Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 7 (6): 841-847, 2007
ISSN 1812-5654

New Method for Vulnerability Assessment of Power System

Ahmed M.A. Haidar, Azah Mohamed and Aini Hussain
Department of Electrical, Electronic and System Engineering,
University Kebangsaan Malaysia, UKM 43600 Bangi, Selangor, Malaysia

Abstract: Vulnerability assessment in power systems is to determine a power system's ability to continue to provide service in case of an unforeseen catastrophic contingency. It combines information on the level of system security as well as information on a wide range of scenarios, events and contingencies. To assess the level of system strength or weakness relative to the occurrence of an undesired event, a quantitative measure based on vulnerability index is often considered. In this study, a new vulnerability assessment method is proposed based on total power system loss which considers power generation loss due to generation outage, power line loss due to line outage, increase in total load and amount of load disconnected. The objective of this study is to investigate the effectiveness of the new proposed method in assessing the vulnerability of power system when subject to various contingencies. The performance of the proposed vulnerability assessment method is compared with other known vulnerability assessment methods based on anticipated loss of load as well as comprehensive system information of individual system components. In this study, vulnerability analysis was carried out on the IEEE 24 bus test system using the Power System Analysis and Toolbox (PSAT) and the vulnerability indices were calculated using the Matlab program. Obtained results, indicate the efficiency of proposed method.

Key words: Vulnerability assessment, power system loss, vulnerability index, contingency analysis

INTRODUCTION

Several cascading failures and large area blackouts occurring in recent years highlighted the need for vulnerability assessment of power systems. In the past, regulated electric utilities were able to justify improvement in system operation or infrastructure based solely on crude methods of security assessment. However, in a deregulated environment with a highly competitive electricity market, this is no longer the case (El-Sharkawi, 2002). The Northeastern blackout in August 2003, the First Energy system operators did not know that they would run their system vulnerable due to the next contingency. If emergency control steps such as load shedding were taken at the Cleveland and Akron Area, the cascading outages could have been avoided (Song and Kezunovic, 2006). Most of the incidents are believed to be related to lack of the vulnerability information about heavily stressed systems where large amounts of real and reactive powers are transported over long transmission lines while appropriate power sources are not available to maintain the system (Amjady and Esmaili, 2003). The increase of power exchanges due to new transactions results in congestion of the transmission grids with the consequence of reduced stability margin and it makes power system more vulnerable. The uncertainties of power system restructuring efforts as well as utility economics have led many companies to operate their systems close to the maximum loadability limits, thereby unwittingly pushing their systems toward the brink of system collapse (Verbic *et al.*, 2006).

A power system can become vulnerable for several reasons, such as power system component failures, communication system failures, human errors and weather conditions. The purpose of vulnerability assessment is to determine a power system's ability to continue to provide service in case of an unforeseen catastrophic contingency such as equipment failure, natural calamity, failure in protection, faults, human errors, heavy loading conditions and intrusion by external agents. A power system can be said to be invulnerable if it can withstand all credible contingencies without violating any of the system constraints. Therefore, the goal of vulnerability assessment is to predict vulnerability of grids to components failures. Accurate vulnerability assessment is very important and a vulnerability index is significantly needed to guide power system operators to steer the system to viable conditions. In power system vulnerability assessment, it takes in to account of

Corresponding Author: Ahmed M.A. Haidar, Department of Electrical, Electronic and System Engineering, University Kebangsaan Malaysia UKM 43600 Bangi, Selangor, Malaysia

information on the level of system security as well as information on a wide range of scenarios, events and contingencies with regards to which a system is vulnerable. Traditionally, power system security assessment is concerned with estimating the security level of a system and it encompasses the vulnerabilities resulting in voltage insecurity, static insecurity and dynamic insecurity. However vulnerability assessment, it takes into account not only the security information but the information of the whole system considering generation loss due to the generation outage, power line loss due to the line outage and increase in total load and amount of load disconnected, etc. (Song and Kezunovic, 2005).

For a power system to be judged as vulnerable or invulnerable, quantitative measures need to be considered to assess the degree of its vulnerability. Many studies have been conducted regarding vulnerability analysis. Some of these studies have proposed methods to assess the vulnerability of power system by using indices which are based on the order information obtained from the voltage collapse simulation (Pepyne *et al*., 2001) and indicators include adequacy indices which consider bus isolation probability, loss of load probability and expected power loss and security index which considers probability of stability (Yu and Singh, 2004). The network contribution factor calculated from the base case load flow condition and network information has been considered for vulnerability assessment (Song and Kezunovic, 2005). Other indices based on distance of the current operating points, anticipated loss of load index (Kim *et al*., 2005) and on the information of individual system components such as real and reactive power generation, generation loss, bus voltage, loadability, line real and reactive powers and bus voltage (Song and Kezunovic, 2006). To overcome the time-consuming computation of vulnerability indices, computational intelligent techniques have been applied to the vulnerability assessment of power systems. The computational intelligent techniques that have been considered such as hybrid technique considering neural network and particle swarm optimization (Kim, 2002) and Artificial Neural Network (Sanyal, 2004). These techniques have shown great potential for achieving fast and accurate evaluation of vulnerability assessment.

In this study, a new vulnerability assessment method is proposed based on total power system loss which considers power generation loss due to generation outage, power line loss due to line outage, increase in total load and amount of load disconnected. The objective of this study is to investigate the effectiveness of the new proposed method in assessing the vulnerability of power system when subject to various contingencies. The performance of the proposed vulnerability assessment method is compared with other known vulnerability assessment methods based on anticipated loss of load (Kim *et al*., 2005) as well as comprehensive system information indices of individual system components (Song and Kezunovic, 2006).

FORMULATION OF VULNERABILITY INDICES

The formulation of the proposed vulnerability assessment methods based on Power System Loss (PSL) and other methods based on the anticipated loss of load index (ALL) and the comprehensive system information of individual system components (CSI) are discussed.

Proposed vulnerability assessment method based on power system loss: The Power System Loss (PSL) index is based on active and reactive powers of system loss considering generation loss due to generation outage, power line loss due to line outage, increase in total load and amount of load disconnected. PSL was subjected to various system conditions using power flow solution based on static data to get the steady state result using the Power System Analysis and Toolbox (PSAT) (Milano, 2005).

The losses in the power transmission system are a function of not only the system load but also of the generation. Each contingency has an effect not only on the system performance but also on power losses in the system and other the relevant parameters. Therefore, it is important to consider total power system loss as a measure for indicating vulnerability of power systems. The outage of transmission line, transformer or generator may result in overload of other lines and causes increased active power loss in transmission lines and reactive power loss in transformers. Similar effect may result if contingency such as loss of load is said to occur. The formulation of the proposed index based on PSL is given as,

$$PSL = \frac{\sqrt{P_{BCL}^2 + Q_{BCL}^2}}{\left(\sqrt{P_{CCL}^2 + Q_{CCL}^2}\right) + S_{IL} + S_{LD} + \sum_{i=1}^{n} S_{LGO,i} W_{G,i} + \sum_{i=1}^{m} S_{LLO,i} W_{L,i}} \qquad (1)$$

where:

P_{BCL}, Q_{BCL} : Active and reactive powers of system loss at base case
P_{CCL}, Q_{CCL} : Active and reactive powers of system loss at contingency case
S_{IL} : Increase in total load
S_{LD} : Amount of load disconnected
$S_{LGO,i}$: Loss of generated MVA due to generator outage
$S_{LLO,i}$: Loss of transported MVA due to line outage
$W_{G,i}$: Weight of individual generator power output
$W_{L,i}$: Weight of individual line power influence
n : Number of generators
m : Number of lines

From Eq. 1, it can be noted that the proposed vulnerability index, PSL will have values in the range of 1-0 in which these values can be categorized into three different range of values. For values of PSL in the range of 1-0.6, it means that a system is invulnerable. For PSL values in the range of 0.59-0.3, it means that a power system is in an alert state while values in the range of 0.29-0, indicates that a system is vulnerable. The assumed limits of index values can be changed or readjusted by a control operator based on any new system configuration. The weight of individual generator and line are chosen based on their importance considering power system operating practices.

Vulnerability assessment method based on anticipated loss of load: The Anticipated Loss of Load (ALL) index is the amount of loads shed due to a contingency in order to avoid a cascading outage. Since the purpose of vulnerability assessment is to avoid a catastrophic power outage, the vulnerability index should reflect the loads that may be lost at such times (Kim *et al*., 2005).

The ALL is derived by first considering the fact that a power system is operated under quasi-equilibrium condition in which it obeys a balance demand and generation given as,

$$\text{Total Loads} + \text{System Loss} = \text{Total Generation} \quad (2)$$

The system frequency is governed by this equilibrium and consequently any unbalance in loads can result in frequency excursions that may lead to loss of synchronism. Excess of load results in a drop of system frequency and load shedding has to be employed in order to rapidly balance the demand and generation. To avoid system unbalance, load shedding has to be implemented in which the amount of load shed is considered as a vulnerability index (Kim *et al*., 2005). Load shedding can be accomplished by using frequency sensitive relays that detect the onset of decay in power system frequency where both frequency and rate of frequency decline are measured. It is usually implemented in stages, each of which is triggered at a different frequency level or at specified rate of frequency decline (Lindahl *et al*., 1997).

One way of determining the ALL is by assuming that the additional power generation that needs to be compensated in case of a contingency is equal to the amount of load shed in order to maintain the stability of a system and recover the frequency drop. The amount of load shed in this case is the ALL.

Vulnerability method based on comprehensive system information: The comprehensive system information (CSI) index gives comprehensive vulnerability information about individual power system components at various system conditions. It considers vulnerability in three major power system components, namely, generator, load and transmission line. At the generator side, generated real and reactive powers and generation loss due to generated outage are considered. At the bus side, the parameters that are of interest are the bus voltage, loadability and load loss. However, at the transmission side, the parameters that are considered are the line real and reactive powers, line charging, line voltage angle difference, distance relay performance and line-switching influence. Different weights of various elements are considered comprehensively based on their importance and power system operating practices (Song and Kezunovic, 2006). Base on the information of three system components, vulnerability indices such as Generator Vulnerability Index (GVI), Line Vulnerability Index (LVI) and Bus Vulnerability Index (BVI) are derived and then combined to give the Comprehensive System Information (CSI) vulnerability index. If the value of the CSI vulnerability index is greater than the value at the base case, it indicates that the system is more vulnerable (Song and Kezunovic, 2006).

The generator vulnerability index (GVI) is given by,

$$VI_{gen} = \sum_{i=1}^{m}\left(VI_{Pg,i} + VI_{Qg,i} + VI_{gen-loos,i}\right) \quad (3)$$

where:

$VI_{Pg,i}$: Vulnerability index of individual generated real power
$VI_{Qg,i}$: Vulnerability index of individual generated reactive power
$VI_{gen-loos,i}$: Vulnerability index of individual generator loss

The Bus Vulnerability Index (BVI) is given by,

$$\mathrm{VI}_{\mathrm{bus}} = \sum_{i=1}^{n}\left(\mathrm{VI}_{\mathrm{V},i} + \mathrm{VI}_{\mathrm{loadab},i} + \mathrm{VI}_{\mathrm{load-loss},i}\right) \qquad (4)$$

where

$\mathrm{VI}_{\mathrm{V},i}$: Vulnerability index of individual bus voltage magnitude

$\mathrm{VI}_{\mathrm{loadab},i}$: Vulnerability index of individual load bus loadability

$\mathrm{VI}_{\mathrm{loadab-looss},i}$: Vulnerability index of individual bus loss in load

The Line Vulnerability Index (LVI) is expressed as,

$$\mathrm{VI}_{\mathrm{line}} = \sum_{i=1}^{P}\begin{pmatrix}\mathrm{VI}_{\mathrm{Pf},i} + \mathrm{VI}_{\mathrm{Qf},i} + \mathrm{VI}_{\mathrm{Qc},i} + \\ \mathrm{VI}_{\mathrm{line-ang},i} + \mathrm{VI}_{\mathrm{Relay},i} + \mathrm{VI}_{\mathrm{line-off},i}\end{pmatrix} \qquad (5)$$

where

$\mathrm{VI}_{\mathrm{Pf},i}$: Vulnerability index of individual line real power

$\mathrm{VI}_{\mathrm{Qf},i}$: Vulnerability index of individual line reactive power

$\mathrm{VI}_{\mathrm{QC},i}$: Vulnerability index of individual line charging

$\mathrm{VI}_{\mathrm{line-ang},i}$: Vulnerability index of individual line voltage angle difference

$\mathrm{VI}_{\mathrm{Relay},i}$: Vulnerability index of individual line distance relay

$\mathrm{VI}_{\mathrm{line-off},i}$: Vulnerability index of individual line outage influence

The CSI vulnerability index (VI) is expressed as,

$$\mathrm{VI} = \mathrm{W}_{\mathrm{gen}}\mathrm{VI}_{\mathrm{gen}} + \mathrm{W}_{\mathrm{bus}}\mathrm{VI}_{\mathrm{bus}} + \mathrm{W}_{\mathrm{line}}\mathrm{VI}_{\mathrm{line}} \qquad (6)$$

where

$\mathrm{VI}_{\mathrm{gen}}$: Total Vulnerability index of all generators

$\mathrm{VI}_{\mathrm{bus}}$: Total Vulnerability index of all load buses

$\mathrm{VI}_{\mathrm{line}}$: Total Vulnerability index of all lines

$\mathrm{W}_{\mathrm{gen}}$: Weight of all generators

$\mathrm{W}_{\mathrm{bus}}$: Weight of all load buses

APPROACH FOR VULNERABILITY ASSESSMENT

The approach to power system vulnerability assessment begins by first analyzing the system behavior at the base case condition. The next step is to analyze the system behavior when subjected to credible system contingencies by considering several test cases such as Line Outage (LO), Generator Outage (GO), increase in total load and amount of load disconnected. The vulnerability indices are then calculated for each test case. The proposed vulnerability index PSL is compared with the indices based on ALL and CSI so as to determine the effectiveness and accuracy of the index in assessing system vulnerability.

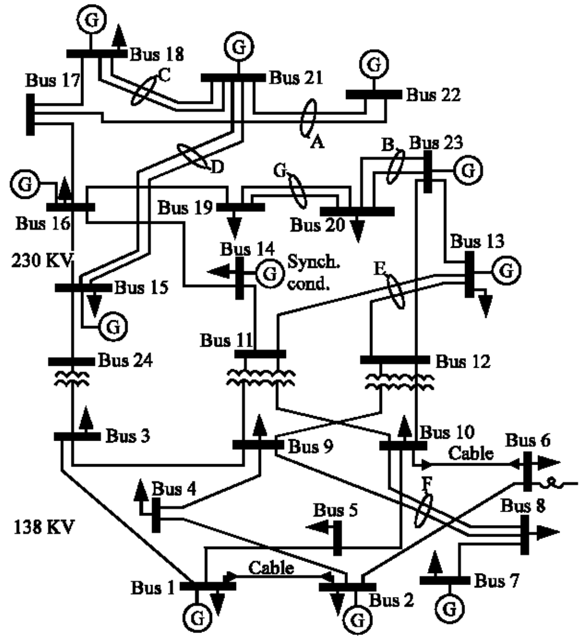

Fig. 1: IEEE 24-bus Reliability Test System (RTS)

In this study, power flow simulations were carried out using the Power System Analysis and Toolbox (PSAT) (Milano, 2005) on the 24-bus Reliability Test System which is shown in Fig. 1. The system data for the 24-bus system can be found in (Grigg *et al.*, 1999). The various vulnerability indices GVI, BVI, LVI, CSI, ALL and PSL were then calculated for various contingency cases using the Matlab program. For the calculation of the GVI, BVI, LVI, CSI and PSL the weights of all the system parameters are set equal one for simplicity in calculation. In practice, system operators may assign different weights to represent the varying importance of selected elements in the system (Song and Kezunovic, 2005).

In the proposed vulnerability assessment method using PSL, power flow simulations were carried out on the IEEE 24 bus test system using the Power System Analysis and Toolbox (PSAT) to get the steady state results as shown in Fig. 2. The first step to analyze system behavior at the base case. The next step is to analyze the

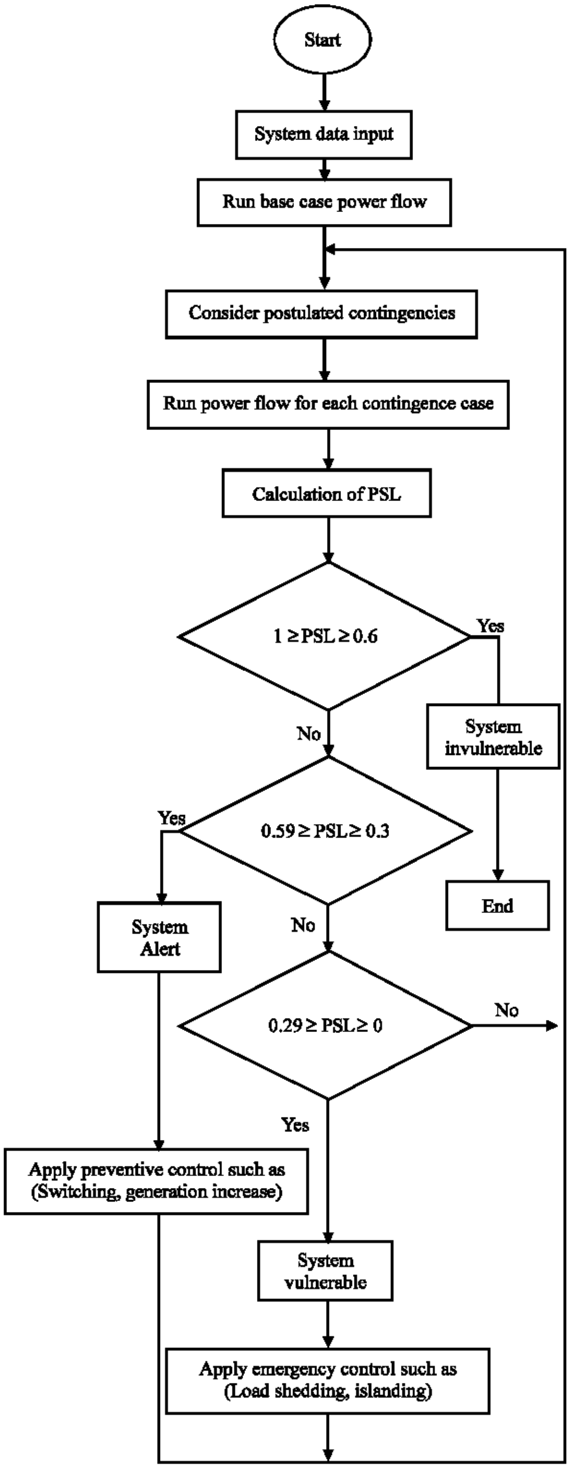

Fig. 2: Vulnerability assessment flow chart based on PSL

system behavior when subjected to credible system contingencies such as Line Outage (LO), Generator Outage (GO), increase in total load and amount of load disconnected. The vulnerability indices are then calculated for each contingency case. According to the limits of the PSL vulnerability index that was assumed invulnerable, alert and vulnerable the operators in the control can take preventive and emergency steps to minimize catastrophic power outages and reduce the associated risk such as switching of some lines to balance the power transfer through the others, generation increase and load shedding.

RESULTS AND DISCUSSION

The results of the various vulnerability indices calculated for each contingency case are summarized as in Table 1 and also shown graphically as in Fig. 3-5. These indices assess the system whether it is vulnerable or not when subjected to various contingencies and may also be used to indicate the critical contingencies. In this case,

Table 1: Vulnerability indices values at different contingencies

Contingency cases	PSL	ALL	CSI
Base Case	1	0	12.8
10% load increase	0.24	2.95	13.48
LO_2(1-3)	0.82	0.11	13.97
LO_4(2-4)	0.73	0.14	14.18
LO_7(3-24)	0.25	1.71	18.01
LO_10(6-10)	0.24	2.34	20.45
LO_18(11-13)	0.49	0.3	14.1
LO_20(12-13)	0.65	0.21	13.89
LO_21(12-23)	0.27	1.27	15.36
LO_22(13-23)	0.28	1.21	15.18
LO_24(15-16)	0.47	0.13	14.15
LO_25_1(15-21)	0.31	0.41	14.71
LO_25_2(15-21)	0.31	0.41	14.71
LO_26(15-24)	0.29	0.13	14.15
LO_27(16-17)	0.23	0.87	16.36
LO_31_1(18-21)	0.62	0.07	13.77
GO_1	0.38	1.96	14.8
GO_2	0.38	1.96	14.85
GO_7	0.24	2.45	21.04
GO_14	0.9	0	13.75
GO_15	0.24	2.07	12.62
GO_16	0.3	1.49	12.85
GO_18	0.14	3.85	12.33
GO_21	0.14	3.83	11.92
GO_22	0.16	2.81	11.6
GO_23	0.1	6.5	14.2
GO_1,2,7	0.09	5.14	41.06
GO_2,14,21	0.13	5.66	15.56
GO_15,16,23	0.08	10.3	16.09
GO_18,21,22	0.07	11.3	21.57
Load _1 = 0	0.42	0	13.63
Load _3 = 0	0.31	0	13.93
Load_6 = 0	0.32	0	13.75
Load_7 = 0	0.4	0	13.06
Load_18 = 0	0.16	2.14	18.68
Load_20 = 0	0.46	0.29	14.2
Two Line Outages LO_19 (11-14) LO_20(12-13)	0.33	0.7	15.38

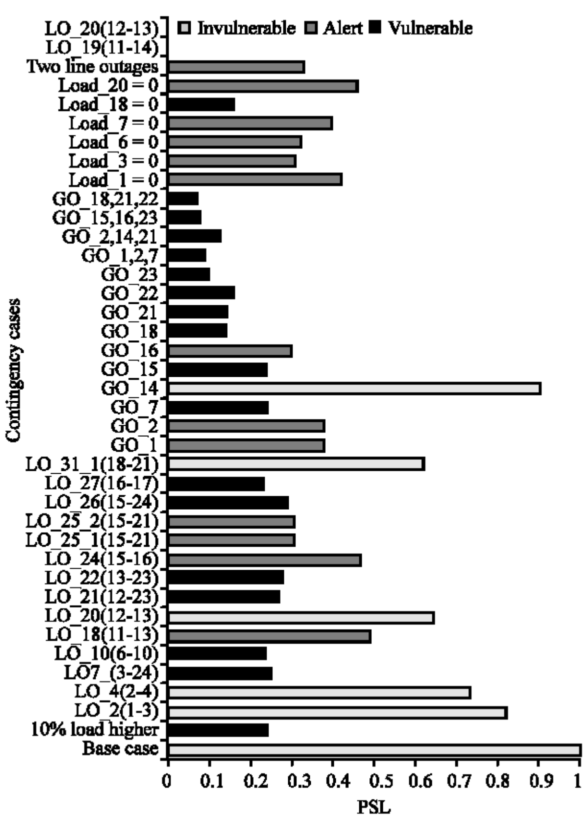

Fig. 3: Vulnerability indices based on active and reactive system loss

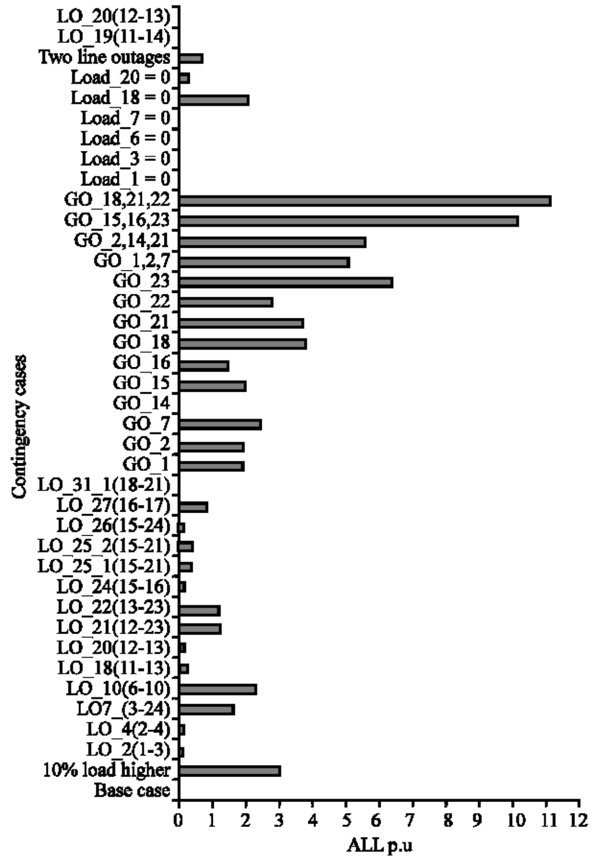

Fig. 4: Vulnerability indices based on anticipated loss of load

the criteria for determining system vulnerability is based on the vulnerability index calculated at base case.

From Fig. 3-5, it can be seen that the system is more vulnerable when contingencies occur due to line outages LO_10 (6-10), LO_7 (3-24) and LO_27 (16-17). This is due to the outage of line 10 which connects bus 6 to bus 10, will cause a drop in voltage at bus 6 and makes the system vulnerable because line 10 is a special cable with large capacitance and also there is a 100MVar reactor connected at bus 6. The outage of line 7 which connects bus 3 to bus 24 will cause disconnection of a transformer and overloading at neighboring lines so as to compensate power transfer to the loads that were supplied by the transformer. The outage of line 27 which connects bus 16 to bus 17 will cause heavy power loss and increase the system vulnerability.

It is noted that the system will become more vulnerable when a generator outage occurs at bus 23 (GO_23) and multiple generator outages occur at buses 18, 21 and 22 (GO_18, 21, 22) as shown in Fig. 4 and a generator outage at bus 7 (GO_7) and multiple generator outages at buses 1, 2 and 7 (GO_1,2,7) as shown in Fig. 5. Referring to Fig. 3, these generator outages are recognized by PSL indices as vulnerable because the indices values are almost 0.3 and such values have been classified as causing the system vulnerable.

For the contingency case due to load disconnection, it can be seen that from Fig. 4 and 5, the system becomes vulnerable due to disconnection of load at bus 18 (Load_18 = 0). Referring to Fig. 3, the PSL index has also identified that the system is vulnerable when such a contingency occurs.

Referring to Fig. 4 and 5, the ALL and CSI indices assess the system as invulnerable for contingency cases of outage of lines 2 and 31 (LO_2 and LO_31) and generator outage 14. With respect to PSL index, these line outages and generator outage also do not cause system vulnerability as can be seen from Fig. 3. It was found that for some of generation outage cases, the CSI index does not give a clear assessment about the vulnerability of the system such as generation outage of GO_21 and GO_22 as shown in Fig. 5. However, these outages were classified by PSL index as making the system vulnerable.

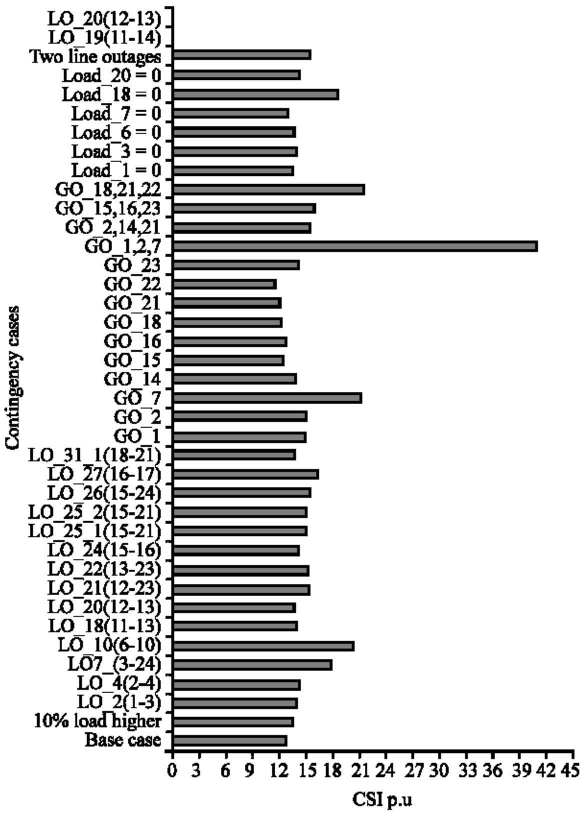

Fig. 5: Vulnerability indices based on comprehensive system information

CONCLUSIONS

In assessing the vulnerability of power systems when subjected to various contingencies, initial works focus on investigating the effectiveness and performance of the new proposed vulnerability index based on Power System Loss (PSL) with other known vulnerability indices using the Anticipated Loss of Load (ALL) and the Comprehensive System Information (CSI). Test results demonstrate that the PSL index is more accurate in assessing the vulnerability of power systems when compared to the ALL and CSI indices. Such vulnerability indices can determine how vulnerable a power system is so that preventive and emergency control steps can be taken to minimize catastrophic power outages.

REFERENCES

Amjady, N. and M. Esmaili, 2003. Improving voltage security assessment and ranking vulnerable buses with consideration of power system limits. J. Electrical Power and Energy System, 25: 705-715.

El-Sharkawi, M.A., 2002. Vulnerability assessment and control of power system. In: Processing of the IEEE Transmission and Distribution Conference Asia Pacific 2002.

Grigg, C., P. Wong and P. Albrecht, 1999. The IEEE reliability test system-1996. A report prepared by the reliability test system task force of the application of probability methods subcommittee. In: Processing of the IEEE Conference on Power Systems, August 1999.

Kim, M., 2002. Application of Computational Intelligence to Power System Vulnerability Assessment and Adaptive Protection Using High Speed Communicate, MSc. Thesis. University of Washington, USA, pp:

Kim, M., M. El-Sharkawi and R. Marks, 2005. Vulnerability indices for power system. In: Processing of the IEEE 13th International Conference on Intelligent Systems Application to Power Systems, Nov. 6-10, 2005.

Lindahl, S., G. Runvik and G. Stranne, 1997. Operational experience of load shedding and new requirements on frequency relays. In: Processing of the IEEE Conference on Developments in Power System Protection, March 1997.

Milano, F., 2005. Power System Analysis Toolbox, PSAT Version 1.3.4, [online] available: http://www.power.uwaterloo.ca/~fmilano/.

Pepyne, D., C. Panayioto, C. Cassandras and H. YC, 2001. Vulnerability assessment and allocation of protection resources in power system. In: Processing of the IEEE American Control Conference Arlington, 2001.

Sanyal, K.K., 2004. Transient stability assessment using artificial neural network. In: Proceeding of the IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies Hong Kong, April 2004.

Song, H. and M. Kezunovic, 2005. Static security analysis based on vulnerability index and network contribution factor method. In: Processing of the IEEE Asia-Pacific Transmission and Distribution Conference and Exposition, China, August 2005.

Song, H. and M. Kezunovic, 2006. Static analysis of vulnerability and security margin of the power system. In Processing of the IEEE PES Transmission and Distribution Conference and Exposition, Dallas, May 2006.

Verbic, G., M. Pantos and F. Gubina, 2006. On voltage collapse and apparent-power losses. J. Electrical Power and Energy System, 76: 760-767

Yu, X. and C. Singh, 2004. A practical approach for integrated power system vulnerability analysis with protection combined algorithms failures. In: Processing of the IEEE Conference on Power System, November 2004.