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A Novel Index for Detecting Line Stability Based on the Structural Characteristics of Power Transmission Systems

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Abstract: ***In general, there is a large mismatch between power generation and power demand. Hence to ensure the power quality of power transmission systems has become a challenging task. One major issue in power quality is voltage collapse, which can cause system blackout if not detected in time. There are many measures to detect voltage collapse, among which identification of weak buses and weak lines plays a major role. Weak buses are identified using the Structural Characteristics Method (SCM). A novel stability index based on network structural characteristics is proposed for the identification of weak lines that can cause voltage collapse. This Electrical Distance Stability Index (EDSI) is determined on the basis of the electrical distance between various buses with that of weak buses determined by a structural characteristics method. The major significance of SCM and EDSI is the determination of weak buses and weak lines respectively without the need for load flow analysis unlike the existing methods. The proposed index is implemented on IEEE 6, 14 and 30 bus systems. The results thus obtained by the EDSI are identical and effective when compared with the results of existing line stability indices.***

Keywords: ***Structural Characteristics Method (SCM), Eigenvalue decomposition, Electrical Distance Stability Index (EDSI), voltage collapse, voltage stability***

I. INTRODUCTION

Currently, power generation cannot adapt to varying power requirements. The transmission network operates close to its operational limits to facilitate better power transfer over existing lines and to avoid building new lines, for economic reasons. Therefore, it is essential to have a measure of power quality, especially the voltage profile. If this measure is not considered, it can lead to a poor voltage profile, which will cause a blackout due to the cascading of many such events. There are various techniques in the literature to identify the areas that are more prone to voltage collapse. The considered power system network is secured from voltage collapse by identifying either weak buses or weak lines and by subsequent preventive measures.

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The weak buses are those situated far from the generator buses and are in greater need of reactive power support. The network structure plays a vital role in power transmission, operation and maintenance. When the weak buses have been determined, it is easier to identify the weak lines that are highly prone to cause an outage under various contingencies that are likely to occur in the network.

Many researchers have proposed various techniques to detect buses that cause voltage collapse in order to secure the network [1]. Some of the techniques used are Q-V and P-V curves [2], Continuation Power Flow method (CPF) [3], numerous power flow solutions [4], modal analysis [5], proximity of voltage stability indicators , singularity of Jacobian matrix [6], power flow solutions centred stability indices [7], [8] and the optimization of reactive power dispatch [9]–[12]. The various VSI include the L-index, V/Vo index, sensitivity methods [13], line indices such as the (FVSI) [14], L_{mn} [15], L_{QP} [16] and the voltage collapse proximity index (VCPI) [17]. The line stability indices are used to monitor the system online [18] and to predict the weak buses, weak lines and the permissible power that can be transmitted. All these indices give a measure of proximity to voltage collapse. Reis and Barbosa [19] provided a comparison of various voltage stability indices.

In most of these methods, it is necessary to obtain the present values of the voltages and other related parameters whenever there is a variation in load demand. Hence, for many methods, it is required to repeatedly run the load flow analysis. When compared with the previously mentioned methods, the SCM gives a similar result without the necessity for repeated load flow analysis. The circuit theory method also denotes the maximum power as the basic circuit concepts are met. The weak buses thus identified remain the permanent locations for the reactive power compensators for the given system topology, both for normal and contingency conditions. The weak buses thus identified can be used to determine the weak lines.

Gao et al. proposed modal analysis. Mansour [20] identified critical buses that cause voltage collapse by modal or eigenvalue analysis of the system Jacobian matrixku. Sikiru et al. [21] discussed the role of system interconnections and gave its mathematical derivation. The networks were classified as weak or strong based on their inherent structural characteristics [22]. Sikiru et al. [23] discussed the association between the generator and the load and its importance for voltage maintenance.

Authors emphasized various characteristic indices that were obtained from the partitioned sub-matrix of the Y_{bus}. The impact of these characteristic indices on the real power transfer (which is subject to various operational constraints) is discussed. Based on the generator to generator characteristic index, a comparison with the T-index proposed by Dhadbanjan et al.

[24] for new generator placement is made. From the above discussion, it is clear that the structural characteristics method involves fewer computational steps with less complexity and no negotiation in accuracy. Hence, the structural characteristics method is observed to be efficient in identifying the weak buses when compared with conventional sensitivity analysis techniques and other voltage stability indices.

II. VOLTAGE STABILITY INDICES

There are many voltage stability indices discussed in the literature for the identification of the weak buses and weak lines that cause voltage collapse. These indices predict the distance of the system to the voltage collapse point and hence play a significant role in securing the system from collapse. A novel index called Electrical Distance Stability Index is proposed and the observed results are compared with existing line stability indices such as the L_{mn}, L_{QP} and FVSI, which are given as follows.

A. Line Stability Index (L_{mn})

L_{mn} is determined as below

$$L_{mn} = \frac{4xQ_r}{[V_s \sin(\theta - \delta)]^2} \tag{1}$$

The considered system is said to be stable if and only if L_{mn} is less than one.

B. Line Stability Factor(L_{qp})

A static index L_{QP} is formulated from the power equations. Conditions for stability are obtained from load flow and are extended as the factors to assess the line stability.

$$L_{QP} = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \tag{2}$$

C. Fast Voltage Stability Index (FVSI)

The FVSI stability index is given as below

$$FVSI_{ij} = \frac{4Z^2Q_j}{V_i^2 X} \tag{3}$$

Variation of reactive load from base to maximum is performed to obtain this index. Hence, this index provides the value of the maximum load that the buses can withstand and identifies the weak buses and weak lines of the system. The FVSI values are obtained for all the lines, and weak lines are that with greater value. System is unstable when the index value move towards 1 and is stable when the value move towards 0. If the value of index exceeds 1, it denotes the large voltage drop during which either of the bus in the line has reached instability point. Hence, when discussing line stability indices such as L_{mn}, L_{QP} and FVSI, it is clear that all these indices are evaluated based on load flow calculations, whereas the proposed EDSI index is relying on the electrical distance of loads connected to weak buses. Weak buses are those that cause voltage collapse and are identified by the SCM.

III. MATHEMATICAL DESCRIPTION OF STRUCTURAL CHARACTERISTICS METHOD [21]:

Structural characteristics method is an accurate method for finding the weak buses to implement reactive power compensators.

As per circuit theory,

$$V = Z * I \tag{4}$$

where

V – voltage of the bus

I – current through the line

Z – impedance of the line

From which I is given by

$$I = Z^{-1} * V \tag{5}$$

where $Z^{-1} = Y_{bus}$

hence, $I = Y_{bus} * V$ (6)

Equations (4) to (6) denote the relationship between current, voltage and the transmission impedance of the corresponding generator and load buses as per basic circuit laws.

Equation (7) denotes the partitioning of the Y_{bus} matrix based on the interconnections that exist between the generators and load buses without affecting the Y_{bus} elements.

$$Y_{bus} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \tag{7}$$

where

Y_{GG} - coupling of generator-generator with dimension G × G

Y_{LG} - load-generator coupling with dimension L x G

Y_{GL} - generator-load coupling with dimension G x L

Y_{LL} – load to load interconnections with L × L

L, G - loads and generators respectively

Y_{bus} is substituted and the resulting equation is

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix}\begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{8}$$

where

I_L – load currents

I_G – generator currents

V_G – generator voltages

V_L – load voltages

Upon rearranging equation (8)

$$\begin{bmatrix} V_G \\ I_L \end{bmatrix} = \begin{bmatrix} Z_{GG} & E_{GL} \\ N_{LG} & R_{LL} \end{bmatrix}\begin{bmatrix} I_G \\ V_L \end{bmatrix} \tag{9}$$

where

$Z_{GG} = Y_{GG}^{-1}$, net impedance of generators accounting for losses

$E_{GL} = -Y_{GG}^{-1}Y_{GL}$, generators influence over load buses, called generator affinity

$N_{LG} = Y_{LG}Y_{GG}^{-1}$, negative transpose of E_{GL} matrix

$R_{LL} = Y_{LL} - Y_{LG}Y_{GG}^{-1}Y_{GL}$, the Schur complement of Y_{GG} in Y_{bus} is equivalent to the product of determinant of Y_{GG} and determinant of R_{LL} as given below

$$\det Y = \det Y_{GG} \det R_{LL} \tag{10}$$

Equation (10) does not change the value of the basic circuit equations (4) to (8) above in any way.

Matrix R_{LL} denotes the equivalent admittance of only the load buses. Effect of interconnections between load buses on power flow is obtained from this matrix.

Equations (8) to (10) discuss the matrix manipulation involved in the isolation of the load to load interconnections, making it suitable to apply the eigenvalue decomposition technique to find the weak buses.

The eigenvalue decomposition of the R_{LL} matrix is given by (11)

$$R_{LL} = VNV^* = \sum_{i=1}^{n} v_i \lambda_i v_i^* \tag{11}$$

in which V is an orthonormal matrix with eigenvectors v_i and N is the diagonal matrix with eigenvalues $\lambda_i, i = 1,2,\ldots n$ as its diagonal elements.

On expanding (9), the voltage of the load bus is obtained as

$$[V_L] = [R_{LL}]^{-1}[I_L - N_{LG} I_G] \tag{12}$$

The relationship between the eigenvalue and the load voltage is given by substitution of (11) into (12)

$$\|V_L\| = \left\| \sum_{i=1}^{n} \frac{v_i v_i^*}{\lambda_i} [I_L - N_{LG} I_G] \right\| \tag{13}$$

where

λ_i are the eigenvalues.

Equations (11) to (13) show the implementation of EVD and the determination of eigenvalues.

The buses with the least eigenvalues are the weak buses based on their reciprocal relationship with the load bus voltages. These are the weak buses that are responsible for the decline in voltage in particular and are the most suitable locations to place the reactive power compensators.

IV. FORMULATION OF PROPOSED LINE STABILITY INDEX

Consider a network with G generators and L loads respectively. The weak buses are identified by SCM, which is discussed in part 3. The weak lines are identified with ascending value of j_{th} bus admittance, Y_{ij}, where i_{th} bus is the weak bus.

N - Count of buses in the system
G – Count of generators
L - Count of loads, (N-P)

$$\forall L, i = 1,2,\ldots L,\ j = 1,2,\ldots L,$$

$$where j \neq i \exists \left|Y_{ij}\right| iff \left|Z_{ij}\right| \neq 0 \tag{14}$$

$$EDSI = ASC(\left|Y_{ij}\right|), where Y_{ij} = 1/Z_{ij}$$

where

Z_{ij} – impedance of the transmission line between the load buses i and j

Y_{ij} – admittance of interconnections between loads

$ASC(\left|Y_{ij}\right|)$ - ascending order of the admittance of all the load buses j, with respect to the i_{th} load bus where i denotes the weak buses determined by the SCM.

The weak lines thus identified by the EDSI are accurate since the identification of weak buses satisfies the basic circuit laws. These weak lines are sorted based on the electrical distance between the other load buses with respect to weak buses. This sorting is based on the fact that the decline in the voltage profile will be much higher at the load buses that are far from the weak bus rather than that at the buses that are located closer to the corresponding weak bus. The EDSI does not require repetitive load flow analysis, unlike the other voltage stability indices, which is a remarkable feature. The implementation of the EDSI on test systems and the closeness of the results with those of other line stability indices are discussed in the following section.

V. RESULTS AND DISCUSSION

A. Implementation of the EDSI on test systems and its validation with other line stability indices

EDSI is demonstrated on IEEE test systems. The weak buses of test systems are identified by SCM and are given in Table. I, II, III respectively.

Table-I: Eigenvalue of 6-bus system

Ranking of the weak buses	Bus No.	Eigenvalue
1	4	0.1739
2	5	12.6716
3	6	18.8166

Table-II: Eigenvalue of 14-bus system

Ranking of the weak buses	Bus No.	Eigenvalue
1	9	0.0214
2	11	2.8066
3	14	4.9626
4	12	5.5783
5	13	5.6996

Table-III: Eigenvalue of 30-bus system

Ranking of the weak buses	Bus No.	Absolute of Eigenvalue
1	19	0.0178
2	20	0.7950
3	24	1.5424
4	21	1.8278
5	25	3.1460
6	26	3.4046
7	28	4.5569
8	29	5.9634
9	30	5.6344

B. Weak buses of the test systems

- ***6-bus system***

It is clear that first weak bus is 4 followed by 5 and 6 respectively

- ***14 bus system***

The top three weakest buses are 9, 11, and 14, in that order. Upon observing the results, it is clear that these buses are weak, as they are located far from the generator buses and are not in direct association with any of the generator buses. However, there is an exception in case of bus 11. This exception is in connection is because three load buses 11, 12 and 13 are connected to the generator bus 6, among which bus 11 has the highest load when compared to that of 12 and 13 and gains less reactive power support from bus 6. Hence, the results reveal, the role of network structure in power transfer and reactive power compensation.

C. Weak lines of the test systems determined by the proposed index, EDSI

- ***6-bus system***

The weak lines of the IEEE 6 bus system identified from the weak buses based on network structural characteristics is given in Table. 4. The sequence of weak lines is (4-5) and (5-6).

Table-IV: Weak lines of IEEE 6 bus system

Bus No.	Critical lines (EDSI)
4	4-5
5	5-6

- ***14 bus system***

Table 5 shows the identification of weak lines and is validated with other voltage stability indices such as L_{mn}, FVSI and L_{QP}. The ascending order of weak lines obtained for bus 9 based on their electrical distances to other connected load buses is (9-4), (9-14), (9-7), and (9-10). The first two weak lines of bus 9, (9-4) and (9-14) are considered to be more significant than (9-7) and (9-10), because bus 9 is located closer to buses 7 and 10 than to 4 and 14. Hence, the sequence of weak lines associated with bus 9 per the EDSI is (9-4) and (9-14). The order of weak lines obtained for bus 11 is (6-11). The sequence of the weak lines based on the electrical distance obtained for bus 14 is (13-14) and (9-14). The weak line corresponding to bus 12 is (12-13).

Table V. Weak lines of IEEE 14 bus system

Weak buses (CT)	Critical lines (EDSI)	Critical lines (L_{mn})[25]	Critical lines (FVSI) [18], [19]	Critical lines (LQP) [18], [19]
9	9-4 9-14	9-4	9-4	9-4
11	6-11	6-11	6-11 10-11	6-11 10-11
14	9-14 13-14	13-14	9-14 13-14	
12	12-13	12-13	12-13	12-13

- ***30 bus system***

The weak lines of 30 bus system and its validation with other line stability indices is given in Table. 6, the EDSI gives similar results, but without the need for repeated load flow analysis.

Table VI: Weak lines of IEEE 30 bus system

Weak Buses (SCM)	Critical lines (EDSI)	Critical lines (L_{mn}) [25]	Critical lines (FVSI) [18], [19]	Critical lines (LQP) [18], [19]
27	27-30 27-29 27-28	27-30	27-30	27-30
30	27-30 29-30	27-30 29-30	27-30 29-30	27-30 29-30
19	19-18 19-20	-	-	-
20	20-10 20-19	-	-	-

D. The impact of implementation of SVCs at weak buses

The implementation of SVCs at these weak buses shows a better improvement in voltage profile. The implemented SVCs provide reactive power support of ±100 MVAR. The improvement in voltage profile obtained by SCM is validated with L-index and the CPF method. SCM results are compared in particular with the L-index since the L-index uses the sub-matrix obtained by restructuring the admittance matrix in a manner similar to that of the SCM. Second, the CPF method is considered since it is capable of defining the weak buses based on their maximum load, similar to the SCM approach, as SCM can support the maximum load for the given network structure. From Figs. 1 and 2, the SCM method requires fewer SVCs to yield a similar voltage profile when compared with that for the voltage stability indices [26]–[28] and the CPF method. Therefore, the SCM method is proven to be cost effective.

E. Algorithm of Electrical Distance Stability Index (EDSI) to identify the weak lines

- Obtain Y_{bus} matrix for the given network.
- Rearrange the Y_{bus} matrix in to sub-matrices concerned with interconnections between generator-generator, generator-load , load –generator and load-load (as per equation (8)).
- Eigenvalue is obtained for load-load sub-matrix and load buses with least eigenvalues are the weak buses.
- EDSI is applied at these weak buses to obtain the weak lines.
- Weak lines are the lines associated with these weak buses and the other load buses which are far apart comparatively.
- SVC is implemented at these buses and improvement in voltage profile is observed.

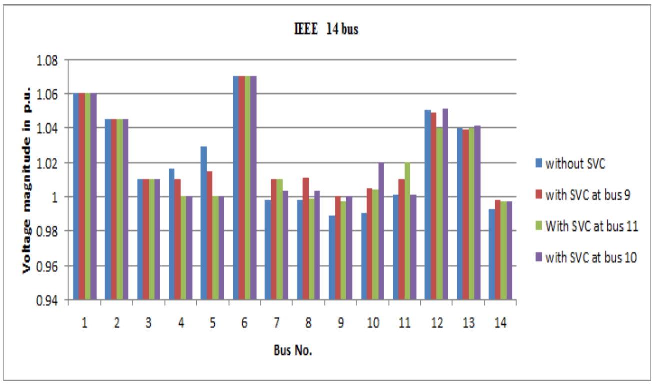

Fig. 1. Voltage magnitude of IEEE 14 bus system with SVC at weak buses concerned with weak lines

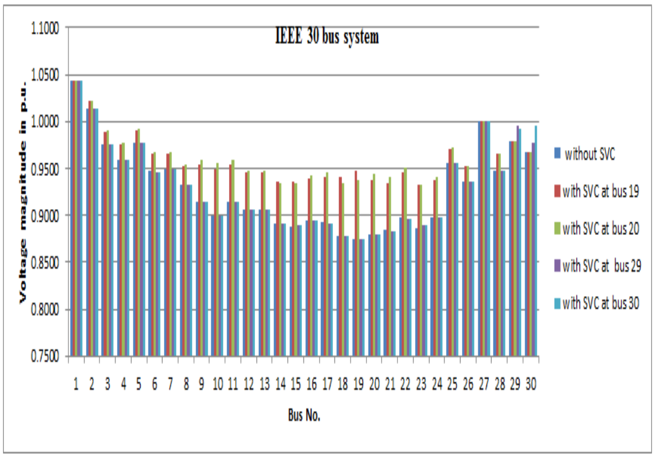

Fig. 2. Voltage magnitude of IEEE 30 bus network with SVC at weak buses concerned with weak lines

VI. CONCLUSION

The identification of weak lines by the proposed EDSI shows that the electrical distance of the loads in connection with weak buses determined by SCM plays a major role. The weak lines thus identified by the EDSI are identical to the weak lines identified by other line stability indices such as the L_{mn}, L_{QP} and FVSI. The EDSI is highly efficient in identifying weak lines in a single step without the need for the repeated load flow analysis as required by other line stability indices. The implementation of reactive power compensators such as SVCs at the weak buses determined by the SCM has shown a better improvement in voltage profile with fewer compensators than those of other methods. Hence, the SCM is economical and robust. In the future, this work may be extended to observe the system behaviour when subjected to a transient condition for online monitoring and system maintenance applications.

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