^2}$		active and reactive power changes	>1.0		= 0	- High accuracy of prediction.- Fast. - Applicability for various types of power system topologies.	[106]
	Integrated Transmission Line Transfer Index	*ITLTI*	$P_R = -\frac{AV_j^2}{B}\cos(\beta - \alpha) + \frac{V_iV_j}{B}\cos(\beta - \alpha)$		transmission line parameters	See details in the reference.			- It is used with radial systems of large scale.It considers the power factor and the power angle between the two buses.- It is applicable online and offline.- It is appropriate for power factor unity, leading, and lagging.	[108]
Bus	*Voltage stability index*	VSI_i	$VSI_i = \left[1 + \left(\frac{I_i}{V_i}\right)\left(\frac{\Delta V_i}{\Delta I_i}\right)\right]^{\alpha}$	$\Delta Vr\Delta Ir = 0$	maximum power transfer theorem	>0	= 0	< 0	- It can give a true distance to voltage collapse with a linear extrapolation technique.- It needs local information	- It is not appropriate for DG issues like sizing and placement.- Very sensitive for the small changes	[51]

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								like magnitude, bus voltage, and load current.- It is used at higher load levels.- Receives the data by PMU, which is very suitable for WAMS.- It takes into account bus Thévenin network impedance.	of load admittance.	
Improved voltage stability index	*IVSI*	$IVSI = \frac{-4\sum_{j=0}^{n}(G_{ij}-B_{ij})(P_i+Q_i)}{[\sum_{j=1}^{n}V_j[G_{ij}(\cos\varepsilon_{ij}+\sin\varepsilon_{ij})-B_{ij}(\cos\varepsilon_{ij}-\sin\varepsilon_{ij})]]^2}$		Power flow formulas	< 1.0	= 1	> 1.0	- It is compatible with the radial systems.		[54]
Voltage Collapse Index	*VCI*	$VCI_i = \left[1+\left(\frac{I_i\Delta V_i}{V_i\Delta I_i}\right)\right]^{\alpha}$		system's apparent power change	>0	= 0	< 0	- It can be used as an objective function or a set of constraints.		[61]
Equivalent Node Voltage Collapse Index	*ENVCI*	$ENVCI = 2V_iV_j\cos\varepsilon_{ij} - V_j^2$		power transmission	>0	= 0	< 0	- It is effective for the local and outside network.- It is used with the real-time application and defines the voltage instability point.- It is used in monitoring and predicting voltage collapse.		[62]
Predicting the Voltage Collapse Index	*V/Vo*	V/Vo		P-V curve	>V/Vo	V/V= small value	<V/Vo	- It gives a comprehensive analysis of the electrical system state.- It is utilized with offline and online implementation.	- The computational cost is poor.- Low accuracy in the prediction of voltage collapse.- Insufficient in nonlinear performances.	[64]
Voltage collapse prediction index	*VCPIbus*	$VCPI_{j,bus} = \left\lvert 1-\frac{\sum_{\substack{i=1\\ i\neq j}}^{n}\dot{V}_i}{V_j}\right\rvert$	There is no relation between the voltage bus index and other buses.	power flow equation	< 1.0	= 1	> 1.0	- It is utilized with offline and online implementation.- It is used to define the weakest buses.- Receives the data by PMU, which is very suitable for WAMS.	- It requires several computations.- Ignores the bus Thévenin network impedance.	[65]
Participation Factor	*PF*	Details in the references			simulation tool			Details in the references		[72]–[74]
Voltage Stability Factor	*VSF*	$VSF = \frac{\Delta V}{\Delta Q}\Big\lvert_{P_d}$			+ sign		- sign			[75]
	VPI/VQI			V-Q and V-P		= 1				[78]

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Voltage active/reactive power index		$VPI = \frac{4P_j}{G_{ij}V_i^2}, VQI = \frac{4Q_j}{B_{ij}V_i^2}$	- The demand power factor is constant. - The receiving end load is constant.- Ignores the voltage angle of the receiving end.		< 1.0		> 1.0	- It is simple and fast.- It gives a comprehensive analysis of power flow dynamics with high accuracy.- It provides information about the maximum reactive and active power transferred in the lines.		
Voltage Deviation Index	*VDI*	$VDI_T = \sum_{j=1}^{N} \lvert 1 - V_j \rvert$	Details in the reference							[54]
Power Stability Index	*PSI*	$PSI = \frac{4R_{ij}(P_L - P_G)}{[V_i \cos(\theta - \delta_{ij})]^2}$		Maximum power transfer theorem	< 1.0	= 1	> 1.0	- Simplicity and accuracy.- Requires less computational time.		[82]
L-index	*L*	$L = \underset{j \in \alpha_L}{MAX} \left\lvert 1 - \frac{\sum_{i \in \alpha_G} F_{ij} V_i}{V_j} \right\rvert$	All generator voltages remain unchanged.	voltage quadratic equation	< 1.0	= 1	> 1.0	- It calculates the impact of the load model.- The computation method is simple.- Receives the data by PMU, which is very suitable for WAMS.		[83]
S difference criterion	*SDC*	$SDC = \lvert 1 + \frac{\Delta V_j I_{ij}^*}{V_j \Delta I_{ij}^*} \rvert$		maximum power transfer theorem	>0	= 0	< 0	- Simple and computationally very fast.- It takes into account the bus Thévenin network impedance.- Receives the data by PMU, which is very suitable for WAMS.	- It is not appropriate for DG issues like sizing and placement.- Very sensitive to the small changes of load admittance.	[88]
Impedance matching Stability Index	*ISI*	$ISI = \frac{Z_L - Z_{th}}{Z_l}$	At disturbances, the mode of the system is constant.	maximum power transfer theorem	>0	= 0	< 0	- Calculation is simple.- It takes into account the bus Thévenin network impedance.- Receives the data by PMU, which is very suitable for WAMS.	- It is not appropriate for DG issues like sizing and placement.- Very sensitive to the small changes of load admittance	[89]
$Z_L = Z_S$ *ratio*	$Z_L = Z_S$	$\frac{Z_L}{Z_S} = \frac{M+1}{-M\cos(\phi_S - \phi_L) + [(M\cos(\phi_S - \phi_L))^2 - M^2 + 1]^{0.5}}$	$73 \geq \varphi_S \leq 87$	maximum power transfer theorem	> 1.0	= 1	1.0 <	- It takes into account the bus Thévenin network impedance.- Receives the data by PMU, which is very suitable for WAMS.	- It is not appropriate for DG issues like sizing and placement.- Very sensitive to the small changes of load admittance.	[.76]

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	Simplified Voltage Stability Index	*SVSI*	$SVSI_j = \frac{\Delta V_j}{\beta * V_j}$	Generator voltage close to the load bus equals the Thévenin network voltage at the same bus.	maximum power transfer theorem and PMU & Local measurements	< 1.0 = 1 > 1.0	- It takes into account the bus Thévenin network impedance.- In the consecutive measurement data, it is not sensitive to tiny changes.	- It cannot give any information about the weak area with a stability problem.- Generator voltage close to the load bus equals the Thévenin network voltage at the same bus.	[39]
	Sensitivity Analysis	*SA*	$\Delta V_i/\Delta P_i$, $\Delta V_i/\Delta Q_i$		eigenvalue theorem and the load flow equations	Details are given in the references.	- It is used to define the weakest bus.- It can determine the penetration level of PV systems in the distribution systems taking the load capacity into account.		[94, 97]
	Critical Voltage	*Vcr*	$Vcr = \frac{E}{2\cos\delta}$		voltage quadratic equation	The critical voltage value.	- Simple.	- It is sometimes inaccurate.	[99]
	VQVI margin vulnerability index	*VQVI*	$VQVI = \frac{post - contingency\ Q\ margin}{pre - contingency\ Q\ margin}$			Details are given in the reference.	- Specifies the weak areas in the system.		[109]
Jacobian Matrix	*Impedance Ration Indicator*	$\frac{Z_{th}}{Z_L}$	$Impedance\ Ration\ Indicator = \frac{Z_{th}}{Z_L}$		Thévenin theorem	< 1.0 = 1 > 1.0	- It can give correct information about operation modes.- It is highly accurate and can predict the load changes	- The calculation of the load bus impedance ratio is not sufficient to define the collapse point- Requires high storage	[91]
	Integral Steady-State Margin	*ISSM*	$ISSm = \lvert\frac{J_c}{J_o}\rvert$			Between 0 and 1	- It is utilized for control applications, online security, and planning.		[98]
	Minimum Eigenvalue and Right Eigenvector (RE) Method	*RE*	$\Delta V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q$			See details in the references.	- It contains detailed models for the components.- It is very suitable for evaluating the voltage collapse of complex systems.		[101], [102]
	Singular Value Indicator		See details in the references.						[103]
	Test Function		See details in the references.				- It can be used to approximate voltage collapses.- It gives a connection between the value of index	- It cannot define the critical bus.	[104]

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Table 2 (*continued*)

						and load demand that the network can resist before the voltage collapse		
	Tangent Vector Index	*TVIi*	$TVI_i = \lvert \frac{dV_i}{dL} \rvert^{-1}$		It depends on the load	It is used to define the distance between the operating and collapse points.- Reduces computational burden.- This index is used to estimate the clustering technique for the operating mode of the critical area.- It is simple and helpful; moreover, the voltage collapse point calculation can be done quickly.		[105]
	Second-Order Index	*i Index*	$i = \frac{1}{i_o} \frac{\sigma_{max}}{d\sigma_{max}/dL_{total}}$	maximum singular value of the inverse LF Jacobian	> 0 $= 0$ < 0	- Used with all system nonlinearity.- It is very appropriate for computing the proximity to bifurcation.		[107]
Others	*Smoothening Reactive Power Loss based Voltage Instability Detection Index*	*SQLVIDI*	$QLVIDI(t) = \frac{CQL(t)}{CQLB(t)} - \frac{CQL(t-\tau)}{CQLB(t-\tau)}$	PMU	Details in the reference.	- This index can discover the near event of long-term voltage instability in a suitable time.- It is reliable, simple, applicable for real-time, and computationally cheap.		[110]
	Real-time short-term voltage stability (STVS) assessment	*STVS*	See details in the reference.	PMU	See details in the reference.	- It has high accuracy.- It is used to discover the fast voltage collapse and the large disturbances; besides, it is suitable for real-time analysis.	- Inaccuracy in data collection.	[111]
	TE parameter estimation method		See details in the reference.	PMU	See details in the reference.	- Appropriate to be applied to practical voltage stability assessment.- Considers Thévenin equivalent parameters- Accuracy.		[112]

definition of the static and dynamic load characteristics needs to define the model of the load structure that maybe cannot be achieved due to the uncertainties behavior of the loads. The TE parameters can be calculated by applying ISI based on the TE and Tellegen's theorem and using two sequential measurements [90]. Moreover, the impedance ration indicator [91], SVSI [39], and impedance ratio [92] are based on the TE model. Basically, the TE method is based on the algorithms and the state of the power system network; therefore, the power system components measurements are dependent on the power system procuration. Moreover, the accuracy of power system parameters used with the TE model may not be best when an unwanted signal is found with the power system, which, in turn, affects the accuracy of the VSI used. In general, there are as yet others VSIs which may be inspected. The above-mentioned overall VSIs have their advantages and disadvantages, listed in Table 2. Therefore, in the industrial and practical community is not feasible to state a particular VSI to be used.

Moreover, to the above discussion and the detailed analysis for each VSI included in the proposed work, Table 2 presents a comprehensive review and summary for each type of VSIs. It provides a technique and the main concept used with each VSI. It gives the method, SI name, SI abbreviation, equation, assumptions, the main concept, stable condition (SC), critical value (CV), unstable condition (USC) to state at which conditions and constraints the VSI can be used. Also, it provides advantages, disadvantages to define, which will be preferable to consider, and the reference. Generally, the stability condition is a significant factor, so it is critical to describe this condition carefully when designing and building the algorithms for voltage stability issues. The SC is assumed to be one of the essential indices to determine voltage callable detection through the VSI technique. Mainly, the large values are considered unpractical, especially in large systems, because of the complexity of the measurements of the components—moreover, the non-linear behavior of the large power systems. Table 2 shows the condition applied with many methods used with voltage stability margin. In the second rank, from an important point of view, during defining the assumptions factor, all effects of the assumptions on the other components of the power system must be considered to fade away the worst-case event. In addition to these two factors, the technique and the main concept used with VSIs are remarkable. The effectiveness and robustness of the proposed approach greatly influence the power system operation. Finally, the advantages and disadvantages are presented in Table 2 to make a choice more accessible to the researchers and have an overall idea about 49 VSIs. Moreover, this article will provide a rich source for the VSIs and save time for the researchers who seek to survey the relevant topics.

10. VSIs with machine learning and cyber-physical system techniques

Recently, new control, monitoring, and computation techniques such as machine learning and cyber-physical system have been used with power system stability issues. The authors in [113] used VSIs proposed in the literature as inputs to an ensemble of machine learning models that forecast the loadability margin. VSIs can be computed using synchrophasor measurements on a real-time basis. The authors in [114] proposed an intelligent collaborative balancing method to support bandwidth allocation and face instability events of the power system. Moreover, they can be applied to define and control the power system dynamically and preserve the optimal operation of the power system. Reference [36] proposed implementing real-time voltage stability monitoring using an artificial neural network (ANN) with LVSI. Application of computational intelligence for VSI has been used with a decision tree (DT) based classification approaches proposed in [115] to assess system voltage security. Meanwhile, DT is used in [116] for LTVS at small disturbances. Reference [117] proposed a methodology for LTVS monitoring in power systems that exploits the feasibility of phasor-type information to evaluate the LTVS status. The required information from the current system is collected through synchronized phasor measurements. The power system is split into sub-areas to enhance its monitoring; then, an artificial intelligence approach that relies on a kernel extreme learning machine is used for LTVS assessment. The authors in [118] presented a method that uses a local index load impedance modulus margin (LIMM) index to state the optimal composition locations of PMUs, which is more efficient. Also, the DNN is utilized to know the nonlinear relevance among the state of the power system operation and its corresponding LIMM. So, the value of the corresponding LIMM can be predicted out of the state variables of buses from the installed PMUs. Therefore, the presented technique improves the computation speed of LIMM and estimates the level of system voltage stability in real-time that helps the system operator judge the operating state and take measures in suitable time.

11. Conclusion

This study discusses and presents the details of 49 types of voltage stability indices. The voltage stability indices are categorized into two main groups: the system variables-based and the Jacobian matrix-based. Each category contains several voltage stability indices with various aspects. Their main characteristics are discussed in this paper. The overall characteristics of most of the voltage stability indices are listed in a large table to help researchers understand them and have a comprehensive idea about the most important voltage stability indices. Moreover, this table allows researchers to choose the best type for their required application. Finally, one of the most important results of this paper is spare time for the other researchers, which leads to not reading many hundreds of papers looking for valuable solutions. Moreover, this paper help to decide which direction is ok and which trends are dead-end. In line with the obtained research outcomes, the key findings can be emphasized as follows:

- The power system stability challenges are presented.
- A comprehensive review of 49 types of voltage stability indices is listed and compared.
- The relationship between renewable energy sources, load changes, and voltage stability indices is discussed.
- The distributed energy sources placement and sizing were discussed with voltage stability indices.
- The application of voltage stability indices in the various power system problems is presented.
- The following data: name, abbreviation, calculating method, assumptions, the main concept, stable condition, critical value,

unstable condition, advantages, and disadvantages for each voltage stability indices are listed.

- The presented work provided a rich source for researchers, students, and employers regarding voltage stability indices.

CRediT authorship contribution statement

Hossam S. Salama: Conceptualization, Methodology, Data curation, Visualization, Investigation. **István Vokony:** Conceptualization, Supervision, Validation, Resources, Data curation, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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