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Review of Voltage Stability Indices

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Review of Voltage Stability Indices

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Abstract. Voltage stability indices (VSIs) are very vital to voltage stability assessment; they have several areas of application such as distributed generation (DG) placement and sizing, detection of the critical regions, lines, and buses and contingency ranking and planning. These indices can be used to activate countermeasures against voltage instability. This article examines voltage stability indices with particular focus on line VSIs, and it highlights the classification, accuracy of VSIs, and enumerates for some selected line VSIs drawbacks and advantages as seen in literature.
Keywords: Voltage stability, Line Voltage Stability Index, DG placement and sizing

1 INTRODUCTION

Load increments, industrialisation, economic and environmental constraints have been identified as significant propellants which have forced more power system networks to run close to their stability limit [1]; hence, power system networks (PSNs) operated under this condition usually have voltage stability problems. Voltage stability can be defined as the capability of a power system to maintain or restore suitable voltage magnitudes at all network buses in the system before and after a disturbance [2]. An inability to do this leads to voltage instability and ultimately voltage collapse; if instability is not mitigated. Voltage collapse is a situation when there are uncharacteristically low voltages (voltage instability) in all or part of a power system network.

Several causes of voltage instability have been enumerated in literature such as but not limited to reactive power mismatch, sudden load increments, loss of power system elements like generators [3]. However, the leading causes of voltage instability are sudden load increment, loss of power system elements, reactive-power mismatch, and malfunctioning of on-load tap changing transformers [4]. Recent incidences of voltage collapse around the world in countries such as United States, Canada, Sweden, Denmark, India, Australia, Japan, Belgium, Germany, France, Iran, Vietnam, and many others reported by the authors in [3] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16]; has garnered immense attention to voltage stability analysis and control. For safe and reliable operation of PSNs, it is crucial that the distance to or from the voltage stability limit be known; so remedial actions can be taken by network engineers to avoid or prevent the effect of voltage instability. The specifics on the proximity to instability can be found by applying some voltage stability assessment techniques listed in [3]. These methods are capable of assessing a power network's proximity to voltage instability.

Voltage stability assessment has been approached in various ways as listed by authors in [3] [4] [17] [18] [19] [20]; however, voltage stability indices (VSIs), are capable of examining the stability of power system networks. They have been categorised as jacobian matrix-based and system variables based voltage stability indices [18] [19] [20]; they can be further classified based on types (what power system element they are based on), concepts (how they were formulated for example using the P-V curve), and impedance dependence [4]. This paper presents a review of line VSIs and highlights for each index, their drawbacks and advantages.
The paper is ordered as follows: a background study of power system stability in section 2, section 3 covers the definition of voltage stability and formulation of line voltage stability indices. Section 4 gives a comparison of the selected line stability indices, and section 5 concludes the paper.

2 BACKGROUND OF STUDY

2.1 Power System Stability

Power system stability is the innate ability of a PSN to remain stable during normal operational states/conditions and restore equilibrium after being perturbed [21]. Power system stability is categorised into three [2] as depicted in figure 1.

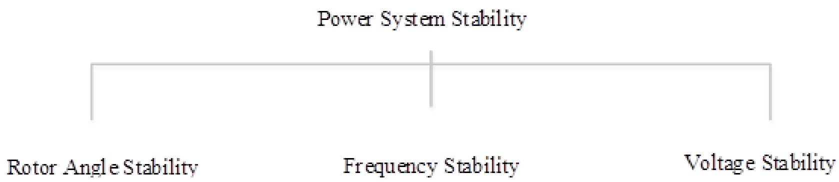

Figure 1: Classification of Power System Stability

Rotor angle stability is the ability of synchronous machines in interconnected PSNs to restore or retain synchronism before and after a system disturbance; done by re-establishing an equilibrium between the electromagnetic and mechanical torques of the machines in the network. Frequency stability is the inherent ability of PSNs network to uphold steady frequency after a substantial and critical system disturbance [3].
Voltage stability is the capability of a power system network to maintain stable voltage magnitudes at all network buses before and after a disturbance [2]; voltage instability often occurs once a system loses this ability and it manifests as a continual fluctuation of voltage magnitude of the network. The potential aftermath of unchecked voltage instability is the loss of load in all or part of the system. A system's voltage is said to be unstable when an increase in reactive power, causes at least one bus in the system to experience a gradual decline in voltage magnitude [3] [22].
Voltage stability is classified into two, depending on the size and duration of disturbance as depicted in figure 2. Based on the size of disturbance, voltage stability is subdivided into small and large disturbance voltage stability. Small disturbance voltage stability focuses on a power system's ability to retain or restore stable voltage magnitude caused by small agitations in the power system, such as variations in system load [21]. In contrast, the latter focuses on a power system's ability to maintain stable voltage magnitudes when subjected to large disturbances such as system faults.
Based on the duration of disturbance, there is short-term and long-term voltage stability. Short-term voltage stability focuses on the transiency of fast-acting load components triggered

by a loss of synchronism, and its duration is a few seconds. While long-term voltage stability deals with slower-acting components, and its period extends several minutes, and it is common in highly stressed systems [20].

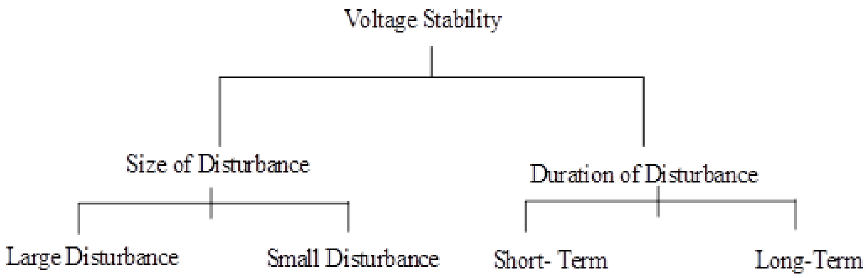

Figure 2: Classification of Voltage Stability

2.2 Voltage Stability Indices (VSIs)

VSIs are invaluable when analysing voltage stability conditions of PSNs because they have proven to be reliable, accurate, easy to use, and computationally inexpensive. They also have the additional ability to estimate the proximity to collapse and identify critical lines or buses in systems; these advantages as mentioned earlier coupled with these abilities make them highly suitable for online voltage stability analysis [3] [20].
According to the authors in [18] [19], VSIs can be classified as a jacobian matrix-based and system variables based VSIs. The jacobian matrix-based VSIs can calculate the voltage stability limit and the voltage stability margin of power systems. Since they are based on the jacobian matrix; this makes them ill-suited for online/real-time voltage stability analysis because the matrix has to be recalculated if there is a change.
In contrast to this, the system variables-based VSIs require fewer computations because they use the system variables and elements of the admittance matrix, such as bus voltages and voltage angle differences. This makes them suitable for real-time/online assessment; however, they are unable to estimate the voltage stability margin accurately.
VSIs are further categorised based on type, concept, and impedance dependence, as highlighted by the authors in [4]. In the formulation of VSIs, "concept" refers to the theories governing the creation of the index; while, "type" is concerned with the element (line or bus) referred to in the power system network. Therefore, types of voltage stability indices are line, bus, and overall voltage stability indices, as shown in figure 3. Details of VSIs based on concept and impedance dependence can be found in [4].

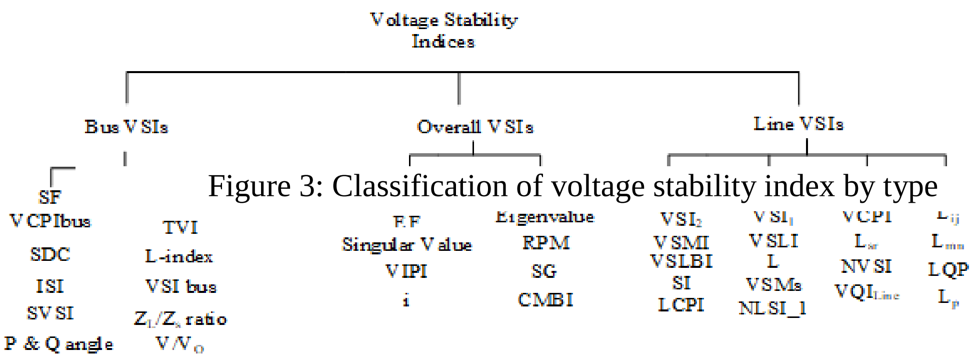

Figure 3: Classification of voltage stability index by type

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3 Formulation of Voltage Stability Indices (VSIs)

VSIs are used to ascertain the proximity to voltage instability, determine critical lines, and buses in PSNs. The index can either be referred to a line, bus or neither-as in overall VSIs. Line VSIs are stability indicators referred to a line. They can accurately ascertain the weakest lines and buses, and bus VSIs are referred to a bus, they provide vital information on the voltage stability state of network buses but not on elements such as lines with possible voltage stability problem. At the same time, overall VSIs are neither concerned with system buses or lines, they can predict the voltage collapse point of a system but none on weak lines or buses in the system [4]. This section focuses on the formulation of line stability indicators.

3.1 Line Voltage Stability Indices

Line VSIs are founded on the two bus representation of a power system whose shunt admittance is ignored as in figure 4. However, the theoretical foundation of most line VSIs is the same except for the assumptions made by each index. To achieve stability, the line stability indicators set their voltage equation's discriminant to greater than or equal to zero [24]. Some line VSIs found in the literature are described briefly in this subsection.

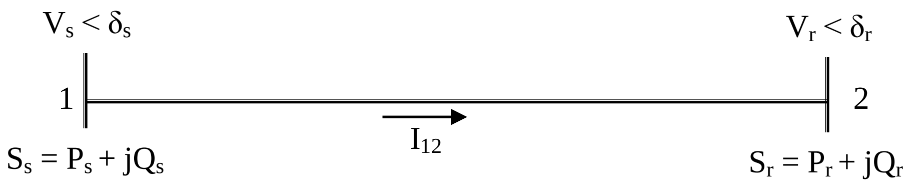

Figure 4: Two Bus Representation of a Power System Network

S_s, S_r is the apparent power at the sending bus 's' and receiving bus 'r'.

P_r is the real power at the receiving bus 'r'.

V_s, V_r are respectively the sending end voltage and the receiving end voltage.

Q_s,Q_r is the reactive power at the sending bus 's' and receiving bus 'r'.

δ_s, δ_r are respectively the voltage angles of the sending end and the receiving end buses.

δ is the difference δ_s and δ_r

θ is the transmission line angle

Z is transmission line impedance

R is the line resistance

X is the line reactance

3.1.1 Line Stability Index (L_{mn})

Moghavemmi & Omar, put forward Line stability index, Lmn founded on the principle that there exist solutions to the quadratic voltage equation; it sets the discriminant in Eqn. (1) to greater than or equal to zero.

$$V_r^4 + \left(2P_r R + 2Q_r X - V_s^2\right)V_r^2 + S_r^2 Z^2 = 0 \tag{1}$$

L_{mn} is given by [25]:

$$L_{mn} = \frac{4XQ_r}{\left(V_s \sin(\theta - \delta)\right)^2} \tag{2}$$

The system is considered to be unstable if the value of the index is greater than one; otherwise, it is stable. The index neglects line shunt admittance and real power's effect on voltage stability.

Moghavvemi & Faruque also proposed the Line stability index (L_p), which is founded on the same concept as L_{mn}. A system is unstable if the value of Lp is greater than one. Lp is defined as [26]:

$$L_p = \frac{4RP_r}{\left(V_s \cos(\theta - \delta)\right)^2} \tag{3}$$

The index assumes that only active power affects voltage stability and neglects line shunt admittance.

3.1.2 Fast Voltage Stability Index (*FVSI*)

FVSI formulated by Musirin & Abdul Rahman is found using a similar concept as L_{mn}. For a system to remain stable, FVSI must be below 1. Otherwise, the system will experiences a sudden drop in voltage and voltage collapse occurs. FVSI is given by [27]:

$$FVSI = \frac{4Z^2 Q_r}{V_s^2 X} \tag{4}$$

It neglects shunt admittance and assumes; $\sin\delta \approx 0, \cos\delta \approx 1, R\sin\delta \approx 0, X\cos\delta \approx \mathrm{X}$

3.1.3 Line Stability Factor (*LQP*)

Mohamed et al. founded the line stability factor, LQP on the same principle as L_{mn} and FVSI [28]. LQP is given as:

$$LQP = 4\left(\frac{X}{V_s^2}\right)\left(Qr + \frac{P_s^2 X}{V_s^2}\right) \tag{5}$$

To maintain stability, LQP must be less than 1. This index ignores shunt admittances and assumes that lines in the power system are lossless (R/X<<1).

3.1.4 Novel Voltage Stability Index (NVSI)

Kanimozhi & Selvi formulated NVSI on the same principle as $L_{p.}$ It was assumed that transmission line resistance is zero. NVSI must be less than 1, for the system to remain stable. NVSI is expressed as [29]:

$$NVSI = \frac{2X\sqrt{P_r^2 + Q_r^2}}{2Q_r X - V_S^2} \tag{6}$$

3.1.5 New Line Stability Index (NLSI_1)

NLSI-1 proposed by Samuel, in [3] is obtained by combining equations (2) and (4). The closeness to voltage instability is computed according to a switching function, σ given by equation (44). To maintain stability, NLSI_1 must be less than 1. NLSI-1 is expressed as [3]:

$$NLSI\_1 = \frac{4Q_2}{|V_1|^2}\left[\frac{(|Z|)^2}{X}\sigma - \frac{X}{\sin^2(\theta-\delta)}(\sigma-1)\right] \leq 1 \quad \sigma = \begin{cases} 1 & \delta < \delta_c \\ 0 & \delta \geq \delta_c \end{cases} \tag{7}$$

4 REVIEW AND COMPARISON OF LINE STABILITY INDICES

This section highlights the advantages and drawbacks of Line VSIs.

Lmn assumes that real power does not affect voltage stability and shunt resistance is zero. Its primary advantage is its insensitivity to the resistance/reactance ratio of transmission lines, as shown by the authors in [30]. However, the assumption that real power does not affect voltage stability might cause the index to be inaccurate under certain operating conditions [31]. On the other hand, when compared with indices such as FVSI and LQP, Lmn was seen to be more responsive to real power changes due to its indirect connection to real power through voltage angle difference δ [3].

FVSI assumes that the voltage angle difference between sending end and receiving end buses is approximately zero. This assumption is a significant drawback as large voltage angle differences are considered a precursor to the voltage collapse as highlighted by authors in [32]. Another disadvantage is the index's sensitivity to the resistance-reactance ratio of transmission line [30]. As an advantage, FVSI is considerably fast.

LQP assumes the lines are lossless, i.e. R/X << 1; which could cause it to be inaccurate under certain operating conditions. The advantage of this index is that it's insensitive to the resistance/reactance ratio of transmission lines [30].

L_p assumes that the effect of reactive power is negligible. This index has the following drawbacks: 1.) it fails if the transmission line resistance is exceptionally close to zero [3], 2.) it is sensitive to the angle difference δ, which can cause healthy lines to be identified as critical lines because $\cos(\theta-\delta)$ is faster than $\sin(\theta-\delta)$ around 90º [17] [3], 3.) Its accuracy is greatly affected whenever the load power factor is low, that is less than 0.80; hence; it can only be used in purely resistive distribution systems [26]. Its implementation is straightforward.

NVSI assumes the transmission line resistance is approximately zero. It is adversely affected by the resistance-reactance ratio of transmission line [30]. It is capable of monitoring power system networks in real-time [29].

NLSI_1 makes no other assumptions asides those made by its parent indices. The drawback has been identified for this index from literature. Its primary advantage is its increased accuracy and speed [3].

5 CONCLUSION

This paper reviewed voltage stability indices, and it shows that VSIs can be categorised based on type, concept and impedance dependence. This paper focuses on line VSIs, and for a few lines, VSIs drawbacks and advantages were highlighted. This paper highlighted the benefits of VSIs for online voltage stability analysis.

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