Evaluation for Voltage Stability Indices in Power System Using Artificial Neural Network


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Abstract

At present, the evaluation of voltage stability assessment experiences sizeable anxiety in the safe operation of power systems. This is due to the complications of a strain power system. With the snowballing of power demand by the consumers and also the restricted amount of power sources, therefore, the system has to perform at its maximum proficiency. Consequently, the noteworthy to discover the maximum ability boundary prior to voltage collapse should be undertaken. A preliminary warning can be perceived to evade the interruption of power system’s capacity. This paper considered the implementation of real-time system monitoring methods that able to provide a timely warning in the power system before the voltage collapse occurred. Numerous types of line voltage stability indices (LVSI) are differentiated in this paper to resolve their effectuality to determine the weakest lines for the power system. The line voltage stability indices are assessed using the IEEE 9-Bus and IEEE 14-Bus Systems to validate their practicability. Besides that, this paper also introduced the implementation of real-time voltage stability monitoring by using Artificial Neural Network (ANN). Results demonstrated that the calculated indices and the estimated indices by using ANN are practically relevant in predicting the manifestation of voltage collapse in the system. Therefore, essential actions can be taken by the operators in order to dodge voltage collapse incident from arising.

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Keywords: Artificial Neural Network (ANN); Line Voltage Stability Indices (LVSI); Maximum Loadability; Voltage Stability Analysis;

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1. Introduction

Present-day, the power systems need to adapt to the new situation since the actual scene no longer exists as it used to be. Due to the climate change throughout the world, it is expected to lead the electricity consuming demand to operate closely to the numbers of generated electricity [1, 2]. Besides that, aggressive business conditions have enforced electric utilities to fully make use of accessible resources. Moreover, the current power systems are extremely loaded as compared to the past because of the arising demand, maximum economic advantages and the effectiveness of utilizing the available transmission capacity [3-5].

After examining the sequence of incidents that caused the major blackout in the year 2003, the reasons of the blackouts were due to a shortage of reliable real-time data [6, 7]. The established decentralized way of operating systems by Transmission System Operators (TSOs) where each TSO take cares of its own control area and limited information to exchange, resulted in insufficient and delay response towards contingencies. Therefore, a real-time security assessment and control are needed to maintain the system security [7]. The significance of real-time data is to allow the operators to carry out important and practically preventive action to avoid cascading or else will lead the system to incorrect or delayed correction actions and thus will give a chance of instability occurrence.

Voltage stability assessment and control are not considered as any new issue [8], but they have now attained special attentions to maintain the stability of the transmission networks in order to avoid recurrence of major blackouts as experienced by the particular countries. The power system can be classified in the voltage stability region if it can maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance [9, 10]. In order to be reliable, the power system must be stable at most of the time. The research works on voltage stability can be break down into various approaches, but the estimation on the power system's distance towards voltage collapse can be very handy to the operators before they take any remedial actions [11, 12]. The details on the distance towards voltage instability can be obtained by using Voltage Stability Indices (VSI) [13].

Voltage stability analysis is still widely being implemented in the industries by calculating the P-V and Q-V curves at selected load buses [14]. Commonly these curves are created by a large number of load flows using conventional methods and models. However, these methods are time consuming and do not provide sufficient practical information towards the stability problems [15].

Various causes are recited in [16] as the commencement of the power systems outages. Most of all, power systems outages can be categorized into two types; unpreventable event and preventable event. Some of the power systems outages can be classified as the unpreventable events from the system operator. During the unpreventable event took place; the system operator cannot control the damaged level happening in the power system.

In the meanwhile, in several cases, the power system outages can be prevented with the utilization of a sufficient system protection and situational awareness. If the power system is not equipped with the suitable protection for the system, then the power system is prone to critical operational situations and leads to instabilities. Hence, voltage instability is one of the significant problems in causing the power outages.

Basically, voltage stability indices can be classified into Jacobian matrix – based voltage stability indices and system variable – based voltage stability indices. In this paper, the motive for focusing on the system variable – based voltage stability indices is because it requires fewer amounts of computing time. Besides that, it can precisely verify the weak bus or lines in the power systems. Therefore, the scope has been narrowed into focusing on system variable based voltage stability indices.

In addition, two test-power system cases are utilized in this paper, which is IEEE 9-Bus test case and IEEE 14-Bus test case. IEEE 9-Bus test case represents a portion of the Western System Coordinating Council (WSCC) 3-Machines 9-Bus system. Fundamentally, this IEEE 9-Bus test case consists of three generators, nine buses and three loads. The IEEE 14-Bus test case actually represents a part of the American Electric Power System which is situated in the Midwestern US. Fundamentally, this system consists of two generators, three units of synchronous condensers, 14 buses and 11 loads.

The rest of this paper was organized as follows. A background study on the overview of definitions of voltage stability and voltage stability indices will be discussed in section 2. The implementation of the voltage stability indices and the details of the simulation cases will be talked about in section 3. Results and discussion will be comprised in section 4. Finally, this paper is concluded in section 5.
2. Background of study

2.1. Definitions of voltage stability

Voltage stability can be interpreted as the potential of the power system to sustain steady voltages at all buses in the system after being vulnerable to a disturbance from a given initial operating condition [9]. Besides that, voltage stability is the consequence on the ability of the power system to maintain or restore the equilibrium between the load demand and load supply [9, 17]. A system is treated as voltage unstable if at least one bus in the system experiencing voltage magnitude decreases once the reactive power injection is increasing [18]. In addition, voltage stability can also be considered as load stability. If the power system lacks of the capability to transfer an infinite amount of electrical power to the loads, hence voltage instability will be present. The main reason for contributing to voltage instability is the inability of the power system to meet the requirements for reactive power in the extremely stressed system keeping the desired voltages [19]. In order to restore the increasing demand of loads in the systems will cause further voltage decrement [17]. Voltage collapse is the event when accompanied by voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system [9].

Voltage instability and collapse effectively extent a time range from seconds to one hour. The time length of a distraction in a power system, originating a possibility of a voltage instability problem, can be categorized into short term and long term. The example of short-term or transient voltage instability can be found mainly caused by rotor angle variance or loss of synchronism. In the meanwhile, long term voltage instability problems mainly occurred in heavily loaded systems where the electrical distance is huge between generator and the load.

Mainly, in order to analyze the voltage stability, it is often convenient to categorize the problem into small-disturbance and large-disturbance voltage stability. Small-disturbance voltage stability refers to the system's capability to continue steady voltages when disposed to small perturbations such as incremental changes in system load [9]. Generally, the analysis for small-disturbances is done in steady-state stability analysis. Steady-state stability analysis is useful in obtaining the qualitative overview of the system such as how stress the system is and the system's stability to the point of instability. Aside from, the large-disturbance voltage stability refers to the system's ability to maintain stable voltages followed by large disturbances such as system faults, disappearance of generation and loss of line. Large-disturbance voltage stability can be analyzed by using non-linear time-domain simulation in short term time frame and load flow analysis in the long term time frame [19].

2.2. Voltage Stability Indices

Voltage stability indices are very applicable in retrieving the voltage stability of the power system. Voltage stability indices are the scalar magnitudes that are being implemented to observe the changes of the parameters in the system. Besides that, the indices are also used to quantify the distance of the particular operating point with the point of voltage collapse [20]. These indices will be very handy to the operators before they started to implement the prevention actions [12].

According to [21, 22], the authors mentioned that voltage stability indices particularly could be subdivided into two parts, which are Jacobian matrix based voltage stability indices and system variables based voltage stability indices. Jacobian matrix based voltage stability indices are able to calculate the voltage collapse point or maximum load ability of the system and discover the voltage stability margin. However, these indices required high computational time and for this particular reason, the Jacobian matrix based voltage stability indices are not appropriate for online assessment. In the meanwhile, system variables based voltage stability indices required less computational time. The reasons are due to the system variable based voltage stability indices that used the elements of the admittance matrix and some system variables such as bus voltages or power flow through the lines. With the benefit of less computational time, system variables based voltage stability indices are suitable to be implemented on the online assessment and monitoring purposes. At the same time, system variables based voltage stability indices cannot efficiently estimate the margin because their responsibilities are more to determine the critical lines and buses.
The differences between Jacobian matrix based voltage stability indices and system variables based voltage stability indices is provided in Table 1. The differentiation is more likely based on the two aspects which were being defined in [9]. The two aspects are proximity towards voltage collapse – (How close is the system to voltage instability?) and mechanism of voltage instability – (How and why does instability occur?).

Table 1. Differentiation between Jacobian matrix based voltage stability indices and system variables based voltage stability indices.

<table>
<thead>
<tr>
<th>Jacobian matrix based voltage stability indices</th>
<th>System variables based voltage stability indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Require more amount of computing time</td>
<td>Require less amount of computing time</td>
</tr>
<tr>
<td>Suitable for offline monitoring purpose</td>
<td>Suitable for online monitoring purpose</td>
</tr>
<tr>
<td>Discover voltage stability margin</td>
<td>Discover weak buses and lines</td>
</tr>
<tr>
<td>(Proximity towards voltage collapse)</td>
<td>(Mechanism of voltage instability)</td>
</tr>
</tbody>
</table>

3. Methodologies

3.1. Power System Test Cases

Two different types of test cases are being utilized in this paper. They are IEEE 9-Bus test system and IEEE 14-Bus test system. The main intention of increasing the number of buses for each test case is to determine the feasibility of line voltage stability indices.

At first, IEEE 9-Bus test system network was used for the simulation. This IEEE 9-Bus system represents a portion of the Western System Coordinating Council (WSCC) 3-Machines 9-Bus System. Basically, this 9-Bus system contains of three generators, nine buses and three loads. The wiring diagram for IEEE 9-Bus system is illustrated in Fig. 1(a). The IEEE 14-Bus test case represents a portion of the American Electric Power System which is located in the Midwestern US as of February, 1962. Basically, this system consists of five generators, 14 buses and 11 loads. The wiring diagram for IEEE 14-Bus system is illustrated in Fig. 1(b).

Fig. 1. (a) IEEE 9-Bus test network; (b) IEEE 14-Bus test network.

3.2. Voltage stability indices formulation

Basically in this research, six different types of line voltage stability indices are being implemented. They are Lmn index, LQP index, FVSI index, VCPI(Power), VCPI(Loss) and LCPI index. Mainly, the line stability indices are formulated based on the power transmission concept in a single line as shown in Fig. 2.
Where:

- $V_s$ and $V_g$ are the sending end and receiving end voltages respectively
- $\delta_s$ and $\delta_g$ are the phase angle at the sending and receiving buses
- $Z$ is the line impedance
- $R$ is the line resistance
- $X$ is the line reactance
- $T$ is the line impedance angle
- $R_P$ is the active power at the receiving end
- $Q_R$ is the reactive power at the receiving end

3.2.1. Line stability index ($L_{mn}$)

This index was derived by [23] by using an overall system stability index based on the concept of power flow through a single line as shown in Fig. 3. This index implemented a technique to reduce the system into a single line equivalent network. The $L_{mn}$ index is provided in Equation 1.

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

3.2.2. Line stability factor ($L_{QP}$)

This line stability factor ($L_{QP}$) is derived in [24] by the authors using the same notion in section 3.2.1. Hence, LQP index is calculated as provided in Equation 2.

$$ L_{QP} = 4\left[\frac{X}{V_s^2}\left(\frac{X}{V_s^2}P_s^2 + Q_R\right)\right] \quad (2) $$

3.2.3. Fast voltage stability index ($F_{VSI}$)

A novel fast voltage stability index ($F_{VSI}$) was proposed by the authors in [25]. This index is being simplified from a pre-developed voltage stability index referred to a line from the voltage quadratic equation at the sending end of a representation of a two bus system. The formulated index was tested on the IEEE 30-Bus reliability test system in order to verify the performance of the proposed indicator. Hence, the equation for $F_{VSI}$ index can be defined in Equation 3.

$$ F_{VSI} = \frac{4Z^2Q_R}{V_s^2X} \quad (3) $$
3.2.4. Voltage collapse proximity indicators (VCPI)

The voltage collapse proximity indicators (VCPI) is proposed in [26] are based on the maximum power transferred through a line in the power network. The VCPI(Power) in Equation 4 and VCPI(Loss) in Equation 5 are used to find the stability point for each line connection between two bus bars in an interconnected network. As long as the indices remain less than one, then the system is considered to be stable.

\[
VCPI(\text{Power}) = \frac{P_R}{P_{R(\text{max})}} \quad \text{or} \quad \frac{Q_R}{Q_{R(\text{max})}} \quad (4)
\]

\[
VCPI(\text{Loss}) = \frac{P_{\text{loss}}}{P_{\text{loss(\text{max})}}} \quad \text{or} \quad \frac{Q_{\text{loss}}}{Q_{\text{loss(\text{max})}}} \quad (5)
\]

3.2.5. Line collapse proximity indicator (VCPI)

The authors in [27] have proposed LCPI index based on the derivation of ABCD parameters in transmission line. The forte of this index is by taking into consideration the line charging reactance during the derivation of equations. The significant of line charging reactance may support voltage stability. The relationship between the parameters can be explained in Equation 6.

\[
LCPI = \frac{4A \cos \alpha \left( P_2 B \cos \beta + Q_2 B \sin \beta \right)}{(V_s \cos \delta)^2}
\]

Where:
- \( A = (1 + Z \ast Y / 2) \equiv A \angle \alpha \)
- \( B = Z \equiv B \angle \beta \)
- \( C = Y \ast (1 + Z \ast Y / 4) \)
- \( D = A \)

3.3. Feed forward back propagation neural network (FFBPNN)

A two-layer feed forward neural network with error back-propagation learning is one of the most commonly implemented neural networks [28]. Neural networks are used to model complex relationships between inputs and outputs or to find patterns in data. In this paper, ANN is used to find the patterns and equation from the data. It is a structure (network) composed of a number of interconnected units. In this paper, the input data was as many as 100 data in which 30 data were used as testing data. The algorithm for this study is illustrated in Fig. 3.

![Fig. 3. Simulation process of FFBPNN method.](image-url)
4. Results and discussion

In this paper, there are six line voltage stability indices and each of the indices consists of different number of inputs but with one general output. The details of the inputs for the indices are summarised in the Table 2.

Table 2. The details of the number of inputs for different line voltage stability indices.

<table>
<thead>
<tr>
<th>Index</th>
<th>Number of inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lmn</td>
<td>6</td>
</tr>
<tr>
<td>FVSI</td>
<td>4</td>
</tr>
<tr>
<td>LQP</td>
<td>4</td>
</tr>
<tr>
<td>VCPI (Power)</td>
<td>5</td>
</tr>
<tr>
<td>VCPI (Loss)</td>
<td>5</td>
</tr>
<tr>
<td>LCPI</td>
<td>9</td>
</tr>
</tbody>
</table>

4.1. Prediction for the most critical line in IEEE 9-Bus test system

The results indicated that line 9 – 6 is the most critical line at 465 seconds during the real-time simulation. Therefore, the prediction is mainly focused on the most critical line by using the artificial neural network model.

![Evaluation of actual line voltage stability indices with artificial neural network prediction](image)

Fig. 4. The comparison between the actual and the predicted line voltage stability indices based on line 9 – 6 at 465 seconds in IEEE 9-Bus test system.

The blue bar in Fig. 4 represents the actual output for the line voltage stability indices while the red bar indicates the predicted line voltage stability indices by using artificial neural network. It can be observed from the figure, the trend of the predicted output values is almost identical with the original calculated values. As it can be seen, the errors found were not significant and there is only a minor difference between both data values in the figure which is acceptable. Overall, the calculated and the predicted values are similar and this showed that artificial neural network is also sufficient to be used for voltage stability monitoring purpose.

The details for the line stability indices based on line 9 – 6 at 465 seconds are presented in Table 3. The first column of the table shows the type of the index. Besides that, column two showed the actual output values for the indices based on the calculation. Consequently, column three showed the prediction output values from the artificial neural network model. Moreover, column four and five showed the network error and error percentage subsequently. In general, the prediction outputs shown in Table 3 are relevant with the actual output and this once again indicates artificial neural network is sufficient to be used for voltage stability assessment purpose.
Table 3. Details for line voltage stability indices based on line 9 – 6 at 465 seconds in IEEE 9-Bus test system.

<table>
<thead>
<tr>
<th>Index</th>
<th>Actual Output</th>
<th>Prediction Output</th>
<th>Network Error</th>
<th>Error Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lmn</td>
<td>0.994159</td>
<td>0.994160</td>
<td>-0.000001</td>
<td>0.000028</td>
</tr>
<tr>
<td>FVS1</td>
<td>0.922800</td>
<td>0.922799</td>
<td>0.000002</td>
<td>0.000166</td>
</tr>
<tr>
<td>LQP</td>
<td>0.980285</td>
<td>0.980284</td>
<td>0.000004</td>
<td>0.000056</td>
</tr>
<tr>
<td>VCPI (Power)</td>
<td>1.010020</td>
<td>1.010000</td>
<td>0.000020</td>
<td>0.000319</td>
</tr>
<tr>
<td>VCPI (Loss)</td>
<td>0.674455</td>
<td>0.674453</td>
<td>0.000002</td>
<td>0.000319</td>
</tr>
<tr>
<td>LCPI</td>
<td>1.011878</td>
<td>1.011878</td>
<td>0.000000</td>
<td>0.000017</td>
</tr>
</tbody>
</table>

4.2. Prediction for the most critical line in IEEE 14-Bus test system

The line voltage stability results indicated that line 5 – 6 is the most critical line at 55 seconds. Therefore, the prediction is based on the most critical line by applying the artificial neural network model.

Fig. 5. The comparison between the actual and the predicted line voltage stability indices based on line 5 – 6 at 55 seconds in IEEE 14-Bus test system.

The blue bar illustrated in Fig. 5 represents the actual output for the line voltage stability indices while the red bar indicates the predicted line voltage stability indices by using artificial neural network. It can be observed from Fig. 5, the trend of the predicted output values is almost similar with the original calculated values. As it can be seen, the errors found were not significant and there is only a minor difference between both data values in the figure which is acceptable. Overall, the calculated and the predicted values are similar and this showed that artificial neural network is also sufficient to be used for voltage stability monitoring purpose.

Table 4. Details for line voltage stability indices based on line 5 – 6 at 55 seconds in IEEE 14-Bus test system.

<table>
<thead>
<tr>
<th>Index</th>
<th>Actual Output</th>
<th>Prediction Output</th>
<th>Network Error</th>
<th>Error Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lmn</td>
<td>1.036085</td>
<td>1.036085</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>FVS1</td>
<td>0.991151</td>
<td>0.992118</td>
<td>-0.000967</td>
<td>0.097611</td>
</tr>
<tr>
<td>LQP</td>
<td>1.081265</td>
<td>1.080954</td>
<td>0.000311</td>
<td>0.028734</td>
</tr>
<tr>
<td>VCPI (Power)</td>
<td>1.074979</td>
<td>1.074977</td>
<td>0.000002</td>
<td>0.000195</td>
</tr>
<tr>
<td>VCPI (Loss)</td>
<td>0.681614</td>
<td>0.681430</td>
<td>0.000184</td>
<td>0.027010</td>
</tr>
<tr>
<td>LCPI</td>
<td>1.081265</td>
<td>1.080954</td>
<td>0.000311</td>
<td>0.028734</td>
</tr>
</tbody>
</table>
The summaries for the line stability indices based on line 5 – 6 at 55 seconds are presented in Table 4. The first column of the table shows the type of the index. Besides that, column two showed the actual output values for the indices based on the calculation. Consequently, column three showed the prediction output values from the artificial neural network model. Moreover, column four and five showed the network error and error percentage respectively. In general, the prediction outputs shown in Table 4 are similar with the actual output and this once again indicates artificial neural network is sufficient to be used for voltage stability assessment purpose.

5. Conclusion

In the nutshell, the application of artificial neural network had been executed in this paper as well. The main purpose for conducting this was to predict the most critical line in the power system based on the line voltage stability indices assessment. In the meantime, this artificial intelligent technique is sufficient to be implemented in the voltage stability monitoring purpose. Feed forward back propagation artificial neural network was used to predict the line voltage stability indices for the most critical line in three different types of power system test networks. The results showed that the implemented ANN model is indicative in forecasting the occurrence of system collapse and hence suitable prevention action can be taken beforehand to avoid voltage collapse.

Acknowledgements

The authors would like to thank the Ministry of Science, Technology and Innovation, Malaysia (MOSTI), and the Office for Research, Innovation, Commercialization, Consultancy Management (ORICC), Universiti Tun Hussein Onn Malaysia (UTHM) for financially supporting this research under the Science Fund grant No.S023.

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