IDENTIFICATION OF WEAK NODES IN POWER SYSTEM BASED ON STANDARD DEVIATION OF VOLTAGE MAGNITUDE

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ABSTRACT
Identification of weak buses in an electric power system is important for operational and planning purposes. In this paper, a framework that uses the standard deviation of the magnitude of voltage at load buses is used to identify weak buses. In the framework, reactive power for all load buses are generated simultaneously based on a probability distribution function. The 39-Bus New England test system is used to test the framework in DigSilent PowerFactory in conjunction with Python programming language. The result shows that weak buses can be identified with the framework.

KEY WORDS
Voltage stability index, Weak buses, Standard Deviation, Bus criticality index, DigSilent PowerFactory, Python Programming language

1 Introduction
Modern electric power systems are sometimes operated under stressed conditions with reduced stability margins, as a result of contingencies or in a quest to improve capacity utilisation. Under such conditions, catastrophe can easily set in, if adequate measures are not put in place to address issues such as transient stability and voltage stability, just to mention a few. In recent time, voltage stability and identification of weak nodes have received a lot of attention. Voltage stability is also being incorporated as one of the criteria that determine the figure of merit of power system operation plans, expansion plan and assessment of electric power system security. Assessment of voltage stability of a power system is a challenging task, not to talk of measures that are needed to improve the voltage stability of a weak network. Before any corrective or preventive action can take place, it is always necessary to identify weak nodes. Hence, identification of weak buses in an electric power system is important for operational and planning purposes.

Several methods that use various techniques have been proposed in the literature for identification of weak nodes or voltage stability assessment of electric power network. Apart from the classical voltage stability assessment, few of the techniques that have been used are fuzzy logic [1], Artificial Neural Network [2], Ant colony [3], Genetic Algorithm based Support Vector Machine (GA-SVM) [4], and catastrophe theory [5]. In [6] the concepts of equilibrium analysis of rigid bodies is used to determine the centroid voltage of the system voltage space. The relative positions of bus voltages with respect to the centroid voltage was determined and are subsequently used to compute a voltage stability index for the load buses in the system. An index that is based on the angle between real and reactive power gradient vectors of load buses is proposed in [7]. The scheme was used to obtain the proximity index to voltage stability of 6-bus and IEEE 30-bus test systems. The proposed index is then used in a real time voltage stability enhancement algorithm. A voltage stability index based equivalent system model that could be used for on-line applications was proposed in [8]. The voltage stability index is termed equivalent node voltage collapse index (ENVCI), and it can identify the weakest node as well as the system voltage collapse point. In [1], Fuzzy voltage stability index was used to locate and assess the status of critical busbars in transmission networks (IEEE 14-bus, 30-bus, and 57-bus). Trapezoidal and triangular membership functions are used in the formulation of the uncertainties in the input parameters as fuzzy sets.

A computationally less expensive technique termed Simplified Voltage Stability Index (SVSI) that uses voltage measurements, power system's topology and some assumptions from the Thevenin model was tested on IEEE 30-bus and 118-bus test systems in [9]. Several operating conditions and contingencies were considered in the work. A multi-criteria integrated voltage stability index for identification of weak buses was proposed in [10]. P-V curve and Q-V curve were used to calculate the bus voltage change index and reactive power margins. A weighting function was then applied to bus voltage change index and reactive power margins to form an aggregated index. It is possible to tune the weights in the weighting function so as to give...
preference to a certain index. The scheme was tested on 10-machine 39-bus New England test system. A probabilistic voltage stability index for determination of the expected voltage instability proximity has also been proposed [11]. Elements are represented by a two-state model in order to account for the system elements’ forced outages. Voltage stability worst scenario are first defined, then critical system elements are identified along with the probability of worst scenario to occur. System sensitivity parameters are then evaluated based on a technique that uses optimal ordering and sparsity in fast decoupled load-flow contingency analysis.

A new voltage stability index that is based on standard deviation of voltage magnitude and a framework for generating reactive power demand at load buses is presented in this paper. The basis of the proposed framework lies on the fact the voltage stability characteristic at bus can be determined by ensembles of reactive power demands at buses. The 39-bus New England test system is used to test the proposed voltage stability index and the framework. The result obtained is compared with some of the results presented in [10]. Simulation results demonstrate the effectiveness of the proposed method in identifying weak load buses.

This paper is organized as follows. In Section 2, the theoretical basis for the the paper is given. Simulation experiment and results are presented in Section 3 and 4 respectively. Finally, the summary and conclusion of the paper are given in Section 5.

2 Theoretical Background

2.1 Classical Voltage Stability Assessment and Indies

Quite a large number of voltage stability methods and indices are available in the literature, and a few of them are discussed in Section 1. Methods based on the relative change in the bus voltage going from the initial operating point to voltage stability limit and that is base on Lagrange multipliers at the critical point are presented in [12].

\[ VC_i = \frac{V^\text{init}_i - V^\text{limit}_i}{V^\text{limit}_i} \quad i \in J_L \]  

(1)

where \( V^\text{init}_i \), \( V^\text{limit}_i \), and \( J_L \) are voltage magnitude at bus \( i \), voltage stability limit at bus \( i \), and a set of load buses.

It is easy to see that, a weak bus will have a high value for equation (1). The weakest bus, is the bus that has the highest value of \( VC_i \).

2.2 Voltage stability based on probability theory

In the this work a probabilistic approach is used to assess the voltage stability and weakness of load buses in a system. Under the assumption of distribution of maximum ignorance of the distribution function of a load demand, a uniform distribution can be used. However, this is seldom the case, the empirical record of load demand at each of the buses whenever it is available should be used to estimate load demand distribution function for each of the buses. Consider bus \( i \), with a load demand function given by \( f_i(s_i) \), where \( s_i \) is a random variable. The collection of the realization of \( s_i \) is denoted by \( S_i \), the size of \( S_i \) is \( N_{S_i} = |S_i| \). \( s_{ij} \) is the \( j^{th} \) instance of realization of \( s_i \). Consequently \( \{s_{ij} \mid v \in J = \{1..N_{S_i}\} \} \) is an index set of all possible ensemble of load demands at bus \( i \). The index set of the load buses is denoted by \( I \), \( \{i \mid 1 \leq i \leq N_L \} \). \( N_L \) the number of load buses. The expectation \( \bar{\mu}_{si} \) and the variance \( \bar{\sigma}_{si}^2 \) of load demand at bus \( i \) are given by equation (2) and (3) respectively.

\[ \bar{\mu}_{si} = \int_{-\infty}^{\infty} s_i f_i(s) ds \]  

(2)

\[ \bar{\sigma}_{si}^2 = \int_{-\infty}^{\infty} (s_i - \bar{\mu}_{si})^2 f_i(s) ds \]  

(3)

The estimates of \( \bar{\mu}_{si} \) at bus \( i \) is \( i \) and \( \bar{\mu}_{si} \) and the estimate of \( \bar{\sigma}_{si}^2 \) at bus \( i \) is \( \bar{\sigma}_{si}^2 \). The estimates are by equation (4) and equation (5).

\[ \bar{\mu}_{si} = \frac{1}{N} \sum_{j \in J} s_{ij} \]  

(4)

\[ \bar{\sigma}_{si}^2 = \frac{1}{N-1} \sum_{j \in J}(s_{ij} - \bar{\mu}_{si})^2 \]  

(5)

However, if the mean power \( \bar{\mu}_{si} \) at the bus is known, then its value can be substituted in equation

\[ \bar{\sigma}_{si}^2 = \frac{1}{N} \sum_{j \in J}(s_{ij} - \bar{\mu}_{si})^2 \]  

(6)

2.3 Loads with normal density function distribution

In a situation where the set of elements at bus \( i \) consists of a large number of independent loads, which is usually the case, the density function of the load aggregate may be approximated with a density function with a normal distribution.

The normal density function of a random variate \( s \) is given by equation (7)

\[ f_i(s) = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{(s-\mu)^2}{2\sigma^2}} \quad -\infty < s < \infty \]  

(7)

The mean of the power \( \bar{\mu}_{si} \) and its variance \( \bar{\sigma}_{si}^2 \) at bus \( i \) can be estimated by

\[ \bar{\mu}_{si} = \frac{1}{N} \sum_{j \in J} s_{ij} \]  

(8)

\[ \bar{\sigma}_{si}^2 = \frac{1}{N} \sum_{j \in J}(s_{ij} - \bar{\mu}_{si})^2 \]  

(9)

where \( s_{i0} \) is the prior base load at bus \( i \), and \( s_{ij}, j = 1..J \) are realisation of loads at bus \( i \), based on the distribution.
function \( f_i(s) \). If there are no priori information about the base or the nominal load demand at bus \( i \), then may be obtained from equation

\[
\tilde{\sigma}_{s_i}^2 = \frac{1}{N-1} \sum_{j \in J} (s_{ij} - \tilde{\mu}_{si})^2
\]

(10)

2.4 Assessment of a bus voltage stability index based on voltage magnitude variance

The criticality of bus \( i \) may be assessed by the voltage magnitude relative variation \( VR_i \) at the bus.

\[ VR_i = \frac{|V_i| - |V_i|_{\text{Nom}}}{|V_i|_{\text{Nom}}} \]

(11)

where \( |V_i|_{\text{Nom}} \) is the nominal voltage at bus \( i \). \( VR_{ij} \) is the voltage variation at bus \( i \) with reference to its nominal voltage \( |V_i|_{\text{Nom}} \), when the power is \( s_{ij} \).

There is a similarity between equation (11) and equation (1), however there is a subtle difference. In equation (1) \( V_{i\text{limit}} \) is voltage stability limit at bus \( i \), whereas in equation (11) the nominal voltage \( |V_i|_{\text{Nom}} \) at bus \( i \).

\[
\mu_{iVR} = \frac{1}{N} \sum_{j \in J} VR_j
\]

(12)

\[
\tilde{\sigma}_{iVR}^2 = \frac{1}{N-1} \sum_{j \in J} (VR_j - \mu_{iVR})^2
\]

(13)

A bus voltage criticality index can be defined based on equation (13). Instead of using the variance as given by equation (13), the standard deviation \( \tilde{\sigma}_{iVR} \) can be used. A new bus voltage criticality index that use \( \tilde{\sigma}_{iVR} \) to identify weak load buses in electrical power network is proposed.

3 Simulation Experiment

There is no empirical data for the density function of the load demand at each buses of the IEEE 39-bus New England bus test system. Under this circumstance, a normal density function assumed for load demands. The nominal load demand at each of the load buses is assumed as the mean load, while the standard deviation is assumed as 20% of the normal load.

The IEEE 39-bus New England bus test system model in DigSilent PowerFactory software is used in the computer experiment. Python programming language is also used in generating stochastic load demand patterns at all load buses simultaneously. The simulation procedure used in this work is as follows:

1 A base case power flow analysis for the network is conducted in order to obtain the magnitude of voltages \( |V_{i0}| \) at bus \( i \).

2 The number of experiment repetition is set to \( n \), in this investigation, \( n = 30 \)

3 A set of load \( S_i \) is generated for each each bus \( i \) based on its load probability density function, such that \( s_{ij} \in S_i, \forall j \in \{1..n\} \)

4 Power flow analysis \( PF_j \) is conducted \( n \) times with the load at each load bus \( i \) assigned from the set \( S_i \).

In the work, the sample size chosen is \( n = 30 \) in order to have enough data to estimate an appropriate statistic for the voltage magnitude variation at each of the load buses.

4 Result and Discussion

The results of the simulation for a sample size of \( N = 30 \) are presented in form of bar chats in Figure 1, Figure 2 and Figure 3. The mean of reactive power demand, mean of voltage magnitude and standard deviation of voltage magnitude are presented in Figure 1, Figure 2, and Figure 2 respectively. Load buses in Figure 2 are arranged in the order of magnitude of the standard deviation. The set of load

![Figure 1: Mean reactive power](image1)

![Figure 2: Mean voltage magnitude](image2)
buses selected as weak buses by the proposed voltage stability index and other schemes in [10] is presented in Table 1. From Table 1, it can be seen that the set of buses identified as weak buses are different by using different voltage stability indices. Nevertheless, the three approaches illustrated in the table have similar entries. Unlike the other two approaches presented in the table that considered all the buses, the proposed framework only considered only load buses. That is the reason why buses 14 and 5 are not selected as weak buses. However, the load bus, bus 15 adjacent to bus 14 is selected as a weak bus, and the load bus 4 which is adjacent to bus 5 is also selected as a weak bus.

<table>
<thead>
<tr>
<th>Analysis method</th>
<th>Proposed scheme</th>
<th>Ideal point method</th>
<th>Modal analysis</th>
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<td>Top 5 weak buses</td>
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<td>4</td>
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<td>5</td>
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Table 1: Identified weak buses based on proposed framework, Ideal Point method [10], and Modal analysis [10]

5 Conclusion

This paper presents a framework for identification of weak load buses in electric power system. A new index based on standard deviation of voltage magnitude is proposed for ranking of load buses. The framework has been tested on IEEE 39-bus New England system. In the future work, empirical data will be collected from a local electric utility in South Africa to estimate load demand distribution function. The proposed index and framework will then be applied to rank all the load buses in the utility’s electric power grid.

References


