A REVIEW ON ON-LINE VOLTAGE STABILITY MONITORING INDICES AND METHODS BASED ON LOCAL PHASOR MEASUREMENTS

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Abstract—On-line voltage stability monitoring based on the local phasor measurements is a very active branch of voltage stability assessment presently. It can be divided into local bus measurements based methods and local branch measurements based methods. The latter can be classified into three versions. They are voltage stability indices based on the feasible solution region of quadratic equation of received bus voltage, the branch power transfer limit and the zero perturbation of branch complex power. A comprehensive review and evaluation on them is given in this paper. The numerical results with IEEE39 bus test system show that those voltage stability indices and methods based on branch local measurements cannot be used in on-line voltage stability monitoring of a real large power system.

Keywords: voltage stability; on-line monitoring; local phasor measurement; Thevenin equivalence; branch voltage stability index

I INTRODUCTION

The voltage collapse is one of the biggest threats for modern power systems. Over thirty years, a series of theories and methods of PV curve and load margin index based voltage stability assessment and control have been established and applied in power industries [1]. At the same time, when the phasor Measurement Unit (PMU) and Wide Area Measurement System (WAMS) have been used widely in power systems, the on-line voltage instability monitoring of power system based on the PMU’s local measurements has arrested wide attentions [2-19]. The real time measurement based voltage stability monitoring can not support the preventive control since the contingency selection and ranking is usually required for it. However, they do not depend on the state estimation, load flow computation and less data required [2-4], which let them to be the hot research subjects in voltage stability analysis.

Up to now, the voltage stability monitoring indices based on the local PMU measurements can be classified into two kinds. One is the bus phasor measurements based indices [5-14]. Another is the branch phasor measurements based indices [15-18].

Chebbo et al. proposed that the voltage stability assessment can be done by using the Thevenin equivalence parameters in [3]. Haque et al. presented a similar voltage stability index in [4]. However, the Thevenin equivalence parameters are calculated from power flow solution. Vu et al. proposed a local phasor measurement based voltage stability index in [5]. The continuous voltage and current phasor measurements of a load bus are used to calculate the Thevenin equivalence parameters. It combined Chebbo’s voltage stability index with synchronous PMU’s measurements, which has a milestone type of contribution. Later local phasor measurement based voltage instability monitoring has become a hot research area [6-14].

Since the Thevenin equivalence parameters are not easy to track, some scholars proposed some voltage stability assessment indices and methods without the identification of the Thevenin equivalence parameters. In [15,16] Moghavvemi proposed a voltage stability index based on the local branch phasor measurements instead of the local bus measurements. In [17] he proposed another index based on the branch transfer power limit. In [18] Gubina presented a voltage stability index based on two sets of branch current and voltage phasors measurements. However, these indices and methods have not strong and strict theoretical basis. A query on some of them was given in [19]. However, it did not indicate the true reasons of their invalidity yet.

In this paper we would give some discussion and reviews on the Thevenin parameter identification based voltage stability indices and methods. Both the Thevenin parameter drift problem and nonlinearity of these indices are two main drawbacks for them. Then we give justification and querying on those branch phasor measurement based voltage stability indices and methods. Our researches show that the Thevenin equivalence process based on local phasor measurements at a load bus can not be replaced in voltage stability monitoring. The local information of the so-called weakest branch can not represent the global voltage stability of whole power system. The numerical results on IEEE 39 bus test system showed that the voltage stability monitoring methods based on the local branch phasor measurements are not suitable for real power systems.

![Image](thenevinEquivalent.png)

**Figure 1:** Thevenin’s Equivalent circuit of power system.
2 REVIEWS ON THE THEVENIN EQUVALENCE BASED VOLTAGE STABILITY ASSESSMENT METHODS

2.1 The Thevenin equivalence based voltage stability assessment methods

The theoretical basis of the Thevenin equivalence based voltage stability assessment methods is the single port Thevenin equivalence of power system [3]. The critical characteristic of voltage instability is that the load reaches its maximum transfer power. Therefore, the critical criterion of voltage collapse in the steady state sense is that the absolute value of load impedance becomes equal to the absolute value of the Thevenin equivalent impedance. According to Fig. 1, it can be written as

$$|Z_{S,eq,i}| = |Z_{L,eq,i}|$$ (1)

where $Z_{S,eq,i}$ and $Z_{L,eq,i}$ are the system-side and load-side equivalent impedances at bus $i$ respectively. The voltage stability index of bus $i$ can be defined as:

$$VSI_i = 1 - \frac{|Z_{S,eq,i}|}{|Z_{L,eq,i}|}$$ (2)

Another form of the above index is

$$VSI_i = 1 - \frac{|Z_{S,eq,i}I_i|}{|Z_{L,eq,i}I_i|}$$

$$= 1 - \frac{\hat{V}_i - \hat{V}_i}{\hat{V}_i}$$ (3)

where $\hat{V}_i$, $I_i$ are the Thevenin equivalent voltage phasor, the current phasor and the load bus voltage phasor respectively.

The maximal transfer power at bus $i$ can be estimated by using the Thevenin parameters [6]:

$$P_i = \frac{E_{eq,i}^2}{2Z_{S,eq,i}} \cos \phi_{L,eq,i}$$ (4)

where $\phi_{S,eq,i}$ and $\phi_{L,eq,i}$ are the Thevenin equivalent impedance angle and the load impedance angle at bus $i$ respectively. Therefore, the relative power margin can be used as a voltage stability index of bus $i$.

$$VSI_i = \frac{P_{i,max} - P_{i,0}}{P_{i,max}}$$ (5)

where $P_{i,0}$ is the current value of load power. The voltage stability index for whole power system is defined as:

$$VSI_{sys} = \min \{ VSI_1, VSI_2, \cdots, VSI_n \}$$ (6)

where $n$ is the number of load buses, bus $k$ at which the index is the minimum called the weakest bus in the sense of voltage stability. With the operation of power system, $VSI_i$ can be seen as a projection of $VSI_{sys}$ on load bus $i$.

2.2 Tracking of the Thevenin equivalence parameters based on real time measurements

The accurate identification of the Thevenin parameters is very important for the above VSA methods and indices. Actually, the identification and tracking of Thevenin equivalence parameters of power grid is an independent research subject. We can calculate the Thevenin equivalence parameters by solving a power flow in which all loads have to be converted into constant impedances [3,4]. However, it requires the real time operation and topology data of whole power system.

In voltage stability monitoring on-line tracking identification of Thevenin parameters is executed by using the synchronous measurements of the continuous time instants [5].

According to Thevenin’s Equivalent circuit in Fig. 1, we can get:

$$\hat{E}_{S,eq,i} = \hat{V}_i + Z_{S,eq,i} \hat{I}_i$$ (7)

$\hat{V}_i, \hat{I}_i$ can be obtained from PMU. To decouple (7) in the rectangular coordinate system, we can get:

$$\begin{bmatrix} E_{S,eq,i} \end{bmatrix} = \begin{bmatrix} V_{i,R} \end{bmatrix} + \begin{bmatrix} I_{i,R} & -I_{i,I} \end{bmatrix} \begin{bmatrix} Z_{S,eq,i} \end{bmatrix} \begin{bmatrix} V_{i,I} \end{bmatrix}$$ (8)

where the subscript $R, I$ denote the real and imaginary part of the corresponding phasors respectively.

In order to compute four Thevenin equivalence parameters $E_{S,eq,i,R}, E_{S,eq,i,I}, Z_{S,eq,i,R}, Z_{S,eq,i,I}$, at least two sets of $V_i$ and $I_i$ measurements are required. If more than two sets of $V_i$ and $I_i$ measurements are obtained, the Thevenin equivalence parameters can be calculated by using the least square method. Usually the length of time window (the number of measurements) is increased to mitigate the effects of the bad measurements and the measurement errors.

2.3 A variation of the above index based on two sets of measurements

According to (2) and (3), only either the Thevenin impedance magnitude or the Thevenin voltage phasor need to be tracked for detection of voltage instability. If the Thevenin impedance magnitude is estimated only and two sets of measurements are obtained [7], we have

$$\frac{|V_{i} - V_{i-1}|}{|I_{i} - I_{i-1}|}$$ (9)

where superscript $t$ and $t-1$ denote the measurements of two sequential moments. Since $|Z_{L,eq,i}| = |V_{i}/I_{i}|$, we can get:

$$VSI_i = 1 - \frac{|(V_i - V_{i-1}) \cdot I_i|}{(|I_i - I_{i-1}| \cdot V_i)}$$ (10)

According to (10), voltage stability monitoring can be executed by using two sets of voltage and current phasor measurements. It looks like having nothing with the Thevenin equivalence parameter tracking.

2.4 Reviews and discussion on the Thevenin equivalence based VSA methods

We give the following reviews on Thevenin equiva-
lence based voltage stability monitoring methods and indices:

1) The Thevenin parameters can not be identified accurately since the real time phasor measurements are inherently stochastic. This is one of fundamental drawbacks for Thevenin equivalence based VSA methods.

There is an assumption behind the local measurement based Thevenin parameter identification methods.

The measurements for any two time instants within a time window satisfy that there is a disturbance at the load side at the same time there is no disturbance at the system side.

This assumption is never satisfied. If the time interval between two consecutive measurements is too short and there is no difference between two sets of measurements, the matrix would be singular or ill-conditioned. If the time interval is too long and there is a disturbance in system side, the equivalence parameters change actually. Even though some data filtering techniques are used to improve the accuracy of identification, the equivalence parameter drift problem cannot be eliminated [8].

2) These indices are nonlinear inherently. This is another fundamental drawback for the Thevenin equivalence based VSA methods. Like the minimum singular value or the minimum eigenvalue, these indices can not consider the nonlinear characteristics of power system. For example, the effects of the reactive power limits of generators, other controls of HVDC and FACTs. The power system is nonlinear inherently and it is linearized into the Thevenin equivalent network in these methods. Even though a maximum transfer power limit was estimated by (4), the indices are not a distance type index (like the load margin index). They are state type indices.

For more accurately describing the voltage stability of power system, it is better to combine these indices with other indices. For example, the reactive power reserve index is proposed and used in [9].

3) The equivalence of these indices with other VSA indices. The Thevenin equivalence based voltage stability assessment is equivalent to the regular method based on the singular Jacobian matrix of load flow equations [1, 2].

4) The precondition of (1) is that the load factor is constant. That is to say, the maximum reactive power is also obtained at the same time. If this condition is released, then the criterion of the maximal real power is

\[ Z_{S, \rho} = Z_{L, \rho} \]  (11)

where superscript * denotes conjugation. It is a special case of (1).

5) Relationship between these indices and the load model. In the derivation process of these indices, the load is converted into impedance, but it is necessary to note that the final criterion and conclusion are related to constant power load. We know if the load is truly pure impedance, actually there is no voltage instability problem in power system. When one part of load is impedance and another part of load is constant power load, the maximum transfer power point (i.e. the nose point of PV Curve) is not the critical point of voltage instability. If we still use these methods, then the impedance part of the load should be converted into the equivalent impedance of system side [9].

6) The index in (10) looks like having no relationship with the tracking of the Thevenin parameters. However, it not only depends on the Thevenin parameter identification, but also is based on the assumption in 1).

7) The detection of rotor angle instability cases. Voltage collapse just is one of instability modes of power system. In some cases, the load bus voltage and the Thevenin equivalent voltage are dropped monotonously, while both the Thevenin impedance and the load impedance maintain their values, and the magnitude of load impedance is bigger than the magnitude of the Thevenin equivalence impedance. These kind of phenomena are belonging to rotor angle instability in steady state sense instead of voltage collapse. Since two different instability modes should be detected and distinguished first, all four Thevenin equivalence parameters have to be tracked and identified. It is incorrect that only the magnitudes of the equivalence impedance need to be tracked.

8) The above indices and methods do not work for any bases. There is an assumption:

It is a sourced two-terminal network seen from the bus to the system side, and it is a non-sourced two-terminal network seen from system to the load side.

If there is a voltage regulated device installed at the load side, then it can not be selected to calculate the indices.

In addition, it is wrong that the simple Thevenin impedance should be replaced by using the \( \pi \) equivalent branch model.

3 QUERY ON BRANCH PHASOR MEASUREMENT BASED VOLTAGE STABILITY ASSESSMENT INDICES AND METHODS

Figure 2: A transmission line of a power system network.

3.1 Overviews of VSA indices based on local branch measurements

The voltage stability indices and methods based on local branch phasor measurements can be classified into three kinds. In [15, 16] Moghavvemi et al. proposed two branch voltage stability indices:
\[
VSI_i = \frac{4P_iZ_i \cos \theta_i}{\left(V_i \cos(\theta_i - \delta_i)\right)^2} \tag{12}
\]

\[
VSI_i = \frac{4Q_i'Z_i \sin \theta_i}{\left(V_i \cos(\theta_i - \delta_i)\right)^2} \tag{13}
\]

where \( V_i \) is the voltage magnitude of sending bus of branch \( i \rightarrow j \), \( Z_i \) and \( \theta_i \) are the magnitude and angle of branch impedance respectively, \( P_i \) and \( Q_i' \) are the real and reactive power at branch receiving terminal respectively, \( \delta_i = \delta - \delta_j \) is the voltage angle difference between the sending bus and the receiving bus. When \( VSI_i \) approached to 1, the corresponding power system reaches its voltage stability critical point. (12) and (13) are derived from an assumption that the quadratic equation about receiving bus voltage magnitude has two same solutions at the maximum transfer power point. The complete derivation process can be seen in [15, 16].

In [17] Moghavvemi et al. proposed another local branch measurement based voltage stability index. The maximal transfer power of a branch can be calculated as:

\[
P_{i,\text{max}} = \frac{V_j^2 \cos \phi}{2Z_i \left(1 + \cos(\theta_j - \phi)\right)} \tag{14}
\]

where \( \phi = \arctan\left(Q_j/P_j\right) \), i.e. the power factor of the branch receiving terminal. The voltage stability index of this branch can be defined as:

\[
VSI_i = \frac{P_{i,0}}{P_{i,\text{max}}} \tag{15}
\]

where \( P_{i,0} \) is the current real power of branch at the receiving terminal. When \( VSI_i \) approach to 1, power system reaches its voltage stability critical point.

In [18] Gubina proposed a branch voltage stability index based on two consecutive phasor measurements.

\[
VSI_i = \left|1 + \frac{\Delta V_j^{(i+1)} \Delta I_j^{(i+1)}}{V_j \Delta I_j^{(i+1)}}\right| \tag{16}
\]

where \( V_j \) is the branch receiving bus voltage phasor at time \( t \), \( \hat{I}_j \) is the branch current phasor at time \( t \), \( \Delta I_j^{(i+1)} = I_j^{(i+1)} - I_j^{(i)} \) is the perturbation of branch current phasors from \( t \) to \( t+1 \) time instant. \( \Delta V_j^{(i+1)} = V_j^{(i+1)} - V_j^{(i)} \) is the perturbation of voltage phasors of branch receiving bus from \( t \) to \( t+1 \) time instant. When \( VSI_i \) approaches to 0, the power system reaches its voltage stability critical point. This index is based on the change rate of the complex power at the branch receiving terminal is 0.

### 3.2 VSA index for a whole power system

At first the voltage stability indices of all branches in a power grid are calculated. The maximal (or minimal) one among them is the voltage stability index of whole power system. The voltage stability index of whole power system is defined as:

\[
VSI_{\text{sys}} = \min \{VSI_1, VSI_2, \ldots, VSI_m\} \tag{17}
\]

where \( m \) is the number of branches, branch \( k \) at which the index is the minimum or maximum called the weakest branch in the sense of voltage stability.

### 3.3 Review and Query on the local branch measurement base VSA indices

We give the following query and reviews on the branch measurement based voltage stability assessment indices and methods.

1) A common point of these VSA methods is that the computation of the Thevenin equivalence parameters are avoided. As presented in Section 2, the accurately tracking of the Thevenin parameters can not be realized by using the real time phasor measurements. Any indices and methods without tracking would attract much attention.

2) Generally the theoretical basis of these methods is weak. There is an assumption behind these methods:

   **If the ‘weakest’ branch can be found out, the information of this branch can represent the voltage stability of whole power system.**

   This assumption is incorrect for general complex power system. It works for only some special cases. The voltage collapse of whole power system may not be presented as individual branch reaching its power transfer limit. The voltage collapse of power system is inherently global as a system-wide instability phenomenon, even though in some cases, it takes on strong local property. In addition, the local unbalance of reactive power would definitely induce the global voltage instability. However, that is not to say, power system voltage collapse would assure to take on the local characteristics.

   For a two bus system, the index (14) is equivalent to the Thevenin equivalence based VSA index [4].

3) The indices in (12), (13) are unreasonable. A querying on these indices was presented in [19]. It proved that even for a single-machine-single-load simple power system, these indices are correct only for a special operational situation. We think their mistakes are very easy to find. The quadratic equation about the power receiving bus voltage magnitude, which is constructed for deriving these indices, is wrong. In the derivation process the angle difference between two buses of branch should be eliminated. In [4] Haque et al. presented a quadratic equation with only the sending bus voltage \( V_j \), which is correct. According to this equation, the corresponding VSA index can be derived as:

\[
VSI_i = \left(\frac{2P_j}{Z_j \cos(\theta - \phi)} - V_j \cos \phi\right) \tag{18}
\]

It is necessary to note that the VSA index proposed in [4] by Haque et al. was based on a Thevenin equivalence network instead of a branch in a power system. That is to say, (18) is work only for single-machine-single-load power system and some simple radiant
power systems. It does not work for a real complex power grid.

4) The theoretical basis of the index (15) is wrong. It has been proved in [20]:

At least one branch already reached or passed its maximal power transfer limit before the voltage collapse point.

This is a necessary condition, but not a sufficient condition. We believe that the following converse proposition does not work. If a branch in a power grid reaches its maximal power transfer limit, then voltage collapse just happens.

In addition, it is necessary to note that the conclusion of [20] has no effect on voltage stability monitoring. Because the operational point at which first branch reaches its limit point may far away from the point at which the whole system reach its voltage collapse. Between them there may be many lines reached their limits continuously.

5) The index in (16) is incorrect. The theoretical basis of this index is that in the vicinity of the voltage collapse, all increase in the complex power supply at the sending end of the line no longer yields an increase in the complex power at the receiving end [18].

\[
\Delta S_{j}^{\pm 1} = V_{j}^{\pm} \Delta I_{j}^{\pm 1} + \Delta V_{j}^{\pm 1} I_{j}^{*} = 0
\]  

(19)

The increases of both real power and reactive power equal to zero.

\[
\begin{align*}
\Delta P_{j}^{\pm 1} &= 0 \\
\Delta Q_{j}^{\pm 1} &= 0
\end{align*}
\]

This condition is too strict. Actually it is wrong. We use the reduction to absurdity to show that it is unreasonable. According to (19), we get

\[
1 + \frac{\Delta V_{j}^{\pm 1} I_{j}^{*}}{V_{j}^{\pm} I_{j}^{\pm 1}} = 1 + a \angle \phi = 0
\]  

(20)

If (20) is hold, then it holds either for a single machine single load power system shown in Fig. 1. We get

\[
\frac{\Delta V_{j}^{\pm 1}}{\Delta I_{j}^{\pm 1} V_{j}^{\pm}} = -R + jX = Z \angle (180^\circ - \phi_j)
\]  

(21)

where \(Z\) and \(\phi_j\) are branch impedance magnitude and impedance angle respectively. Then we have

\[
V_{j}^{\pm} = R_j - jX_j = Z_L \angle - \phi_L
\]  

(22)

where \(Z_L\) and \(\phi_L\) are load impedance magnitude and impedance angle respectively. Therefore, we have

\[
1 + \frac{\Delta V_{j}^{\pm 1} I_{j}^{*}}{V_{j}^{\pm} \Delta I_{j}^{\pm 1} V_{j}^{\pm}} = 1 + \frac{Z \angle 180^\circ - \phi_L}{Z_L \angle - \phi_L} = 0
\]  

(23)

The conclusion is:

\[
\begin{align*}
Z &= Z_L \\
\phi &= \phi_L
\end{align*}
\]  

(24)

That is to say, when both the real part and imaginary part of the load impedance are equal to those of the line impedance respectively, voltage collapse would happen. It is in contradiction with facts in which the load impedance magnitude is equal to that of branch impedance. It is just a special case. Even for a single machine single load system in Fig. 1, this index work only for a special situation. Therefore, this index does not work for voltage stability assessment of a complex power system.

4 Numerical Analysis

IEEE39 bus test system was used to evaluate the indices and methods reviewed in this paper. Since there are no reactive power limits of generators in data. The following simulations do not consider the generator reactive power limit, which has no impact on verifying and comparing to these indices. In the following comparison the load margin calculated by a continuation power flow (CPF) tool are used as the benchmark criterion.

4.1 Comparison of the voltage stability indices based on Thevenin equivalence parameters

To increase the real power and reactive power of bus 8 with constant power factor while keep other loads unchanged. The increased real power was matched by the slack generator. The numerical results about voltage stability indices based on the Thevenin equivalence are shown in figure 3.

It can be seen in Fig. 3 that the voltage magnitude of bus 8 decreased when the load at bus 8 is increased continuously. \(\text{VSI}_i\) of bus 8, calculated by the Thevenin equivalence method, is decreasing. At the nose point of PV curve, \(\text{VSI}_i\) of bus 8 approached to 0. Since the generator reactive power constraints were not considered, the PV curve is smooth. The voltage stability index \(\text{VSI}_i\) at bus 18 was also shown at Fig. 3. It approached gradually to 0 either. The numerical results shown that the \(\text{VSI}_i\) of other buses always approach to 0 at the voltage collapse point either. That is to say, in the vicinity of the voltage collapse to calculate the Thevenin equivalence parameters to any load bus in a power system, same information about voltage collapse can be obtained. However, if the indices at some non-weak buses are calculated instead of the weak bus (like bus 8), the voltage instability early-warning can not be done well.

4.2 Evaluation of VSI based on the branch measurements

We evaluated the voltage stability indices and methods based on the local branch measurements. For the sake of distinction, we denote the voltage stability indices \(\text{VSI}_{i,m}\) from (12), (13), (18), (14) and (16) as \(L_F\), \(L_O\), \(L_V\), \(L_{PT}\) and \(L_{SDE}\) respectively. Two different load increasing modes are used. One is load increasing at a single load bus, another is that load increasing at all load buses.
a. Load increasing at single load bus

To increase gradually the real and reactive power at bus 8 with constant power factor while maintain the loads of other buses. The increased real power was matched by the slack generator at bus 31. The numerical results were shown in Figure 4 and Figure 5.

b. Load increasing at all load buses

All loads are increased with their original power factors. All generators increase their real power outputs with their current proportion to match the increased real power. The numerical results are shown in Table 1.

According to our numerical tests, in the process of power system operation approaching the voltage collapse, the voltage stability indices based on the branch measurements can not indicate the true stability state of power system and can not give correct early-warning at the voltage collapse points.

5 CONCLUSIONS AND DISCUSSION

With the development and wide application of PMU/WAMS technology, the local phasor measurement based voltage stability monitoring of global power system became one of the hot issues in recent years. A comprehensive review and analysis on the existing methods and indices were presented in this paper. The Thevenin equivalence based voltage stability monitoring methods and indices have correct theoretical background. However, the Thevenin parameters cannot be tracked by using the real time stochastic phasor measurements. We give a query on some voltage stability assessment methods and indices based on local branch measurements. The numerical results of IEEE-39 bus.
test system showed that the presented conclusions are correct. One should try to limit themselves to tables with an acceptable number of lines and columns so as to focus the readers’ attention on the illustrated information.

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Table 1: Simulation results for the whole system with load increasing

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