Ministry of Education and Scientific Research
Elmergib University
Faculty of Engineering Al-khoms
Department of Electrical and Computer Engineering
Elmergib Journal of Electrical and Electronic Engineering

وزارة التعليم العالي والبحث العلمي
جامعة المرقب
كلية الهندسة الخمس
قسم الهندسة الكهربائية والحاسوب
مجلة المرقب للهندسة الكهربائية والالكترونية

Volume **1,** Issue **1,** Nov **2022**

Voltage Stability Assessment and Improvement Index using Load Shedding and a Shunt Capacitor

Hesain Milad Alfrd[1], Mahmoud .Y. KHamaira [2]
[1] hussein.alfared@gmail.com, Lecturer at Electrical & Computer Dept,University of Elmergib, Libya
[2] mykhamair@elmergib.edu.ly, Assistant Professor at Electrical & Computer Dept,University of Elmergib, Libya

Abstract- Voltage stability of large interconnected power systems has been recognized as a complex problem for identifying the fundamental mechanism of voltage stability due to the multiplicity of power system operation and control components, complicated configuration, and overall performance of the systems. Heavy loading and system faults are factors that contribute to voltage instability in power systems. Treating heavy loading at stressed buses necessitates the selection of the appropriate bus, which has become difficult to find and predict, especially in an interconnected system. In this paper, a voltage stability assessment index is derived using linear algebra and the Singular Value Decomposition (SVD) and Pseudo-inverse of the power flow Jacobian matrix. Singular values and the right eigenvector are used as load shedding recognition indicators. Meanwhile, VSM (Voltage Stability Margin) improvement is being pursued through load shedding with sensitivity ranking for the assessment index, and installing a shunt capacitor at the most sensitive bus bar for obtaining a better P-V Curve. Finally, the study was tested on IEEE 14-bus as a case study.

Keywords **-**Load shedding, Sensitivity, Shunt Capacitor Allocation, Voltage stability assessment index, Weak bus recognition.

INTRODUCTION

Increased power demand and limited electric power sources have resulted in a more complicated interconnected system, forcing it to function closer to the system's stability constraints. Voltage stability is a topic of great importance to industry and research around the world because the power system is being operated at maximum capacity, but network development is limited for a variety of reasons, including a lack of investment or major environmental issues [1]. When a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable drop in voltage, the system enters a state of voltage instability [2]. The effect of fluctuations in reactive and active power in the load region on the voltages at the load buses determines voltage stability. Voltage stability indices and load shedding have been the subject of numerous studies in the literature. With the usage of P-V and P-Q curves, reference [3] developed a multi-criteria integrated voltage stability index for identifying weak buses [4] quantifies the link between reactive power reserves and VSM (Voltage Stability Margin). Sinha [5] offered a comparative investigation of voltage stability utilizing index-L and modal analysis, with the three indices added together. [6], [7] investigate the use of shunt capacitors for reactive power compensation and reactive power planning.[8] the optimum size and location of the shunt capacitor and DG connected to the distribution system are studied by using an optimal control theory with an excellent solution approach (Newton Raphson). In [10], [11], modal analysis and Jacobian matrix are employed to evaluate VSM. In contrast, [9] developed a strategy for improving VSM by using shunt capacitors and also used the modal analysis methodology. [12] a voltage stability assessment index is derived using linear algebra and the Singular Value Decomposition (SVD) and Pseudo-inverse of the power flow Jacobian matrix. Singular values and the right eigenvector are used as load shedding recognition indicators. [13] Proposed a method for identifying the position and quantity of the load to be shed using a voltage stability indicator calculated mathematically.

Submitted 12 Sep. 2022; Final Version Received 17 Oct. 2022; Accepted 15 Oct. 2022; Published Online in Dec. 2022

The L Index and the study of voltage collapse index are based on the voltage collapse point theory, which states that power flow becomes intractable at this point [5], [13]. The other indices are also taken into account. Other indices, such as, are also counted as voltage stability limits. Other indices, such as the sensitivity index and singular value index [14], the load proximity index [15], [16], and the line stability index [17], are also considered voltage stability limits. Various factors are taken into account when creating these indices. Other indices, such as, are also counted as voltage stability limits.

In this paper, Jacobian eigenvalue and eigenvector indexes are primarily used with the help of linear algebra with sensitivity ranking for assessing voltage stability and improving VSM. The current method relies on load shedding at the appropriate worst bus/area. The test systems demonstrate that this assessment index method can be obtained to distinguish the weak and sensitive buses in the power system for load shedding; concurrently, the criterion voltage magnitudes on weak buses can be acquired through load shedding. Case studies are pursued under various conditions, critical and normal operation, to demonstrate the accuracy and effectiveness of the proposed assessment index. In addition, improving VSM by using shunt capacitors at the appropriate worst bus/area.

I. FORMULA FOR AN ASSESSMENT INDEX

The voltage stability of an electric power system can be analyzed during normal operation by computing the eigenvalue and right and left eigenvectors of a Jacobian matrix[9]. The premise is that when a power system reaches its voltage stability limit (collapse point), the determinant of the Jacobian matrix of the load flow solution becomes zero. At the operation point, the Jacobian matrix is defined using the linearized voltage-power equation as follows [18], [19]:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta \delta\\ \Delta V\end{bmatrix} \tag{1}$$

$$\mathrm{J_R} = \begin{bmatrix}\mathrm{J_1} & \mathrm{J_2}\\ \mathrm{J_3} & \mathrm{J_4}\end{bmatrix} = \begin{bmatrix}\frac{\partial \Delta \mathrm{P}}{\partial \delta} & \frac{\partial \Delta \mathrm{P}}{\partial \mathrm{V}}\\ \frac{\partial \Delta \mathrm{Q}}{\partial \delta} & \frac{\partial \Delta \mathrm{Q}}{\partial \mathrm{V}}\end{bmatrix} \tag{2}$$

Where J1, J2, J3, and J4 are Jacobian sub-matrices that reflect active and reactive power sensitivities, respectively.
$[\Delta P \quad \Delta Q]^T$
$[\Delta \delta \quad \Delta V]^T$ in terms of voltage angles and magnitudes.
By specifying $\Delta P = 0$, of the power flow Jacobian matrix presented by (1).This results in;

$$\Delta Q_i = J_R \Delta V_i \tag{3}$$

$$J_R = J_4 - J_3 J_1^{-1} J_2 \tag{4}$$

Where J_4 is the system's reduced Jacobian matrix.
Decomposition can be used to evaluate voltage stability in a power system directly. The Singular Value Decomposition (SVD) and Pseudo-inverse method (linear algebra) are used in this research. The determinant of the Jacobian matrix of the load flow solution becomes zero at the voltage stability limit in a power system.
Under the condition that U and V are orthonormal columns, singular-value decomposition and Pseudoinverse [21] are used.

$$A = U \sum V^T \tag{5}$$

$\sum$ is a nonnegative scalar and U and V are nonzero vectors.

$$\Sigma = \begin{bmatrix}D & 0\\ 0 & 0\end{bmatrix} \tag{7}$$

While, $\sum$ is a singular value of A(A is a $m \times n$ matrix) and, U and V are corresponding right and left singular vectors, consecutively. Where, $r = m = n$, then $\sum = D$ (D is $r \times r$ diagonal, nonnegative real values called singular values). $D = \mathrm{diag}(\sigma_1, \sigma_2, \dots, \sigma_n)$ ordered so that $\sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_n$. In this study, σ is a singular value of A, its square is an eigenvalue of $A^T A$. Therefore, $V^T = V$.
From Pseudo-inverse (linear algebra method) [19]:

$$A^{-1} = U \overset{-1}{\sum} V^T \tag{8}$$

$$\Sigma^{-1} = \begin{bmatrix} D^{-1} & 0 \\ 0 & 0 \end{bmatrix} \tag{9}$$

$$J_R = U\Sigma V^T \tag{10}$$

$$J_R^{-1} = U\overset{-1}{\Sigma}V^T \Leftrightarrow UD^{-1}V \tag{11}$$

$$D^{-1} = \operatorname{diag}\left(\frac{1}{\sigma_1}, \frac{1}{\sigma_2}, \cdots, \frac{1}{\sigma_n}\right)$$

If $U = u_1, u_2, \cdots, u_n$ and $V = v_1, v_2, \cdots, v_n$, then:

$$J_R = \sum_{i=1}^{n} \sigma_i u_i v_i \tag{12}$$

This summation can be calculated from 1 to r, where r is the rank of J_R.

By using (3):

$$\Delta V_i = \Delta Q_i J_R^{-1} \tag{13}$$

With the substitution of J_R^{-1}, the voltage stability assessment index can be obtained:

$$\Delta V_i = \sum_{i=1}^{n} \frac{1}{\sigma_i} u_i v_i \Delta Q_i \tag{14}$$

Form this index, one can easily observe the relations of σ_i, u_i and v_i with sensitivity index $\left(\frac{\Delta V_i}{\Delta Q_i}\right)$. The bus with the highest eigenvalue and the smallest right eigenvectors (left eigenvectors do not affect sensitivity) can be the most sensitive or the least sensitive in the system. As a result, based on the identification of the proper weak bus, the assessment index can be used as a first decision-making reference for subsequent procedures of VSM improvement in the system.

A bus that easily causes voltage instability is known as a weak bus [14], and this behavior is frequently identified via bus sensitivity. The bus voltage sensitivity index concerning active power load $\frac{\Delta V_i}{\Delta P_i}$ [5].

Furthermore, the current-voltage stability evaluation index identifies voltage-weak buses/areas that are sensitive to voltage instability for load shedding purposes. Case studies were conducted to demonstrate the accuracy and effectiveness of the suggested assessment index, allowing for a more exact assessment of weak buses.

II. CASE STUDIES

The research was carried out using IEEE 14 bus test cases. The voltage stability assessment index (14) developed in section I is put into practice. The voltage stability function of NEPLAN® software is used to calculate the Jacobian matrix, eigenvalue, eigenvectors, and sensitivity for analysis. For two scenarios, power stability and load shedding were investigated. Case I examines the validity of the assessment index using a weak bus and bus sensitivity analysis. Through numerical representation, Case 2 depicts load shedding and VSM improvement, Case 3 illustrates VSM improvement by installing a shunt capacitor. Today, several stability margins for electricity systems are considered, such as %5, and %6. The minimum stability margin in this investigation is chosen at 5%[9].

A. Weak Bus Recognition and Bus Sensitivity

In this case, the IEEE 14 Bus test system is used. Buses 14, 10, and 9 were identified as weak buses for analysis, as shown in the Appendix. Sensitivity analysis is useful in identifying weak buses; however, the sensitivity index alone will not be sufficient to identify weak buses, especially in a networked system.

The least eigenvalue and greatest right eigenvector should be considered when calculating the assessment index. At the minimal eigenvalue, buses 14,10, and 9 have the greatest right eigenvectors. As a result, these buses were named the "weakest" in the system. Meanwhile, bus 7 is the system's fourth weakest bus, with a sensitivity that is higher than that of bus 9. The indexes with the smallest eigenvalue 2.079206 and maximum eigenvectors 0.4861,0.4839,0.4767 corresponding to bus 14,10, and 9 respectively are shown in Table 1.

Table I: IEEE 14-BUS TEST SYSTEM

Bus	100 % loading	
	$\sigma_{\min} = 2.0792$	
	$\boldsymbol{v_i}$	$\boldsymbol{\Delta V/\Delta Q}$
14	0.4861	0.2233
10	0.4839	0.1621
09	0.4767	0.1376
07	0.4015	0.1416
11	0.3024	0.1352
13	0.1389	0.0872
04	0.1198	0.0439
12	0.0964	0.1376
05	0.0801	0.0427

[*] This case is simulated for 5 eigenvalues, the σ is the minimum value.

B. Load Shedding Performance Evaluation and Voltage Stability

In this scenario, IEEE 14 Bus test system (see the Appendix) is simulated utilizing the load-shedding method to improve voltage stability and reduce eigenvalues to minimal values. Bus 14 (the weakest bus) was chosen for load shedding in this scenario. At bus 14, the 50% load is shed in the first scenario, while the entire connected load (15.717 MVA) is shed in the second. At bus 14, the bus voltage is altered from 1.02 p.u to 1.03p.u and 1.04 p.u. These scenarios depict the movement of bus 14 to a stable zone through increasing eigenvalues and lowering eigenvectors, as shown in Table 2. It can be observed from the data in Table 2 that load shedding corresponds to the principle of the assessment index.

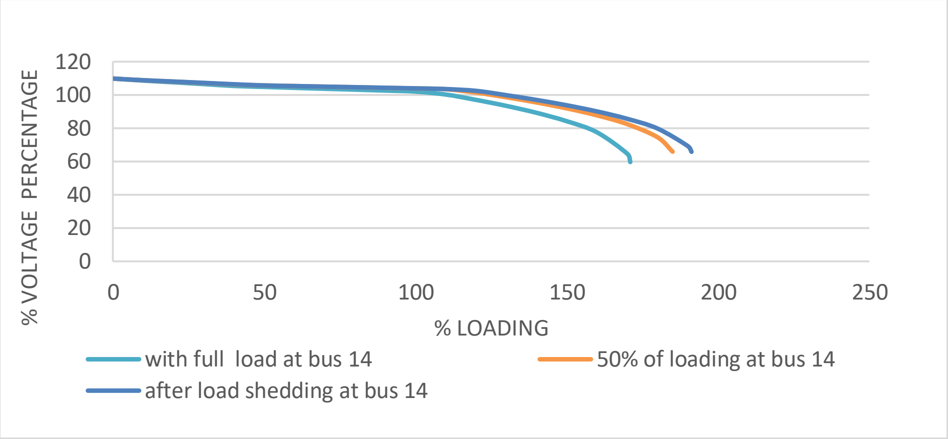


Figure 1 load shedding at bus 14.

Submitted 12 Sep. 2022; Final Version Received 17 Oct. 2022; Accepted 15 Oct. 2022; Published Online in Dec. 2022

The eigenvalue is modified from 2.0792 to 2.7250 in the first scenario, and it is increased from 2.7250 to 2.7489 in the second scenario, with a decrease in eigenvectors. With the highest voltage collapse point, lowest reactive power margin, and biggest % change in voltage, Bus 14 is the weakest. All these can be evidence of assessment index validity and load shedding effectiveness. Obtaining voltage profiles or short P-V curves of important buses as a function of their loading conditions can be used to examine voltage stability steady-state assessments [23]. As a function of the parameter value, Figure 1 demonstrates an increase in voltage magnitude at the operating point, as well as an improvement in voltage stability of the entire system with a 20.86MW load decrease at bus 14.

Table II: The font the spacing styles for EJEEE submission

Bus	50% loading Operation		Load shedding operation	
	σ_{min} = 2. 7250		σ_{min} = 2. 7489	
	v_i	$\Delta V/\Delta Q$	v_i	$\Delta V/\Delta Q$
4	0.0926	0.0405	0.093	0.0404
5	0.0634	0.0413	0.0638	0.0412
7	0.264	0.0778	0.2653	0.0776
9	0.4494	0.1068	0.4509	0.1064
10	0.4939	0.1408	0.4969	0.1404
11	0.3341	0.1297	0.3373	0.1295
12	0.1361	0.1373	0.1361	0.1371
13	0.1771	0.0862	0.1765	0.0859
14	0.557	0.2069	0.5507	0.2033

C. Installing a shunt capacitor at the weakest bus no 14.

A shunt capacitor is installed at bus 14 with a connected load of (15.717 MVA) considering the bus voltage equals 1 pu, whereas, the value of the capacitor to achieve that is (6.09 Mvar). Hence P-V curve has been improved for better voltage stability [9], and the Eigenvalue is modified from 1.8050 to 2.0792 which means obtaining voltage stability enhancement as shown in figure 2.

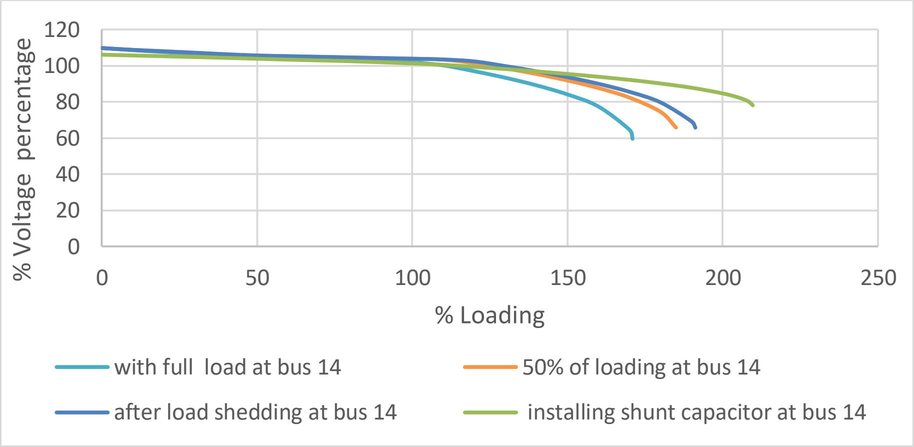


Figure 2 . Installing a shunt capacitor at bus 14.

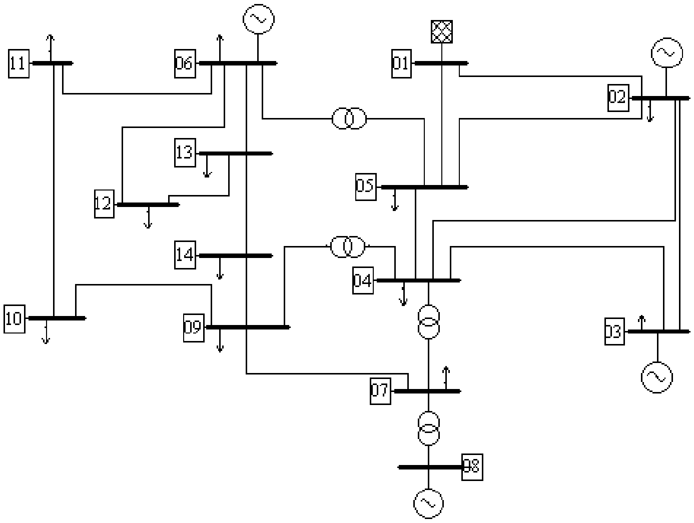
III. CONCLUSION

As a result of increased loads, the voltage stability problem has become a prevalent concern in power systems. One way to

Submitted 12 Sep. 2022; Final Version Received 17 Oct. 2022; Accepted 15 Oct. 2022; Published Online in Dec. 2022

mitigate voltage instability is to reduce the load on the system's essential buses and locations. The proposed assessment index load shedding by weak bus identification is the subject of this research, which focuses on a different element of voltage stability. The suggested assessment index's effectiveness is evaluated using two relevant test systems in regular and critical operations. Singular value decomposition and pseudo-inverse are used to simplify the Jacobian matrix (linear algebra). The study's synchronization of all operations can provide a fast snapshot of the system's steady-state voltage stability.

APPENDIX



Single line diagram of IEEE-14 Bus test system

.

REFERENCES

[1] W. Nakawiro and I. Erlich, "Online voltage stability monitoring using Artificial Neural Network," in Nanjuing. Apr. 2008, Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies Conf., pp. 941-947.

[2] P. Kundur, "Power system stability and control," 2nd ed., vol. 1-2. New York: McGraw-Hill, 1994, pp. 960.

[3] Gao Peng, Shi Libao, Yao Liangzhong and Ni Yixin, "Multi-criteria integrated voltage stability index for weak buses identification," in Seoul. 2008 Asia and Pacific Transmission & Distribution Conf., pp. 1- 5.

[4] A. Arunagiri and B. Venkatesh, "Simulation of voltage stability and alleviation through knowledge based system," Science Publications. American Journal of Applied Sciences, vol. 4, pp. 354-357, 2004.

[5] A.K. Sinha and D. Hazarika, "A comparative study of voltage stability indices in a power system," ELSEVIER. Electrical Power and Energy Systems, vol. 22, pp. 589-596, 2000.

[6] D. Chattopadhyay and B.B. Chakrabari, "Reactive power planning in incorporating voltage stability," ELSEVIER. Electrical Power and Energy Systems, vol. 24, pp. 185-200, 2002.

[7] O. Alizadeh Mousavi, M. Bozorg and R. Cherkaoui, "Preventive reactive power management for improving voltage stability margin," ELSEVIER. Electrical Power and Energy Systems, vol. 96, pp. 36-46, 2013.

[8] ALFRD, Hesain Milad. Optimal Power Loss Minimization using Optimal Size and Location of Shunt Capacitors, and DG. In: Proceeding Book of First Conference for Engineering Sciences and Technology (CEST-2018)(Part 2). 2018.

[9] H. Omidi, B. Mozafari, A. Parastar and M.A. Khaburi, “Voltage stability margin improvement using shunt capacitors and active and reactive power management,” Montreal. 2009 IEEE Electrical Power & Energy Conf., pp. 1-5.

[10] Su Yongchun, Cheng Shijie, Wen Jinyu and Zhang Yonggao, “Reactive Power Generation Management for the Improvement of Power System Voltage Stability Margin,” Dalian. 2006 The Sixth World Congress on Intelligent Control and Automation., vol. 2, pp. 7466-7469.

[11] R.B. Prada and J.O.R. dos Santos, “Fast nodal assessment of static voltage stability including contingency analysis,” ELSEVIER. Electrical Power and Energy Systems, vol. 51, pp. 55-59, 1999.

[12] M. S. S. Danish, A. Yona, and T. Senjyu, "Voltage stability assessment index for recognition of proper bus for load shedding," in 2014 International Conference on Information Science, Electronics and Electrical Engineering, 2014, vol. 1, pp. 636-639: IEEE.

[13] P Ajay-D-Vimal Raj and M. Sudhakaran. (2010, Jan.). Optimum Load Shedding in Power System Strategies with Voltage Stability Indicators. SciRes., Atlanta, Georgia. [Online]. Available: http://www.scirp.org/jounal/eng/

[14] M.M. Begovic and A.G. Phadke, "Control of voltage stability using sensitivity analysis," IEEE Trans. Power System, vol. 7, pp. 114-123, Feb. 1992.

[15] T. Nagao, K. Tanaka and K. Takenaka, "Development of static and simulation programs for voltage stability studies of bulk power system," IEEE Trans. Power System, vol. 12, pp. 273-281, Feb. 1997.

[16] K.Iba, H. Suzuki, M. Egawa and T. Watanabe, "Calculation of critical loading condition with nose curve using homotopy continuation method," IEEE Trans. Power System, vol. 6, pp. 584-593, May. 1991.

[17] C. Reis, a. Andrade and F.P. Maciel, “Line stability indices for voltage collapse prediction,” Lisbon. 2009 International Conference on Power Engineering, Energy and Electrical Drives., pp. 239-243.

[18] J. Duncan Glover, S. Mulukutla Sarma and J. Thomas Overbye, “Power system analysis and design,” 5th ed. Stamford: Cengage Learning, 2012, pp. 311-352.

[19] L. Mariesa Crow, “Computational method for electric power systems,” 2nd ed. Boca Raton, Florida: Tylor and Francis Group, LLC, 2010, pp. 72-98.

[20] Germund Dahlquist and Ake Bjorck, “Numerical Methods,” 1st ed. Stamford: Prentice-Hall, Inc, 1974, pp. 142-144.

[21] N. Philip Sabes, "Linear Algebraic Equations, SVD, and the Pseudo- Invers," San Francisco, Oct. 2001.

[22] Yao Zhang and Wennan Song, “Power system static voltage stability limit and the identification of weak bus,” Beijing. 1993 IEEE Region 10 Conference on Computer, Communication, Control and Power Engineering., vol. 5, pp. 157-160.

[23] M.M. Aly and M. Abdel-Akher, “A continuation power-flow for distribution systems voltage stability analysis,” Kota Kinabalu. 2012 IEEE International Conference on Power and Energy (PECon)., pp. 470- 475.