Online prediction of voltage collapse using a node voltage stability index

Swati Padhee[1] , Santi Behera[2], M. Tripathy[3] and Tapan Prakash[4]

***Abstract*—This paper discusses about classification of voltage vulnerability of a power system. The paper proposes an equivalent system model (ESM), which includes effects of both local network and system outside the local network. A new node voltage stability index called the equivalent node voltage collapse index (ENVCI), based on ESM is presented which uses only local voltage phasors. The simulation results show that the ENVCI can identify not only the weakest node (bus) causing system instability but also the system voltage collapse point when it is near zero. This feature enables us to set an index threshold to monitor and predict system stability on-line so that a proper action can be taken to prevent the system from collapse.**

***Index Terms*—Energy Management System(EMS),System collapse, Voltage stability index, Voltage collapse.**

I. INTRODUCTION

THE importance of voltage collapse phenomena are presently well recognized. In recent years, voltage instability has been the cause for several major network collapses. Voltage stability is concerned with the ability of a power system to maintain acceptable voltage at all buses in the system under normal conditions and after being subjected to a disturbance. Static voltage stability can be assessed using continuation power flow calculations [1–3] by using static voltage assessment methods such as the minimum singularity value method, mode analysis method and sensitivity method [4–6]. The main disadvantage of these methods is their incapability of identifying weak lines or buses that cause system collapse. The process of system losing voltage stability starts in a local network and then eventually extends to the entire system. We can predict static voltage stability using local measurements. There are two types of local evaluation techniques for voltage stability: line-based and node (bus)-based techniques. The theory says that if a line or a node in the system is critically voltage-instable, the whole system approaches a collapse point [7–11]. The voltage stability assessment techniques using local bus phasors [7, 8]can be compared with different line based voltage stability indices[9-11].

This paper proposes a new voltage stability index i.e. equivalent node voltage collapse index (ENVCI)[6]. It has the following features:

• Accuracy: The effect of a system outside the local network is included through an equivalent model of the system which is not done in existing line-based voltage indices, thus approaching accuracy of the index in modeling.

•Impedances: The equivalent system impedance that needs to be estimated using two system states is only a small part of the total impedance whereas the impedances of local network (branches that are directly connected to the considered node) are known and need not be estimated using two system states as in case of the internal and external impedance method.

• Computational time: The computation of ENVCI is much faster since it is associated with very simple calculations and no system-wide power flow is required as in case of the conventional method based on continuation power flows,

•EMS: The calculation of ENVCI only requires the information of local voltage phasors, which can either be obtained via synchronized phasor measurement units (PMU) or through the state estimation of energy management system (EMS) at control centers of utilities. This enables ENVCI to be easily applied in on-line (EMS) or real time (PMU) environment.

•Identifying weak nodes: The ENVCI values of all monitored nodes can identify the weakest node(s) of the system. The ENVCI at the weakest node will be very near zero when the system approaches its voltage collapse point. Therefore, a threshold of ENVCI can be easily set up to trigger an emergency remedial action scheme to protect the system from voltage collapse.

II. EQUIVALENT SYSTEM MODEL(ESM)

A local network for any node (bus) N in a transmission system is defined as all the components that are directly connected to it. A dummy voltage source E_k with impedance Z_{km} is added to include the effect of the system outside the local network, as shown in Fig.1.

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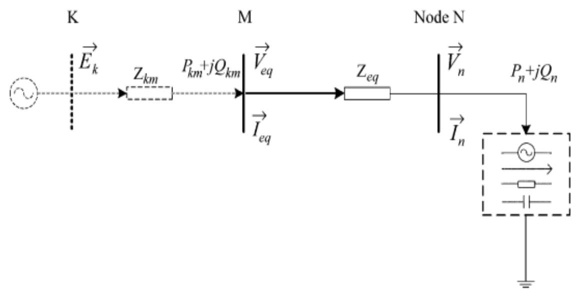

Fig.1

In the above figure, the solid lines represent the equivalent network of the local network considered and the dashed portion represents the external network introduced i.e. the system outside the local network.

Here P_{km} and Q_{km} are the real and reactive powers flowing into the local network, the voltage phasor at the node N is $V_n \angle \theta_n$, the intermediate equivalent voltage phasor is $V_{eq} \angle \theta_{eq}$.

The total power flowing out of the node N is the sum of line power flows on all the lines with outgoing flows, the load, generator power and compensated reactive power at the node N. The outgoing current at the node N can be expressed as:

$$\vec{I}_n = \frac{S_n^*}{\vec{V}_n^*} = \sum_{i=1}^{M} Y_{ni} \left(\vec{V}_i - \vec{V}_n\right) = \sum_{i=1}^{M} Y_{ni} \vec{V}_i - Y_{eq} \vec{V}_n \tag{1}$$

where, $Y_{ni} = \frac{1}{Z_{ni}}$, $Y_{eq} = \sum_{i=1}^{M} Y_{ni}$

where, Y_{ni} and Z_{ni} are the admittance and impedance of lines between the nodes *i* and *n* respectively; $\vec{V}_i$ and $\vec{V}_n$ are the voltage phasors at the node *I* and *n*; the superscript * represents conjugate in the paper and thus $\vec{V}_n^*$ is the conjugate phasor of $\vec{V}_n$; and *M* is the number of lines with power flows entering the node N.

The reactive charging powers at the sending ends of the lines are represented by grounding branches and power flows entering the node N have been assumed to be part of Z_{km}. For E_k and Z_{km} to have the same effect as the whole system outside the local network, the voltage phasors and power flows for the equivalent line need to be identical for which the following equation has to be satisfied:

$$(P_{km} + jQ_{km})^* = \overrightarrow{V_{eq}}^* . \frac{\overrightarrow{E_k} - \overrightarrow{V_{eq}}}{Z_{km}} = \overrightarrow{V_{eq}}^* . \frac{\overrightarrow{V_{eq}} - \overrightarrow{V_n}}{Z_{eq}} \tag{2}$$

III. FORMULATION OF ENVCI

With the single line equivalent system model for the node N as shown in Fig. 1, the outgoing power at this node can be represented as:

$$(P_n + jQ_n) = \overrightarrow{V_n}^* . \left(\frac{\overrightarrow{V_{eq}} - \overrightarrow{V_n}}{Z_{eq}}\right)^* \tag{3}$$

Let us represent the voltage phasors at the two nodes of the equivalent single line model in rectangular coordinates, i.e., $\overrightarrow{E_k} = e_k + jf_k$ and $\overrightarrow{V_n} = e_n + jf_n$.

Similarly the line impedance can be $Z_{kn} = R_{kn} + jX_{kn}$. Putting these rectangular coordinates in equation (3) and separating the real and imaginary parts:

$$\begin{gathered} P_n R_{kn} + Q_n X_{kn} = e_n(e_k - e_n) + f_n(f_k - f_n) \\ P_n X_{kn} + Q_n R_{kn} = f_k e_n - e_k f_n \end{gathered} \tag{4}$$

Eq.(3)represents the power flow equation for solving the voltage phasor at the receiving node (i.e., the node N) of the equivalent line of whole system(both local network and system outside the local network) provided that the voltage phasor at the sending node is known.

If each ESM for all equivalent lines in a system state has a mathematical solution for its receiving node i.e. voltages at all nodes in the system state exist, then the system should have an overall power flow solution and the system voltage stability holds. Conversely, if an ESM for at least one receiving node does not have a mathematical solution i.e. the operational voltage any node does not exist, the system cannot have a system-wide power flow solution and will lose voltage stability. Hence the system stability depends on the solvability of Eqs.(3)for all nodes in the system. The solvability of Eqs.(4) can be judged by singularity of its Jacobian matrix, i.e.,

$$J = \begin{bmatrix} e_k - 2e_n & f_k - 2f_n \\ f_k & -e_k \end{bmatrix} \tag{5}$$

$$\det(J) = 2(e_k e_n - f_k f_n) - (e_k^2 + f_k^2) = 0 \tag{6}$$

where the symbol det denotes the determinant of the Jacobian matrix J.

Eq.(5)provides a new voltage stability index, which is called the equivalent node voltage collapse index given by the equation:

$$\text{ENVCI} = 2(e_k e_n - f_k f_n) - (e_k^2 + f_k^2) \tag{7}$$

Also, the expression of ENVCI in the polar coordinates can be expressed as:

$$\text{ENVCI} = 2E_k V_n \cos\theta_{kn} - E_k^2 \tag{8}$$

where, $\theta_{kn} = \theta_k - \theta_n$

It can be seen that the calculation of ENVCI only needs voltage phasors at the two ends of the ESM. Each node has an ESM. When the ENVCI of at least one node is close to zero in a system state, the system approaches the voltage collapse point and the corresponding node is the weakest node that causes system instability.

The ENVCI can be easily used in a real time or on-line environment since it can be calculated very fast using the voltage phasors that are obtained from the state estimator of EMS. It is worthy to note that in general, not all nodes but selected nodes need to be monitored in actual applications as operators know the fact that the system will never lose voltage stability at many nodes. Conceptually, however, it is not difficult to calculate the ENVCI for all nodes if necessary.

IV. TEST SYSTEM AND RESULTS

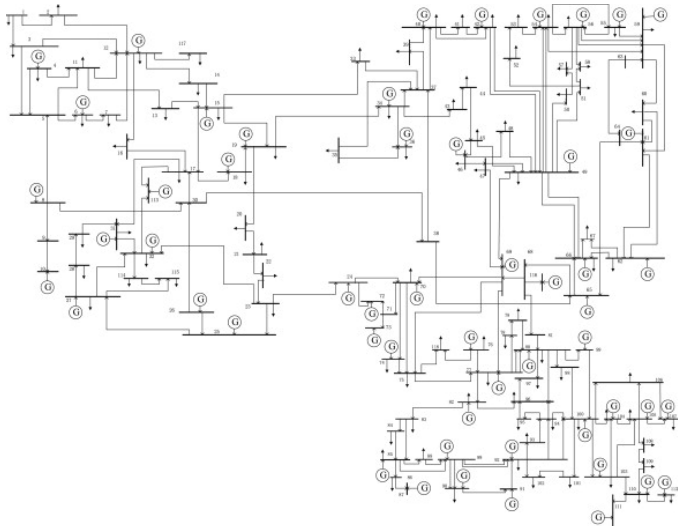

Fig.2

The IEEE-118 bus System as shown in Fig.2, which is composed of 118 buses and 186 lines, has been used to test the proposed methodology.

The data for IEEE-118-bus System consists of 118 buses which are renumbered to make bus-69 as slack bus having pre-specified voltage as $1.00\angle 0°$ p.u., 53 numbers of PV buses out of which 18 number of buses are generating, and 64 number of load (PQ) buses out of which 53 number of buses are practically loaded as listed in Table I.

In this study, step increase of active (P) loads is done keeping reactive (Q) loads constant. P load is changed in one bus at a time and again for next bus. Node loads are gradually and proportionally increased by multiplying the factor Lambda in each stressing step. Lambda is increased stepwise by 1% variation.

The simulation results for Nodes 2, 3 , 13 and 16 are as shown in Table II and arranged in order of decreasing weakness. Initially load flow is performed without increasing the active loads and then with increasing the active loads. The voltage variation at various nodes are observed as shown in Fig.3 (a) and Fig.3 (b). The variation of ENVCI of the node is displayed with an increase of Lambda in Fig.4 (a),Fig.4 (b) ,Fig.4 (c) and Fig.4 (d). The ENVCI indices of all key nodes decrease gradually and monotonically as Lambda increases.

TABLE I

DATA FOR IEEE 118 BUS TEST SYSTEM

PV Buses	1,4,6,8,10,12,15,18,19,24,26,27,31,32,34,36,40,42,46,49,54, 55,56,59,61,62,65,66,70,72,73,74,76,77,80,85,87,89,90,91,92, 99,100,103,104,105,107,110,111,112,113116
Actually generating PV Buses	10, 12, 25 ,26, 27, 31, 46, 49, 54, 59, 61, 65, 66, 80, 87, 89,100,103, 111
Practically loaded PQ Buses	2, 3, 7, 11, 13, 14, 16, 17,20, 21, 22, 23, 28, 29, 33, 35, 39, 41, 43, 44, 45, 48, 50, 51, 52, 53, 57, 58, 60,67,75,78,79,82,83,84, 86,88,93,94,95,96,97,98,101,102,106,108,109,114,115,117, 118

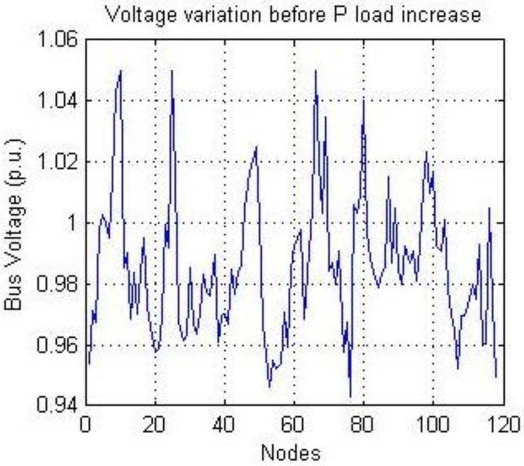

Fig.3 (a). Voltage variation of 118 nodes in IEEE-118 Bus test system without any change in P load.

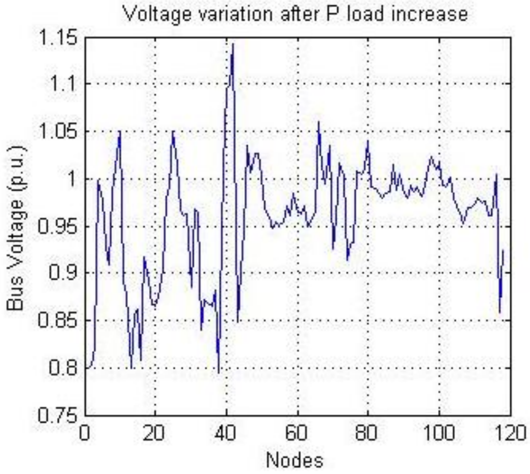

Fig.3 (b).Voltage variation of 118 nodes in IEEE-118 Bus test system after increase in P load.

TABLE II

RESULT FOR IEEE-118 BUS TEST SYSTEM
(NODES ARRANGED IN DESCENDING ORDER OF WEAKNESS)

SL. NO.	NODE	OPERATING VOLTAGE (P.U.)	ENVCI_	LAMBDA	LOADABILITY (KW)
1	2	1.0096	0.0787	26.04	520.800
2	16	1.0104	0.0872	22.654	566.350
3	13	1.0080	0.1009	15.305	520.370
4	3	1.0124	0.1116	15.096	588.744

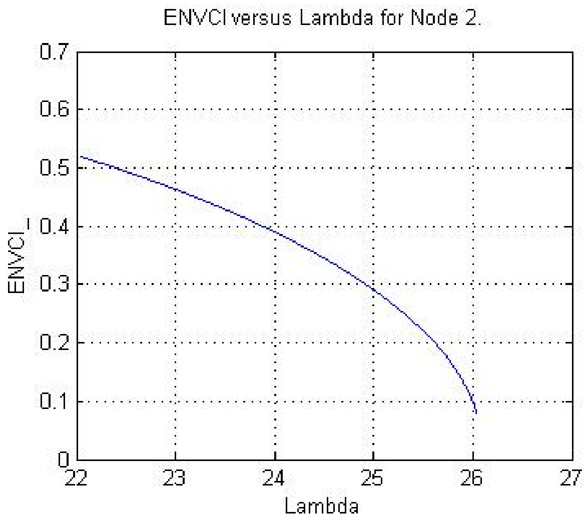

Fig.4 (a) .ENVCI_ of node 2 versus Lambda in IEEE 118 system

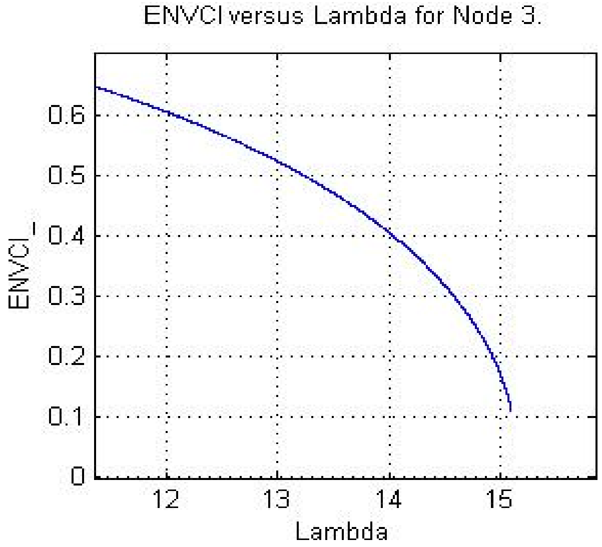

Fig.4 (b) .ENVCI_ of node 3 versus Lambda in IEEE 118 system

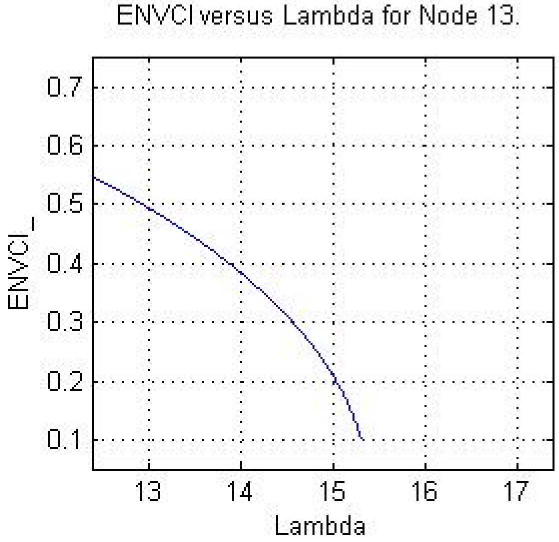

Fig.4 (c) .ENVCI_ of node 13 versus Lambda in IEEE 118 system

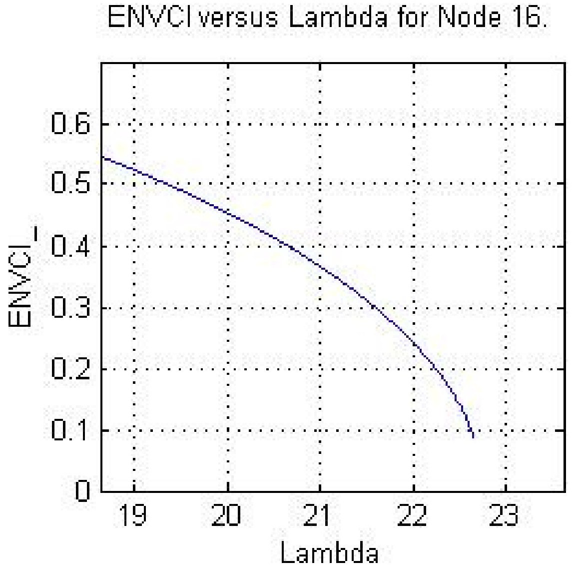

Fig.4 (d). ENVCI_ of node 16 versus Lambda in IEEE 118 system.

V. CONCLUSION

The paper presents the method of ESM for calculating the voltage stability index of each node (bus) in a transmission system. An index ENVCI for identifying system voltage instability based on ESM is proposed for recognition of the weakest node. The results of IEEE-118 bus test system demonstrate the effectiveness of the proposed index and method. A system will lose voltage stability whenever the ENVCI of at least one node approaches zero. Thus voltage stability index can be set to predict the critical states thereby preventing system collapse.

VI. ACKNOWLEDGEMENT

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