A COMPARATIVE STUDY OF DYNAMIC VOLTAGE COLLAPSE PREDICTION INDICES IN A POWER SYSTEM

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ABSTRACT

The paper presents a study in comparing the performance of several indices used for predicting dynamic voltage collapse. The indices considered in the study are named as the power margin, impedance stability index, line index and voltage collapse prediction index. To evaluate and compare the effectiveness of these indices in predicting proximity to voltage collapse, simulations are carried out using the WSCC 9 bus test system. Test results show that the impedance stability index and the voltage collapse prediction index give a reliable and faster indication of dynamic voltage collapse compared to the power margin and the line index.

Keyword: dynamics voltage collapse, voltage instability predictor, impedance stability index, line index, voltage collapse prediction index

INTRODUCTION

In the last few years, the restricted growth of electric transmission systems and increasingly higher power demands have forced utilities to operate power networks relatively close to their transmission limits and created new voltage stability problems. As system load increases, voltage magnitudes throughout a network slowly decline. However, continuing increases in load may eventually drive a system to an unstable state which is characterized by rapidly decreasing bus voltage magnitudes and lead to system voltage collapse. Recent blackouts around the world are mainly due to voltage collapse occurring in stressed power systems in which the main symptoms are low voltage profiles, heavy reactive power flows, inadequate reactive support and heavily loaded systems. The consequences of collapse often require long system restoration while large groups of customers are left without supply for extended periods of time. Therefore, presently the study of voltage stability and voltage collapse is still of importance.

In the recent literature, many methods have been developed to predict the occurrence of voltage collapse. Some of the important ones are the method of predicting voltage collapse based on the bifurcation theory (Hedeman et.al., 2004, Zambon, 2000) and the use of voltage collapse indicators such as impedance stability index (Bergovic et al., 2002), line index (Garng & Nirmal, 2001), voltage collapse prediction index (Balamourgan...
et.al., 2004) and Power margin (Bergovic et.al., 2002 and Julian et.al., 2000). These indicators are mainly used to predict static voltage collapse. However, in this work, these indicators are used to predict dynamic voltage collapse. Works carried out initially focus on simulating dynamic voltage collapse in the WSCC 9 bus test system. A comparison is then made on the use of four voltage collapse prediction indices, namely, the power margin (PM), impedance stability index (ISI), line index (L index) and voltage collapse prediction index (VCPI). The objective of the study is to investigate the performance and effectiveness of these indices in predicting the proximity to voltage collapse.

BACKGROUND THEORY

The voltage collapse prediction indices that have been proposed in the literature, namely, the power margin, impedance stability index, line index and voltage collapse prediction index are described and given as follows:

Power Margin
The power margin index which is used to track the closeness to voltage collapse is based on the distance of apparent power and derived from the concept of voltage instability predictor (VIP). As for the use of the VIP, the proximity to voltage collapse is expressed in terms of distance between two voltage curves or between two impedance curves. Figure 1 shows a Thevenin equivalent of a power system which is used to derive the VIP.

Power margin describes the proximity to voltage collapse in terms of power and can be looked upon as the power available to be pushed through the VIP before the network collapses. It is defined as the power difference between the maximum power using linear forecast and the current power observed by VIP (Julian et.al., 2000). Power margin can also be defined as the extra MVA that can be delivered to the load before voltage collapse occurs (Bergovic et.al., 2002).

Mathematically, the power margin is given by,

$$\Delta S_m = Z_m I_m^2 - Z_{dev} I_m^2$$

(1)

where,

- $\Delta S_m$ is the power margin at bus $m$
- $Z_m$ is the load impedance at bus $m$
- $Z_{dev}$ is the equivalent network impedance
- $I_m$ is the current measured at bus $m$

From equation (1), when the power margin approaches zero, it means that no more power can be increased and system collapse will occur if additional power in a system is increased.

Impedance Stability Index

The impedance stability index is also derived based on the VIP concept. It is defined as the difference between the value of the Thevenin impedance, $Z_{thev}$ at a particular time instant and the impedance given by the ratio V/I (Bergovic et.al., 2002, Julian et.al., 2000). This predictor is derived from a simple two-bus equivalent system in which a slack bus is connected to a load bus by a single branch as shown in Figure 2.

The line is represented by an impedance $Z_{eq} = R_{eq} + jX_{eq}$ whereas the source is represented by a voltage phasor.
Voltage instability is said to occur in the system when the equivalent impedance \( Z_{eq} \) is equal to the load bus impedance \( Z_m \) which is given by \( Z_m = \frac{V_m}{I_m} \). The load bus distance to collapse is assessed by tracking the values of the impedance stability index (ISI). The index is given by,

\[
ISI_m = \frac{Z_{eq}}{Z_m}
\]  

(2)

where,

\( Z_{eq} \) is network impedance
\( Z_m \) is load impedance at bus \( m \)

The values of ISI are in the range of 0 and 1. When the ISI value reach unity, it means that a voltage collapse is said to occur.

![Figure 2. A simple two-bus equivalent system to predict ISI](image)

Line Index

The line index (L index) introduced by Kessel and Glavitch (Garng&Nirmal, 2001, Mohamed 1994, Salama et.al, 1999) was derived from a two bus system model and generalized for a multi-node power system. The index is simple to calculate because it utilizes information obtained from a normal load flow solution. The L index calculated for each bus \( j \) is given by,

\[
L_j = \frac{S_j^*}{|V_j^*|^2 V_j^*}
\]

(3)

where

\( S_j^* \) is the transformed injected complex power
\( Y_j^* \) is the transformed admittance given by
\( Y_j^* = 1/Z_j \)

\( V_j \) is the voltage magnitude at bus \( j \)

The transformed power \( S_j^* \) consist of two parts in which \( S_j^* = S_j + S_j^{cor} \), for which \( S_j^{cor} \) is given by,

\[
S_j^{cor} = \sum_{k \in V} \left( \frac{Z_{jk}^* Z_{kj}^*}{Z_{jk}^*} \right) S_k
\]

(4)

where, \( Z_{jk} \), \( Z_{kj} \) are the off diagonal and diagonal elements of the impedance matrix, respectively. \( V \) is the set of load buses and \( V \) is the complex voltage.

\( V_j \) is affected by bus power \( S_j \) and equivalent power \( S_j^{cor} \), which stems from the other loads in a system. The values of \( L \) index vary in the range between 0 (no load condition) and 1 (voltage collapse condition). The L index has been used and tested to predict dynamic voltage collapse (Garng&Nirmal, 2001).

Voltage Collapse Prediction Index

The voltage collapse prediction index requires voltage phasor information of the participating buses in a system and a network admittance matrix (Balamourougan, 2004). The formulation of the index is given by,

\[
VCPIk = 1 - \left| \frac{\sum_{m=1}^{N} V_m^*}{V_k} \right|
\]

(5)

where, \( V_m^* \) is the participating voltage at bus \( m \), \( V_k \) is the voltage at bus \( k \) and \( N \) is the total number of buses in a system. \( V_m^* \) in equation (5) is given by
\[ V_m = \frac{Y_{km}}{\sum_{j=1}^{n} Y_{kj}} V_m \]  \hspace{1cm} (6)

where:
- \( V_m \) is the voltage phasor at bus \( m \)
- \( Y_{km} \) is the admittance between bus \( k \) and bus \( m \)
- \( Y_{kj} \) is the admittance between bus \( k \) and bus \( j \)
- Bus \( k \) is monitoring bus
- Bus \( m \) is the other bus besides bus \( m \)

**DYNAMIC SIMULATION OF VOLTAGE COLLAPSE**

The dynamic power system models, the test system considered in the study and the procedures for the dynamic simulation of voltage collapse are described accordingly.

**Dynamic Power System Models**

The generator governor model using mechanical-hydraulic governor for hydraulic turbine (Kundur, 1994) as shown in Figure 3a and the excitation system model using IEEE type AC1A as shown in Figure 3b is used in the simulation.

The load model considered is the composite load which is given by,

\[ P = P_o \left( \frac{V}{V_o} \right)^{n_p} \] \hspace{1cm} (7)

\[ Q = Q_o \left( \frac{V}{V_o} \right)^{n_q} \] \hspace{1cm} (8)

where \( P_o \) and \( Q_o \) are the active and reactive load powers at initial condition, \( n_p \) and \( n_q \) are the load parameters obtained from the slopes \( dP/dV \) or \( dQ/dV \).

For the case where \( n_p \) and \( n_q \) are equal to 0, 1, 2, the load model will represent, constant power, constant current and constant impedance loads, respectively.

The load model parameters considered in the study are given as in Table 1 (Navarro, 2002).

**Table 1. Load model parameters**

<table>
<thead>
<tr>
<th>Load Component</th>
<th>( n_p )</th>
<th>( n_q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Conditioner</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Fluorescent Lighting</td>
<td>1.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Pumps, fan</td>
<td>0.08</td>
<td>1.6</td>
</tr>
<tr>
<td>Large Industrial Motor</td>
<td>0.05</td>
<td>0.3</td>
</tr>
<tr>
<td>Small Industrial Motor</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Resistance Space heater</td>
<td>2.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Figure 3a. Governor model for hydraulic turbine**
Test System

The 9 bus test system used in the dynamic simulation of voltage collapse is as shown in Figure 4. The line parameters for the system are tabulated as shown in Table 2. The system consists of three generators connected at buses 1, 2 and 3. Generator 1, generator 2 and generator 3 are of ratings 250 MVA, 300 MVA and 150 MVA, respectively. Their inertia constants (H) are 23.64 MWs/MVA, 6.4 MWs/MVA and 3.01 MWs/MVA accordingly. The governor and excitation system parameters are given as
shown in Tables 3 and 4, respectively (Kundur, 1994). The static loads considered in the system at bus 7 and bus 9 are $100 + j35$ MVA and $125 + j50$ MVA, respectively. In the simulation considering first contingency, composite loads are connected at bus 5 in which the loads comprise of air conditioner, fluorescent lighting, pumps, large industrial motors and small industrial motors as shown in Table 1. For the simulation considering the second contingency, loads connected at bus 5 have been changed to resistance space heaters which are represented by the constant impedance loads and the parameters are also given as shown in Table 1.

**Table 2. Line parameters**

<table>
<thead>
<tr>
<th>Line</th>
<th>Resistance (pu)</th>
<th>Reactance (pu)</th>
<th>Susceptance (pu)</th>
<th>MVA rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>0.0000</td>
<td>0.0076</td>
<td>0.0000</td>
<td>250</td>
</tr>
<tr>
<td>4-5</td>
<td>0.0170</td>
<td>0.0920</td>
<td>0.1580</td>
<td>250</td>
</tr>
<tr>
<td>5-6</td>
<td>0.0390</td>
<td>0.1700</td>
<td>0.3580</td>
<td>150</td>
</tr>
<tr>
<td>6-7</td>
<td>0.0070</td>
<td>0.0076</td>
<td>0.0000</td>
<td>300</td>
</tr>
<tr>
<td>6-7</td>
<td>0.0070</td>
<td>0.0076</td>
<td>0.0000</td>
<td>150</td>
</tr>
<tr>
<td>7-8</td>
<td>0.0085</td>
<td>0.0720</td>
<td>0.1490</td>
<td>250</td>
</tr>
<tr>
<td>8-2</td>
<td>0.0000</td>
<td>0.0625</td>
<td>0.0000</td>
<td>250</td>
</tr>
<tr>
<td>8-9</td>
<td>0.0320</td>
<td>0.1610</td>
<td>0.3060</td>
<td>250</td>
</tr>
<tr>
<td>9-4</td>
<td>0.0100</td>
<td>0.0850</td>
<td>0.1760</td>
<td>250</td>
</tr>
</tbody>
</table>

where,
- $Q$ = servo gain
- $KF$ = Rate feedback Gain
- $TR$ = dashpot reset time
- $TF$ = Rate feedback constant
- $RT$ = Temporary drop
- $KA$ = Regulator gain

$Tg$ = Main servo time constant
$TA$ = Regulator Time constant
$TW$ = Water Starting Time
$TB$ = Lag Time constant
$TC$ = Lead Time constant
$VRMAX$ = max regulator output
$VRMIN$ = min regulator output

**Procedure for Dynamic Simulation of Voltage Collapse**

The dynamic simulation of voltage collapse has been carried out using the PSCAD/EMTDC program. Two contingencies have been considered in the simulations in which the first contingency considers load increase at bus 5 at a rate of $(0.2 + j0.2)$ p.u from the base power of $(0.186 + j0.147)$ p.u MVA. For the second contingency, real power load is increased at bus 5 at a rate of 0.2 p.u per second.

The procedures involved in the dynamic simulation of voltage collapse are described as follows:

1) Input load, generator and line data of the test system in PSCAD/EMTDC.
2) Create a short circuit at bus 5 so as to determine the Norton current, I and an open circuit at bus 5 to determine the Thevenin voltage, E. From I and E, the Thevenin impedance, $Z$ is calculated. The Thevenin impedance is used in the calculation of the power margin and the ISI.
3) Run the simulation considering each contingency case for time $t = 5$ seconds to 80 seconds.

**Table 3. Parameters of governor**

<table>
<thead>
<tr>
<th>Q</th>
<th>TR</th>
<th>RT</th>
<th>Tg</th>
<th>TW</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5 sec</td>
<td>0.4 pu</td>
<td>0.2 sec</td>
<td>2 sec</td>
</tr>
</tbody>
</table>

**Table 4. Parameters of excitation system – Type AC1A**

<table>
<thead>
<tr>
<th>KF</th>
<th>TF</th>
<th>KA</th>
<th>TA</th>
<th>TB</th>
<th>TC</th>
<th>VRMAX</th>
<th>VRMIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03 pu</td>
<td>1.0 sec</td>
<td>400 pu</td>
<td>0.02 sec</td>
<td>0 sec</td>
<td>0 sec</td>
<td>7.3 pu</td>
<td>-6.6 pu</td>
</tr>
</tbody>
</table>

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4) At every time step of 1 second, measure the voltage, current, real power and reactive power at the monitoring bus. In this case, bus 5 is the monitoring bus.
5) Using the data obtained from step (iv), calculate the indices, namely, power margin, ISI, VCPI and L index for every time step of 1 second.
6) Plot the indices against time.
7) Return to step (iii) to repeat the procedures for another contingency case.

TEST RESULTS

The indices for predicting dynamic voltage collapse using the power margin, ISI, L index and VCPI have been verified on the 9 bus test system and the results are presented accordingly. Figures 5a), b), c) and d) show the plots of the ISI, L index, VCPI and power margin against time for the first contingency case whereas Figures 6a), b), c) and d) show the plots of the indices for the second contingency case. For both cases, the indices are plotted at the monitoring bus 5.

Figures 5a and 5c show that voltage collapse occur at time t = 39.5 sec when the ISI index and the VCPI index reach unity at that time and the voltage magnitude is 0.64 p.u. On the other hand, Figure 5b) shows that voltage collapse occur at time t = 50.5 sec which is the point when the L index reach unity and the voltage magnitude is 0.56 p.u. The time to voltage collapse is greater for the case of the L index compared to the VCPI and ISI indices. Figure 5d) illustrates the relation between the power margin and the voltage magnitude at bus 5. When the voltage magnitude decreases until it reaches 0.645 p.u., the power margin at that point reaches zero. It is happened when the time t = 40 sec. Voltage collapse is said to occur at this time because no more (zero) extra MVA can be delivered to the load before collapse (Bergovic et. al. 2002).

Figures 6a) and 6c) show similar voltage collapse phenomena in which voltage collapse is said to occur when the ISI and VCPI indices reach unity at time t = 45 seconds. However, Figure 6b) shows that voltage collapse occur at time t = 61 sec which is the point when the L index reach unity and the voltage magnitude is 0.75 p.u. The time to voltage collapse is greater for the case of the L index compared to the VCPI and ISI indices.

Figure 6d) illustrate the relation between the power margin and the voltage magnitude at bus 5. When the voltage magnitude decreases until it reaches 0.59 p.u., the power margin at that point reaches zero voltage collapse said collapse at that time. Voltage collapse is said to occur at this time because no more (zero) extra MVA can be delivered to the load before collapse. It is happened when the time t = 45 sec. From two contingency shown the result of ISI and VCPI are giving faster and better indicator than L index. Both contingency illustrates voltage magnitude will drop as function of load increase per time unit (sec). In term of voltage magnitude against time plot, it can be shown that greater drop between voltages in certain time interval indicate faster time collapse will occurrence. First contingency give voltage slope against time greater than second contingency, hence the first contingency result give time to collapse faster than second one.

CONCLUSION

In this work, four voltage collapse indices have been developed and compared to investigate their effectiveness in dynamic voltage collapse prediction.
Verification of the indices was carried out by testing on the 9 bus test system. From the simulation results, it can be concluded that the ISI and VCPI gives faster and better voltage collapse prediction than the L index. The ISI and VCPI are very sensitive in detecting dynamic voltage collapse and faster than L index. Power margin (PM) gives more information about how much system has extra MVA before collapse. PM indicator - very good is method for control purpose. Power margin indices time of collapse nearly same result as ISI and VCPI. Future works to be carried out such as the development of a new dynamic voltage collapse predictor and voltage control predictor together to prevent for Voltage collapse.

Figure 5a. Plot of ISI against time  
Figure 5b. Plot of L index against time  
Figure 5c. Plot of VCPI against time  
Figure 5d. Plot of Power Margin against time  

Figure 5.(a)-(d) Result for first Contingency at each indices
Figure 6a. Plot of ISI against time

Figure 6b. Plot of L index against time

Figure 6c. Plot of VCPI against time

Figure 6d. Plot of Power Margin against time

Figure 6. (a)-(d) Result for Second Contingency at each indices

REFERENCES


