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EFFICIENT PERFORMANCE INDICES FOR VOLTAGE COLLAPSE DETECTION

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ABSTRACT

This paper proposes six performance indices (PIs) for efficient detecting the most weakness load buses which may be subjected to voltage collapse occurrence at normal and emergency conditions. The classification of the suggested ranking PIs are dependent on their severity on the voltage collapse. The suggested PIs are based on the following physical quantities: equivalent system impedance and the related load impedance at each load bus, equivalent system admittance and the related load admittance at each load bus, load bus voltages and loading levels at different loading buses.

These PIs derived based on circuit's theory and tested using one standard system, namely IEEE 14-bus. In addition, the capability of these PIs is demonstrated using the west Delta network (WDN) as a real part of the Unified Egyptian Network (UEN). The results detect efficiently the most sever load buses which may be subjected to voltage collapse occurrence.

يقترح هذا البحث ستة معاملات أداء (PIs) لتحديد قضبان الأحمال المعرضة لإنهيار الجهود فى حالات التشغيل العادية والطارئة لنظم القوى الكهربية. حيث أن ترتيب القضبان بالنسبة لخطورتها لحدوث إنهيار الجهد أعتمدت على المعاملات المقترحة. كما أعتمدت على الكميات الطبيعية التالية: معاوقة المنظومة الكهربية المكافئة و معاوقة الحمل عند قضبان الأحمال، سماحية المنظومة الكهربية المكافئة و سماحية الحمل عند قضبان الأحمال، جهود قضبان الأحمال و مستويات تحميل القدرة الفعالة الكهربية عند حالات التحميل المختلفة.

أعتمدت هذه المعاملات فى إستنتاجها على مبادىء نظرية الدوائر الكهربية و تم تطبيقها على نظام قياسى وهو نظام 14 قضيب. بالاضافة الى تطبيقها على منظومة شبكة غرب الدلتا (WDN) كجزء من نظام حقيقى داخل الشبكة الموحدة لجمهورية مصر العربية. وقد أوضحت النتائج أن المعاملات المقترحة ذات كفاءة فى ترتيب قضبان التحميل الاكثر عرضة لإنهيار الجهود.

Keywords: Performance indices, Voltage collapse, Sensitive, Insensitive, Load bus, Risk, Ranking

1. INTRODUCTION

Nowadays, the power systems become more complicated and having many buses and transmission lines after interconnecting the power systems to become interconnected networks in several areas in the world. The operation of power systems closer to their load limits is dictated by the needs of deregulated electricity markets. However, as a result, several blackouts have occurred due to voltage instability. This means that voltage stability has become a matter of serious concern for system operators and is the subject of considerable investigation because of its importance in terms of the security of the system and the quality of the power. Significant efforts are still being directed towards definitions, classifications, new concepts, practices and tools for solving the voltage-stability and security-analysis problems [1].

Voltage collapse is a major concern in modern power systems, which are steadily approaching the operating limits imposed by economic and environmental constraints. The expansion of the conventional power system allows for incidences where unexpected contingencies to go unconsidered, particularly due to the deregulation process in power systems. It is, therefore, difficult to predefine all the outages and complexities and control counterparts. Stability, security and efficiency are of utmost importance in planning and operating the power systems.

Many performance indices for categorizing voltage stability in static security stability assessment in power systems have been developed over the years. Most of them are defined by the current operating point to different stability boundaries or collapse point and are typically based on sensitivity techniques and multiple load flow results. Techniques such as the Voltage Collapse Proximity Indicator (VCPI), Voltage Instability Predictor Index (VIPI) and energy method, L-Indicator which was derived from load flow and continuation power flow, and an Integrated Logarithmic Index (ILI) are some typical methods for assessing static voltage instability problems. So that, it is very important to detect the voltage stability through making a suitable rank procedure to identify the state of load buses and/or critical lines according to their severity risk. Hence, the critical buses and/or critical lines are defined.

Musirin and Abdul Rahman [2] demonstrated the use of line stability index termed as fast voltage stability index (FVSI) in order to determine the maximum loadability in a power system. The bus that is ranked highest is identified as the weakest bus since it can withstand a small amount of load before causing voltage collapse. Nithiyananthan *et al.* [3] proposed a methodology for line outage ranking based on Reactive Compensation Index (RCI) using artificial shunt compensators to maintain the load bus voltages to its pre-outage values. Sutha and Kamaraj [4] used Wavelet Transform Based Artificial Neural Networks (WNN) to estimate the Real Power Index (RPI) of all the critical contingencies under any loading conditions. Silveira *et al.* [5] proposed Sensitivity indices based on the ratio of the differential change in a variable to the differential change in the other variable. Zhu *et al.* [6] presented PIs for evaluating the impact of VAr optimization with coordinated static VAr compensator (SVC) model no loss minimization and voltage improvement.

2. PROPOSED PERFORMANCE INDICES

A six performance indices are proposed in this paper to rank the load buses according to their severity as follows:

2.1. Two PIs Based on System Impedance

Based on Thevenin's theorem that provides an extremely valuable means for reducing a complex circuit to a simple circuit containing an ideal voltage source in series with equivalent impedance, thus, the complex power circuit shown in Fig. 1(a) can always be reduced to the Thevenin's equivalent as shown in Fig. 1(b).

From this circuit, the real power transmitted to load can be calculated, as:

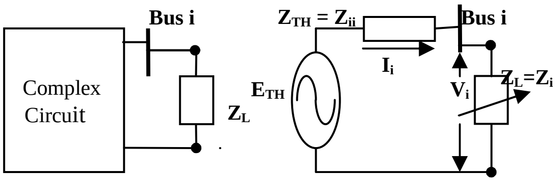
$$P_L = real\left\{V_i I_i^*\right\}$$

$$= real \left\{ \frac{Z_i E_{TH}}{Z_i + Z_{ii}} \times \frac{E_{TH}^*}{\left[Z_i + Z_{ii}\right]^*} \right\}$$

or,

$$P_L = real \left\{ \frac{Z_i}{\left[Z_i + Z_{ii}\right]^2} E_{TH}^2 \right\} \quad (1)$$

To obtain the maximum power transmitted (P_L^{max}) to the load, $\partial P_L/\partial Z_i$ is calculated and equals to zero as follows:



(a) Original circuit (b) Thevenin equivalent circuit

Fig. 1 Reduction network using Thevenin's theorem

$$\frac{\partial P_L}{\partial Z_i} = 0$$

$$real \left\{ \frac{\left[Z_i + Z_{ii}\right]^2 E_{TH}^2 - 2 \times Z_i E_{TH}^2 \left[Z_i + Z_{ii}\right]}{\left[Z_i + Z_{ii}\right]^4} \right\} = 0$$

Hence, the maximum power transmitted to the load occurs at $Z_i = Z_{ii}$ can be calculated, as:

$$P_L^{max} = real \left\{ \frac{E_{TH}^2}{4\left|Z_{ii}\right|} \right\} \quad (2)$$

For preventing the occurrence of the voltage collapse in power systems, it should satisfy the following inequality:

$$\left|Z_{ii} / Z_i\right| \leq 1.0 ; i = 1, ... N \quad (3)$$

Where,

Z_{ii} is the *ith* diagonal elements of the Thevenin's equivalent impedance matrix.

N is the number of load buses.

Z_i is the load impedance, which is calculated, as:

$$Z_i = \left|V_{Li}\right|^2 / S_i^* \quad (4)$$

Where,

$|V_{Li}|$ is the magnitude of the load voltage under normal and emergency conditions at bus *i*.

S_i^* is the conjugate of the apparent power at bus *i*.

However, the active and reactive powers of the loads and generators are represented by shunt elements with appropriate signs. Now, referring to equation (3), a first performance voltage collapse index (PI) based on system impedance is introduced to rank the load-bus voltages according to their severity risk situation for normal and emergency conditions as:

$$(PI_{1Z})_i = (\left|Z_{ii}\right| - \left|Z_i\right|) / \left|Z_i\right|, i = 1, ...N \quad (5)$$

The values of $|Z_{ii}|$ and $|Z_i|$ indicate the largest and the smallest PI. Hence, the buses that have the largest negative values of PI are considered as insensitive to the voltage collapse, and these buses will be indexed at the bottom of PI list. While, the buses that have the smallest negative values of PI will be indexed at the top of this list. These buses are considered as the most sensitive buses to the voltage collapse.

Figure 2 shows the PV nominal curve at bus *i*. In this figure, the maximum loading point (MLP) occurs at $Z_i = Z_{ii}$, and the nominal loading margin is the distance between the base case loading and the loading at the nose of the curve. In other words, the best loading condition is occurred $Z_i \geq Z_{ii}$. So, for preventing the occurrence of the voltage collapse in power system, it should satisfy the following inequality:

$$\left| P_{Li} \ / \ P_{Li}^{\max} \right| \leq 1.0 ; i = 1,.... \ N \qquad (6)$$

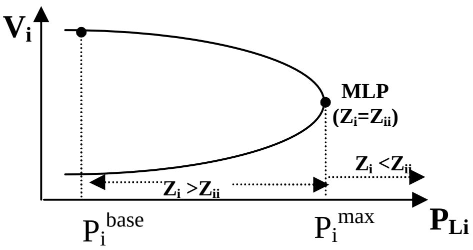


Fig. 2 PV nominal curve at bus *i*

By substituting from Equations (1) and (2) into (6), the second performance voltage collapse index (PI) is obtained based on system impedance to rank the load-bus voltages according to their severity risk situation for normal and emergency conditions, as:

$$(PI_{2Z})_i = \frac{4|Z_i||Z_{ii}|}{|Z_i + Z_{ii}|^2} \leq 1, i = 1,......N \qquad (7)$$

From equation (7), the buses that have the smallest positive values of PI are considered as insensitive to voltage collapse, and these buses will be indexed at the bottom of a list. While, the buses that have the largest positive values of PI will be indexed at the top of this list. These buses are considered as the most sensitive buses to the voltage collapse

2.2. Two PIs Based on System Admittance

Based on Norton's theorem, that provides an extremely valuable means for reducing a complex circuit to a simple circuit containing an ideal current source in parallel with equivalent impedance. Thus, the complex power circuit in Fig. 3(a) can be reduced to the Norton's equivalent in Fig. 3(b).

From this circuit, the real power transmitted to the load can be calculated as:

$$P_L = real \ \{V_i I_i^*\}$$

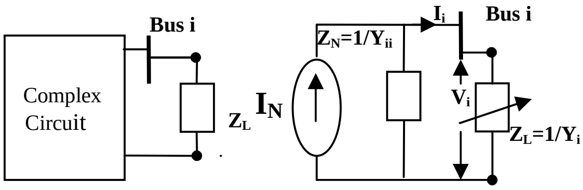
$$= real\left\{\frac{I_N}{Y_{ii}Y_i[1/Y_i + 1/Y_{ii}]} \times \frac{I_N^*}{Y_{ii}^*[1/Y_i + 1/Y_{ii}]^*}\right\}$$

$$= real \ \left\{\frac{I_N^2}{Y_i Y_{ii}^2 [1/Y_i + 1/Y_{ii}]^2}\right\} \qquad (8)$$

The maximum power transmitted to the load (P_L^{max}) occurs at $\partial P_L/\partial Y_i = 0$, that gives $Y_i = Y_{ii}$. So that,

$$P_L^{\max} = real \ \left\{\frac{I_N^2}{4|Y_{ii}|}\right\} \qquad (9)$$

Similarly, for preventing the occurrence of voltage collapse in power systems, it should satisfy the following inequality:



(a) Original circuit (b) Norton equivalent circuit

Fig. 3 Reduction network using Norton's theorem

$$\left| Y_{ii} \ / \ Y_i \right| \geq 1.0 ; i = 1,.... \ N \qquad (10)$$

Where,

Y_{ii} is the the *ith* diagonal elements of the admittance matrix.

Y_i is the load admittance and equals to the inverse of load impedance at bus *i*.

Now, referring to equation (10), the first performance voltage collapse index (PI) based on system admittance is introduced to rank the load-bus voltages according to their severity risk situation for normal and emergency conditions, as:

$$(PI_{1Y})_i = (|Y_{ii}| - |Y_i|)/|Y_{ii}|, i = 1,......N \qquad (11)$$

From equation (11), the buses that have the largest positive values of PI are considered as insensitive to voltage collapse, and these buses will be indexed at the bottom of a list. While, the buses that have the smallest positive values of PI will be indexed at the top of this list. These buses are considered as the most sensitive buses to voltage collapse.

Similarly, substatiting from equations (8) and (9) into (6), the second performance voltage collapse index (PI) based on system admittance to rank the load-bus voltages according to their severity risk situation for normal and emergency conditions can be expressed as:

$$(PI_{2Y})_i = \frac{4}{Y_i Y_{ii} \left|1/Y_i + 1/Y_{ii}\right|^2} \le 1, i = 1, ...N \qquad (12)$$

After computing PIs, the buses that have the smallest positive values of PIs are considered as insensitive to voltage collapse, and these buses will be indexed at the bottom of a list. While, the buses that have the largest positive values of PIs will be indexed at the top of this list. These buses are considered as the most sensitive buses to voltage collapse.

2.3. Voltage Performance Index

It measures the voltage deviation of each load bus, at normal and emergency conditions, with respect to specified voltage which equals to one p.u. So that, voltage performance index can be calculated from:

$$(PI_V)_i = (\left|V_{sp} - V_i\right|)/V_{sp}, i = 1, ...N \qquad (13)$$

Where,

V_{sp} is the specified voltage (equals to one per unit)

V_i is the voltage magnitude at node *i*.

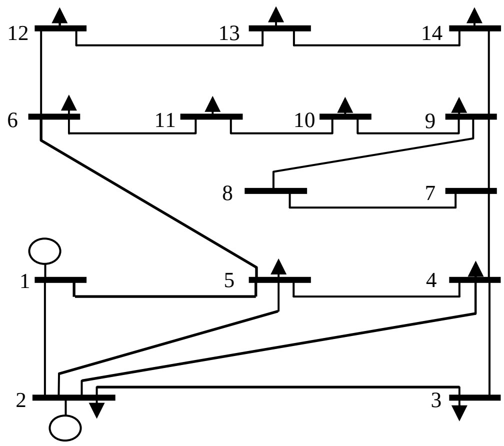


Fig. 4 Single line diagram for 14-bus test system

The load buses can be indexed according to equation (13). Where, the buses that have the largest positive values are indexed at the top of the list which is considered as the most sensitive buses to voltage collapse. While, the buses that have the smallest positive values are indexed at the bottom of this list which are considered as insensitive buses to voltage collapse.

2.4. Loading Performance Index

The performance index based on the active power is determined based on the load deviation at each load bus with respect to the total load of the system, as:

$$(PI_P)_i = (P_{Lt} - P_{Li})/P_{Lt}, i = 1, ...N \qquad (14)$$

Where,

P_{Lt} is the total active load powers at all nodes.

P_{Li} is the load power at node *i*.

From equation (14), the buses that have the smallest positive values of PIs have heavily loaded are considered as sensitive to voltage collapse, and these buses will be indexed at the top of the list. While, the buses that have the largest positive values have light loaded, the PIs will be indexed at the bottom of this list. These buses are considered as insensitive buses to voltage collapse.

3. APPLICATIONS

3.1. Test Systems

The proposed performance indices are applied on *IEEE* standard 14-bus (Fig. 4) [7] and a real power system of the WDN system as a part of the Unified Egyptian Network (UEN) [8]. Bus 1 in all test systems is taken as slack bus. In addition, the load flow is done using MATPOWER toolbox in MatLab code program.

Different emergency conditions are assumed as:

- For the 14-bus test system.
  - a – Lines 2-3 and 4-5 are outage.
  - b –Load at bus 14 is increased with 50 %.
- For the west delta system.
  - a – Lines 24-25, and 5-31 are outage.
  - b –Load at bus 36 is increased with 50 %.

3.2. Results and Comments

3.2.1 Normal conditions

Tables 1 and 2 show the proposed PIs of load-buses according to their severity due to the voltage collapse based on the system impedance, admittance, voltage and loading for 14-bus test system. From these tables, it can be shown that, bus 3 is the most sensitive bus based on PI_{1Z}, PI_{2Z} PI_{1Y}, PI_{2Y} and PI_P which is heavily loaded with a minimum voltage deviation. So that, the impedance deviation of Z_{ii} with respect to Z_i is decreased (the admittance deviation of Y_i with respect to Y_{ii} is decreased). While, this bus is the most insensitive bus based on PI_V because it has a minimum voltage deviation with respect to flat voltage. On the contrary, bus 5 is the most insensitive bus based on PI_{1Z}, PI_{2Z} PI_{1Y} and PI_{2Y} where the impedance deviation of Z_{ii} with respect to Z_i is increased (the admittance deviation of Y_i with respect to Y_{ii} is increased). In another side, bus 8 is the most sensitive bus based on PI_V because it has a maximum voltage deviation. Based on PI_P, bus 11 is the most insensitive bus where it has lightly loaded. Moreover, Two PIs based on the system impedance give the same ordering. Also, the same ordering obtained using two PIs based on the system admittance.

Table 1 Ranking of load buses based on impedance and admittance matrices at normal condition for 14-bus system

Rank	PI_{1Z}	Rank	PI_{2Z}	Rank	PI_{1Y}	Rank	PI_{2Y}
3	-0.854	3	0.445	3	0.910	3	0.302
9	-0.928	9	0.252	8	0.974	8	0.098
8	-0.941	8	0.211	14	0.975	14	0.094
14	-0.944	14	0.201	9	0.988	9	0.048
4	-0.954	4	0.170	4	0.988	4	0.045
13	-0.957	13	0.159	13	0.989	13	0.041
10	-0.972	10	0.105	2	0.990	2	0.039
6	-0.973	6	0.103	12	0.992	12	0.033
12	-0.977	12	0.087	10	0.994	10	0.024
2	-0.983	2	0.065	6	0.994	6	0.023
11	-0.989	11	0.045	11	0.996	11	0.015
5	-0.993	5	0.027	5	0.998	5	0.008

Table 2 Ranking of load buses based on voltage and loading PIs at normal condition for 14-bus system

Rank	PIV	Rank	PIP
8	0.090	3	0.6363
6	0.070	4	0.8154
11	0.057	9	0.8861
9	0.056	2	0.9162
12	0.055	14	0.9425
10	0.051	13	0.9479
13	0.051	6	0.9568
2	0.045	10	0.9653
14	0.036	5	0.9707
5	0.020	12	0.9764
4	0.019	11	0.9865
3	0.010	1, 7, 8	---

"---" denotes that no load demand at this bus.

Figures 5 - 7 show the proposed PIs of load-buses according to their severity due to the voltage collapse for WDN system. In figure 5, it can be shown that, bus 33 is the most sensitive bus based on PI_{1Z} and PI_{2Z}, which have the most heavily loaded. So, the impedance deviation of Z_{ii} with respect to Z_i is decreased. On the contrary, bus 52 is the most insensitive bus based on PI_{1Z} and PI_{2Z}, because the impedance deviation of Z_{ii} with respect to Z_i is increased. In figure 6, bus 33 is also the most sensitive bus based on PI_{1Y} and PI_{2Y}, because the admittance deviation of Y_i with respect to Y_{ii} is decreased. While, bus 52 is the most insensitive bus based on PI_{1Y} and PI_{2Y}, the admittance deviation of Y_i with respect to Y_{ii} is increased. From figure 7, buses 20 and 7 are the most sensitive buses based on PI_V and PI_P respectively, because bus 20 has a maximum voltage deviation with respect to specified voltage. While, bus 7 is heavily loaded. On the contrary, buses from 2 to 8, 26 and 25 are the most insensitive buses based on PI_V, where these buses have a zero voltage deviation with respect to specified voltage. Based on PI_P, bus 8 is the most insensitive bus because this bus hasn't any load.

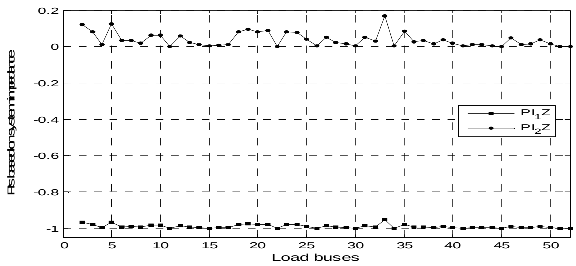


Fig. 5 PIs based on impedance matrix at normal condition for WDN system.

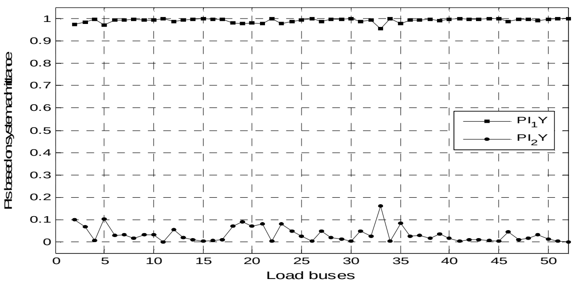


Fig. 6 PIs based on admittance matrix at normal condition for WDN system.

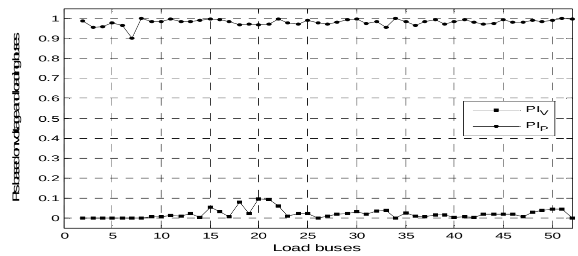


Fig. 7 PIs based on system load bus voltage and loading power indices at normal condition for WDN system.

3.2.2 Emergency conditions

- ***Unexpected outage of transmission line***

Tables 3 and 4 show the proposed PIs of load-buses according to their severity due to the voltage collapse based on the system impedance, admittance matrices and voltage PIs for 14-bus test system. In these tables, it can be shown that, bus 3 is still the most sensitive bus based on system impedance and admittance PIs. On the contrary, bus 5 is still the most insensitive bus based on PI_{1Z} and PI_{2Z}. While, bus 11 becomes the most insensitive based on PI_{1Y} and PI_{2Y}. Based on PI_V, bus 8 is still the most sensitive bus. While, bus 4 becomes the most insensitive bus. In table III, the PIs, which based on system impedance, bus 4 is jumped towards to the sensitive bus. While, buses 9, 8, and 14 shifted one position towards the insensitive buses and the other buses are still in their list positions as in normal condition. Based on two PIs that based on system admittance, buses 2, 5 and 4 are shifted one and three positions towards the sensitive buses because these buses are connected to the two lines which are removed via bus 3. While, buses 8, 9, 11, 13, and 14 are jumped one position towards the insensitive bus. In table IV, buses 2, 12, and 13 are jumped towards the sensitive buses. While, buses 9, 10, and 11 are jumped towards the insensitive buses.

Table 3 Ranking of load buses based on impedance and admittance matrices at lines outage for 14-bus system

Rank	PI_{1Z}	Rank	PI_{2Z}	Rank	PI_{1Y}	Rank	PI_{2Y}
3	-0.640	3	0.778	3	0.829	3	0.499
4	-0.907	4	0.350	4	0.973	4	0.117
9	-0.915	9	0.321	8	0.974	14	0.102
8	-0.932	8	0.237	14	0.975	8	0.098
14	-0.941	14	0.229	9	0.988	9	0.054
13	-0.956	13	0.166	2	0.988	2	0.047
10	-0.969	10	0.129	13	0.989	13	0.042
6	-0.972	6	0.105	12	0.992	12	0.033
12	-0.977	12	0.089	10	0.994	10	0.027
2	-0.983	2	0.067	6	0.994	6	0.023
11	-0.988	11	0.050	5	0.995	5	0.023
5	-0.992	5	0.034	11	0.996	11	0.016

Table 4 Ranking of load buses based on voltage PI at lines outage for 14-bus system

Rank	PI_V
8	0.090
6	0.070
12	0.054
13	0.045
2	0.045
11	0.043
9	0.032
10	0.029
14	0.018
5	0.013
3	0.010
4	0.001

Figures 8 – 10 show the proposed PIs of load-buses according to their severity due to the voltage collapse for WDN system. In figure 8, it is shown that, buses 33 and 52 are still the most sensitive and insensitive buses based on PI_{1Z} and PI_{2Z}, respectively. Buses 5, 24, 25, 31 and 33 are jumped towards the sensitive buses, where the two lines that removed affect the buses 5, 24, 25, 31 which are connected with them. In figure 9, buses 33 and 52 are still the most sensitive and insensitive buses based on PI_{1Y} and PI_{2Y}, respectively. While, buses 5, 24, 25 and 31 are also jumped towards the sensitive direction. In figure 10, bus 20 is still the most sensitive bus based on PI_V. Also, buses from 2 to 8, 26 and 25 are still the most insensitive buses based on PI_V. While, buses 11, 13, 24, 28, 29, 30, 31, and 32 are jumped towards the sensitive buses, and the bus 25 is jumped towards the insensitive bus.

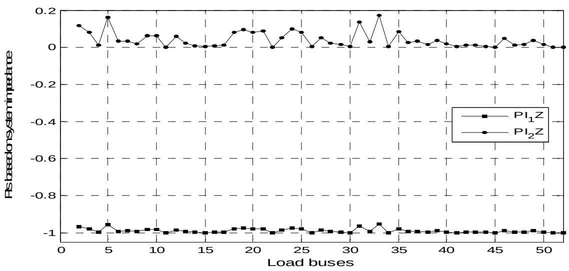


Fig. 8 PIs based on impedance matrix at line outage condition for WDN system.

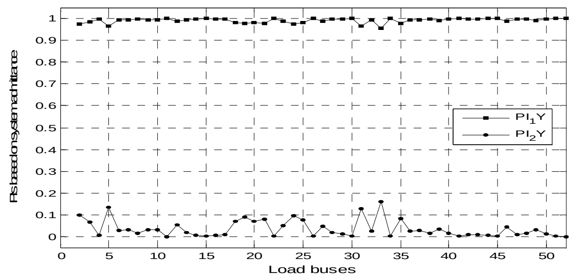


Fig. 9 PIs based on admittance matrix at line outage condition for WDN system.

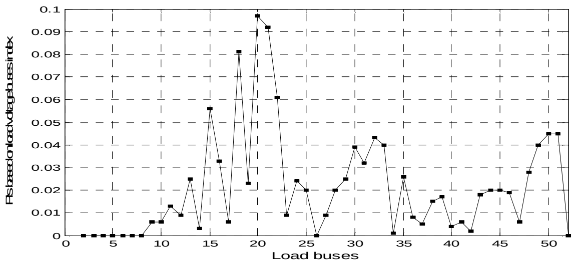


Fig. 10 PIs based on system load bus voltage index at line outage condition for WDN system.

- ***Sudden increase in the load demand***

Tables 5 and 6 show the proposed PIs of load-buses according to their severity due to the voltage collapse based on the system impedance, admittance matrices and voltage PIs for 14-bus test system. In these tables, it can be shown that, buses 3 and 5 are still the most sensitive and insensitive buses respectively, based on system impedance and admittance PIs as at normal condition. While, buses 8 and 3 are still the most sensitive and insensitive buses based on PI_V. In table V, bus 14 is jumped towards the sensitive bus, due to the load increasing at this bus with 50 %. The two PIs based on the system impedance give the same ordering. Also, the two PIs based on the admittance give the same ordering.

Table 5 Ranking of load buses based on impedance and admittance matrices at load increasing for 14-bus system

Rank	PI_{1Z}	Rank	PI_{2Z}	Rank	PI_{1Y}	Rank	PI_{2Y}
3	-0.854	3	0.445	3	0.910	3	0.302
14	-0.918	14	0.283	14	0.964	14	0.136
9	-0.928	9	0.253	8	0.974	8	0.098
8	-0.941	8	0.211	9	0.988	9	0.048
4	-0.954	4	0.171	4	0.988	4	0.046
13	-0.957	13	0.159	13	0.989	13	0.042
10	-0.972	10	0.106	2	0.990	2	0.039
6	-0.973	6	0.103	12	0.992	12	0.033
12	-0.977	12	0.087	10	0.994	10	0.024
2	-0.983	2	0.065	6	0.994	6	0.023
11	-0.989	11	0.448	11	0.996	11	0.015
5	-0.993	5	0.027	5	0.998	5	0.008

Table 6 Ranking of load buses based on voltage PI at load increasing for 14-bus system

Rank	PI_V
8	0.090
6	0.070
11	0.056
12	0.055
9	0.054
10	0.050
13	0.048
2	0.045
14	0.028
5	0.018
4	0.016
3	0.010

Figures 11-13 show the proposed PIs of load-buses according to their severity due to the voltage collapse for the WDN system. In figure 11, it is shown that, buses 33 and 52 are still the most sensitive and insensitive buses based on PI_{1Z} and PI_{2Z}, respectively. Bus 36 is jumped towards the sensitive bus, because of increasing the load at that bus by 50%. In figure 12, buses 33 and 52 are still the most sensitive and insensitive buses based on PI_{1Y} and PI_{2Y}, respectively. Also, bus 36 is jumped towards the sensitive bus. In figure 13, bus 20 is still the most sensitive bus based on PI_V. Also, buses from 2 to 8, 26 and 25 are still the most insensitive buses.

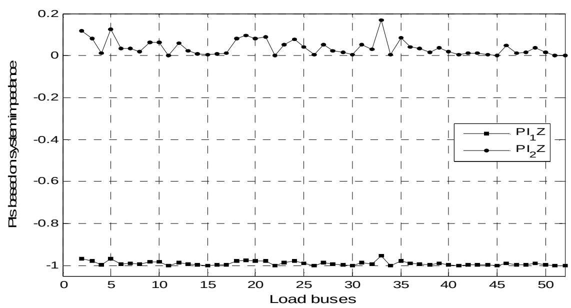


Fig. 11 PIs based on impedance matrix at load increasing condition for WDN system.

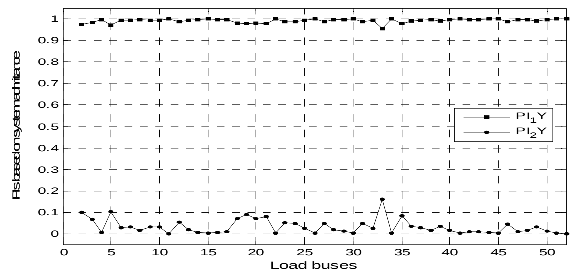


Fig. 12 PIs based on admittance matrix at load increasing condition for WDN system.

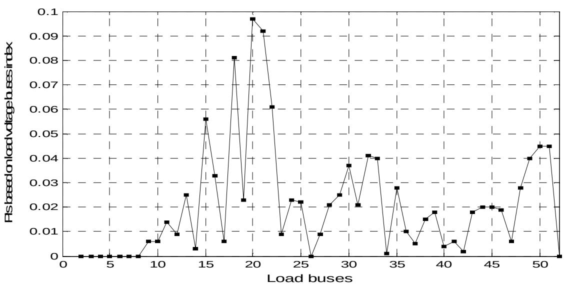


Fig. 13 PIs based on system load bus voltage index at load increasing condition for WDN system.

4. CONCLUSION

Different proposed of performance indices based on system impedance, admittance, voltage, and loading active power quantities under normal and emergency conditions have been efficiently presented. The results show that, the most sensitive and insensitive buses are the same or jumped one position at the normal and emergency conditions. This means that, the predicted most sensitive buses at the normal conditions are correctly picked. The four PIs based on impedance and admittance matrices give the same ordering of buses. The PIs based on load bus voltages and loading power, which measures the voltage deviation with respect to specified voltage and active power load deviation with respect to the total load power are efficiently applied. The advantages of the proposed performance indices are an efficient, simple, minimum time computation, noniterative process, and suitable for large scale systems.

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