Performance Comparison of Voltage Stability Indices for Weak Bus Identification in Power Systems

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Abstract. Voltage collapse event is identified as complex and localized in nature but its effect is extensive once occurred. The vital effect of voltage collapse would be the total system collapse or blackouts which would cost a large loss to utility companies. Eventually, on-line monitoring of power system stability has become an important factor for electric power utilities. The last utmost option to avert voltage collapse incident from occurring is by the implementation of under voltage load shedding scheme. The identification of location for load shedding is the main motivation of the study. The weakest bus in a power system is identified as the location for load shedding. This location is obtained using voltage stability index Ld. The performance and effectiveness of Ld index is compared with Fast Voltage Stability Index (FVSI) and Le Index. The results obtained indicate that Ld Index can be used to identify the weak bus in a power system and consequently for the placement of UVLS relays in a power system network.

1. Introduction

Power systems at present are much more vulnerable to voltage collapse than many years ago because the systems are being stressed due to huge power transfers across the grids which cause transmission lines to operate close to the limits. In addition, generation reserves are minimal and often the reactive power is insufficient to satisfy the load demands [1]. Due to these reasons, power systems become more susceptible to disturbances, outages and instability.

Under voltage load shedding (UVLS) is specifically designed as a safety measure to prevent widespread voltage collapse in the event of severe deficit in local or system wide area reactive power reserves. UVLS has become the preferred strategy by power utilities due to its cost-effective solution to address voltage stability issues. However, before implementing under voltage load shedding, several issues have to be addressed, such as the location of load shed, the quantum to shed at the identified locations and also the timing of when to load shed.

This paper aims to evaluate the performance of various voltage stability indices in identifying the locations for load shedding. The weakest bus in a power network is identified to be the most effective location for load shedding. The various voltage stability indices considered in this study are the stability index, Ld [2], Lq index and FVSI index [3, 4]. Power flow and voltage collapse simulations

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were implemented on the IEEE 30 bus test system using the PSS/E software program. The voltage stability indices are then calculated and evaluated at each simulation so as to identify the suitable location for load shedding.

2. Voltage Stability Indices

Typically, line stability indices are formulated based on the power transmission concept in a single line. A single line diagram of an interconnected network is shown in Figure 1.

![Single Line Diagram of a Two-Bus system](image)

**Figure 1.** Single Line Diagram of a Two-Bus system [5]

2.2 Voltage Stability Index Formulation for Testing System

There are three types of line voltage stability indices that are used for the analysis. They are Voltage Stability Index $L_d$, Line Stability Index $L_e$, and Fast Voltage Stability Index (FVSI).

2.2.1 Voltage Stability Index, $L_d$:

The mathematical formulation of this index is derived from voltage equation of the radial distribution system. The developed indicator is given as:

$$L_d = \frac{4\sqrt{\left(P_{i+1}^2 + Q_{i+1}^2\right)(r^2 + x^2)}}{V_{i+1}^2}$$  \hspace{1cm} (1)

where $P_i$ and $Q_i$ are active and reactive sending end power, $P_{i+1}$ and $Q_{i+1}$ are active and reactive receiving end power, $V_i$ and $V_{i+1}$ are sending end and receiving end voltage and $r$ and $x$ are the line impedance [11]. The line that gives index value closest to 1 will be the most critical line of the system and may lead to wide voltage collapse.

2.2.2 Voltage Stability Index, $L_e$:

The equation for this index is given as below:

$$L_e = \frac{2\left[Q_{i+1} \left(P_{i+1} + Q_{i+1} x_i\right) + (P_{i+1} x_i - Q_{i+1} x_{i+1})^2\right]}{V_i^2}$$  \hspace{1cm} (2)

Similar to the previous index $L_d$, $P_{i+1}$ and $Q_{i+1}$ are active and reactive receiving end power, $V_i$ is sending end and receiving end voltage and $r$ and $x$ are the line impedance [11]. It is noted that $L_e$ index has to be less than 1 in order to satisfy the stability condition. When the value of the index approaches 1, it indicates that the system in becoming unstable.

2.2.3 Fast Voltage Stability Index, FVSI:

This index is proposed by I. Musirin and it is calculated by [12]:

$$FVSI = \frac{4Z^2Q_r}{V_s^2X}$$  \hspace{1cm} (3)

As previously defined, $V_s$ and $V_r$ are the sending end and receiving end voltages, $Q_r$ is the reactive power at the receiving end while $Z$ is the line impedance and $X$ is the line reactance. FVSI index less than 1 shows that the system is stable while FVSI index value of 0 shows system is collapse.

3. Test System Analysis and Results

The standard model of IEEE 30 Bus test system is used as a test case for the study purpose [5]. The system consists of 6 synchronous generators and 4 transformers. The system has 21 load points totalling 283.4 MW and 126.2 MVAR.
The simulation was carried out and index calculation was performed using MATLAB in order to verify the most sensitive indicator in identifying and locating the weakest bus prior to load shedding. Tables below shows the index value obtained for three different scenarios. Table 1 shows the index value calculated for Base Case. Table 2 shows the results obtained for MW increment at selected load buses, while Table 3 shows the results obtained for MW and MVAR increment at selected load buses. All the indicators range from 0 at most stable to 1 at the most unstable.

From Table 1, it is obvious that all the index values are in the range of most stable. A low index value indicates a high voltage value for a particular bus in the system. Overall, Ld index is found to show a higher value as compared to Le Index and FVSI index.

On the other hand, Table 2 shows the index calculated for a MW increment at loads using PSS/E. The system is stressed as the generators are incapable to cater for the increasing demand at the loads. The system operates until it reaches voltage instability situation. The high index value at certain branches shows that the lines are heavily loaded and can cause cascaded wide area collapse. Bus 26 to Bus 30 exhibits a high index value and correspondingly lower voltage value. Bus 26 to Bus 30 are identified as the weakest point in the whole system.

Results obtained in Table 3 show the index calculated for MW and MVAR increment at loads via PSS/E. Much more severe voltage drop occurs when MVARs are transferred as compared to the drop that occurs when MW are transferred.

### Table 1. Comparison Study for Index Calculated at Base Case

| Case 1 | From Bus | To Bus | (Vi, p.u) | FVSI | Ld   | Le   |
|--------|----------|--------|-----------|------|------|------|
| 6      | 7        | 0.97230| 0.01120   | 0.03738| 0.00984|
| 8      | 0.97230  | 0.04568| 0.06286   | 0.04095|
| 9      | 0.97230  | 0.03465| 0.05467   | 0.03321|
| 10     | 0.97230  | 0.04265| 0.07527   | 0.04129|
| 28     | 0.97230  | 0.00536| 0.00993   | 0.00462|
| 25     | 26       | 0.99050| 0.05328   | 0.08164| 0.04545|
| 27     | 0.99050  | 0.01528| 0.05750   | 0.01510|
| 27     | 28       | 1.00000| 0.10720   | 0.19067| 0.11250|
| 29     | 1.00000  | 0.03640| 0.12706   | 0.04255|
| 30     | 1.00000  | 0.05241| 0.21197   | 0.07541|

### Table 2. Comparison Study for Index Calculated with MW Increment at Loads

| Case 2 | From Bus | To Bus | (Vi, p.u) | FVSI | Ld   | Le   |
|--------|----------|--------|-----------|------|------|------|
| 6      | 7        | 0.95300| 0.01768   | 0.01881| 0.01416|
| 8      | 0.95300  | 0.06476| 0.10179   | 0.05628|
| 9      | 0.95300  | 0.65853| 0.66251   | 0.61723|
| 10     | 0.95300  | 0.18498| 0.41243   | 0.20745|
| 28     | 0.95300  | 0.06489| 0.13347   | 0.05537|
| 25     | 26       | 0.84380| 0.48024   | 1.00000| 0.61241|
| 27     | 0.84380  | 0.16388| 0.14341   | 0.09357|
| 27     | 28       | 0.87620| 0.03960   | 1.00000| 0.48566|
| 29     | 0.87620  | 0.68881| 1.00000   | 0.87495|
| 30     | 0.87620  | 0.81511| 1.00000   | 1.09513|

### Table 3. Comparison Study for Index Calculated with MW and MVAR Increment at Loads

| Case 3 | From Bus | To   | (Vi, p.u) | FVSI | Ld   | Le   |
|--------|----------|------|-----------|------|------|------|
| 6      | 7        | (Vi, p.u) | FVSI | Ld   | Le   |
| 8      | 0.95300  | 0.01768   | 0.01881| 0.01416|
| 9      | 0.95300  | 0.06476   | 0.10179| 0.05628|
| 10     | 0.95300  | 0.65853   | 0.66251| 0.61723|
| 28     | 0.95300  | 0.18498   | 0.41243| 0.20745|
| 25     | 26       | 0.48024   | 1.00000| 0.61241|
| 27     | 0.16388  | 0.14341   | 0.09357|
| 27     | 28       | 0.03960   | 1.00000| 0.48566|
| 29     | 0.68881  | 1.00000   | 0.87495|
| 30     | 0.81511  | 1.00000   | 1.09513|
The greater voltage drop is caused by the fact that the current is more lagging. The index values found to have reached the unstable value of 1 for Bus 26, 29 and Bus 30. Again, the weakest bus is found to be Bus 30 and all the neighboring bus which are Bus 26 till 29 displays a critical unstable value which is close to 1.

All the results obtained are consistent. In conclusion, Ld Index appears to be the most sensitive index at signifying the weakest bus in a test system, followed by FVSI Index and then the Le Index. Thus Ld index can be used to accurately identify the weak point in a system and hence as an indicator to the best location to perform load shedding.

4. Conclusions
Overall, the performance of the voltage stability index value is compared and analyzed for the purpose of identifying the best location for load shedding. The simulations results run on IEEE 30 Bus Test System show all indices provide the same ranking for the weak buses on the test system. Also, it can be concluded that Ld index appeared to be the most sensitive index in indicating the weak area and lines in the system. Thus, the simulation results demonstrate a strong correlation between Ld Index and the placement of UVLS relays for a power system network.

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