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Power System Voltage Stability Index

Atef A. Elemary[1], M.M.R Ahmed[2]
Department of Electrical Engineering
Jazan University
Jazan, Saudi Arabia

Ebtisam M. Saied[3], Mohamed A. Hamdy[4]
Department of Electrical Engineering
Benha University
Cairo, Egypt

***Abstract*— After some damaging blackouts, voltage instability and collapse have become worldwide concern problems. Voltage instability is a nonlinear local phenomenon, which occurs due to insufficient reactive power production or as the inability to transfer it to consumers. In most dangerous cases, it can result in voltage collapse. Therefore, early identification of the process is essential. A power system is decomposed into selected radial paths regarding reactive power flow. Next, two bus equivalents for these radial transmission paths are determined. The analytical proof of maximal stable power transfer for two bus equivalents is available. However, each candidate critical load bus may be fed via more transmission paths. It is essential that a set of power sources, feeding the particular candidate's critical reactive power drain bus, has sufficient reactive power reverse. Therefore, the proposed voltage collapse assessment procedure combines the voltage collapse proximity generators index and an available reactive power reserve of the involved generators. The method's properties and numerical results are presented.**

Keywords*— *Power System, voltage stability, indicator

I. INTRODUCTION

In recent years, economical and environmental reasons have forced power systems to be operated closer to their security limits. Traditionally, their limits are associated with thermal and stability limitations have become less restrictive as nowadays most of electric utilities use faster relays to reduce the fault clearing time, fast response excitation systems and FAC,TS devices to reduce the amplitude of the disturbance. As a result, the power systems world is increasingly concerned with voltage stability and collapse problems, especially after blackouts of some world (New York, London,,…), some of which have been reported to be associated with voltage collapse [1,3, 11-15].

Recently IEEE/CIGRE task recommended numerous definitions in regarding to power system stability including voltage stability. Figure 1 summarizes these explanations. In general terms voltage index is applied to study voltage stability [1].

In order to prevent voltage collapse, fast and accurate voltage stability index is needed to help in monitoring the operating condition. In past articles, some useful voltage stability indices have been presented, such methods of testing the Jacobian, the voltage stability assessment using optimization, the point of collapse method (POC), the voltage proximity indicator (VCPI), fast voltage stability index (FVSI) [6]. Methods of Thevennin's impedance indicator, identifying the weak elements of a power system and the multiple load flow solutions (MLF)as in which, the voltage collapse indicators (VCPI) or (L-index) [2, 16-21] has raised especial regards for its simple algorithm and clear physical meaning. Banasila [9] used it in the optimal reactive power dispatch and expert system.

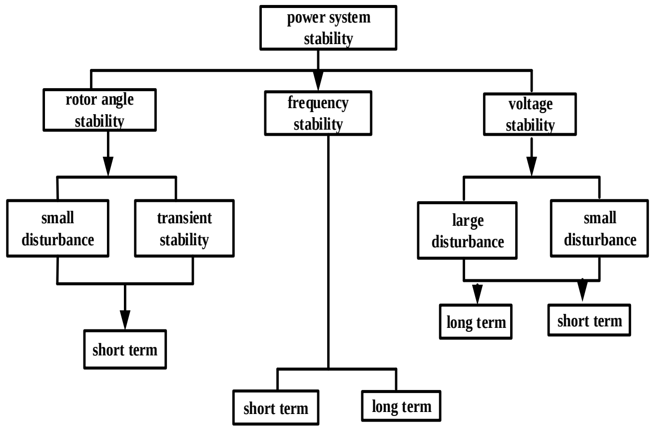

Fig. 1. Classifications of power system stability.

II. VOLTAGE STABILITY

The voltage stability can be described with different definitions according to the points of views. It's the system ability to keep its voltage within assured specified limits at all loading conditions all over the hour. From the load point of view it can be defined as the load ability or (P-V curve) to give more power as the load point of view it can be described as the load ability to supply more power as the loading is increased without voltage dips outside the limits as shown in Figure (2).

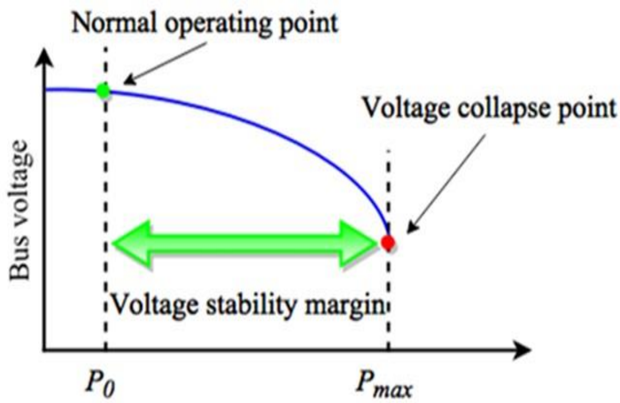

Fig. 2. P-V curve for the simple

The most common technique of analyzing the transfer capacity of a system against voltage stability is to create a so-called P-V curve of the bus bar with load or production. P-V curves are often respecting to as “nose curves” due to their shape [22-25]. The nose point (generally raised to as the critical point) of the curve provides the maximum power which can be supplied to the load.

An alternative common technique of analyzing the transfer capacity of a system respecting voltage is to gso-called so called Q-V curve for a bus bar [4, 9]. Figure 3, shows the reactive power which must be inserted into a bus bar to keep a specific voltage. These curves are plots of the critical bus voltage against the reactive power of the same bus. To obtain Q-V curve of a bus a fictitious synchronous capacitor is represented at that precise bus and the bus is supposed to be a voltage-controlled bus without reactive bounds.

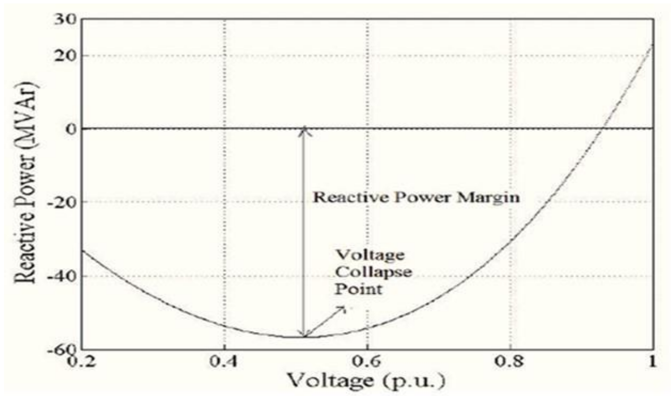

Fig. 3. Q curve and reactive power margin

III. VOLTAGE INSTABILITY

As the disturbance increases in load or system changes this causes quick drop in voltage or drift downward, and operates and automatic system controls fail to halt the decay.

Causes of voltage instability can be summarized in the following:

a) Stressed power system (high active power loading P_r, and/ or also high reactive power loading Q_r, in the system).
b) Low power factor of loads of loads, which results higher values of Q.
c) Load characteristics at low voltage magnitudes different from their designed values.

IV. STEADY STATE VOLTAGE STABILITY ASSESSMENT

There are different methods used to steady state voltage stability assessment. These methods are basically depends on one of the following approaches:

A. *Voltage Collapse Proximity Indicators (VCPI)*

The criteria of this indicator is defined as follows [7,9].

$$L_j = |L_j| = \left|1 - \frac{\sum_{i\epsilon\alpha_G} C_{ji} V_i}{V_j}\right| \qquad j\epsilon\alpha_L \quad (1)$$

where:

L_j: voltage collapse proximity indicators

α_l: set of load buses

α_G: set of generators buses

C_{ji}: elements of matrix C determined by:

$$[C] = -[Y_{LL}]^{-1}[Y_{LG}]$$

L- indicator varies in the range between 0 (no load system) and 1 (voltage collapse).

B. *Fast Voltage Stability Index (VVSI)*

The stability index of this method is defined by the following formula [7]

$$FVSI_{ij} = \frac{4Z^2 Q_L}{V_i^3 X} \qquad (2)$$

where:

Z: line impedance

X: line reactance

Q_j : receiving end reactive power at load bus j

V_i : complex voltage at generator bus i

Such that the stability index range is defined by:

$$if \begin{cases} FVSI > 1 \text{ then the system is stable} \\ FVSI < 1 \text{ then the system is unstable} \end{cases}$$

C. *Thevennin’s Impedance Indicator*

To calculate this indicator it is required to calculate the equivalent Thevennin’s impedance (Z_{th}) for each load bus in the system. The ratio of this impedance to the equivalent load impedance (Z_L) at the same bus is taken as the indicator. Z_{th} of a load bus is calculated by removing the load at this bus, replacing all loads and generators in the system by an equivalent impedances with appropriate signs, forming Y_{bus} and inverting it to obtain Z_{bus} , and Z_{Th} is equal to the diagonal elements of Z_{bus} corresponding to the bus required. These steps repeated at each bus as well as load flow is to be carried out for each case to determine the equivalent Thevennin’s voltage. The certerion for voltage stability by this indicator is given by:

$$if \begin{cases} (Z_{Th}/Z_l) < 1 \text{ then the system is stable} \\ (Z_{Th}/Z_L) \geq 1 \text{ then the system is unstable} \end{cases}$$

V. MATHEMATICAL DERVIATION

In this section a proposed method is made to calculate the indicator based on the change of reactive and active powers. The L- indicator [7,9] depend on the calculation of load flow in each once. To overcome this problem a proposed method is investigated. Figure 4 shows two buses connected by transmission line to derive a new mathematical formula of change voltage and its angle based on change of active and reactive power angle. Figure 5, shows phasor diagram of the system shown in figure 4.

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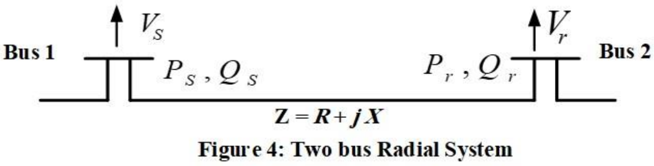

Fig. 4. Two bus radial system

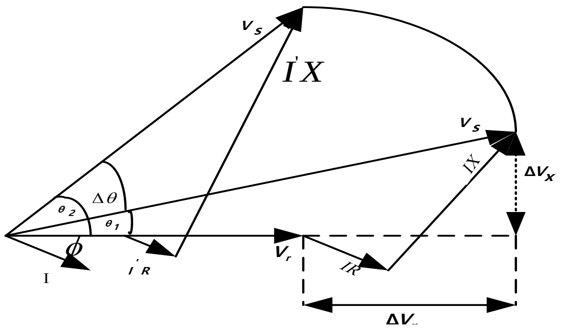

Fig. 5. Phasor diagram

From figure 5 the following relation are calculated [10]

$$\Delta V_r = \frac{PR+QX}{V_r} \quad (3)$$

$$\Delta V_x = \frac{PX-QR}{V_r} \quad (4)$$

$$\cos\theta_1 = \frac{V_r+\frac{PR+QX}{V_r}}{V_s} = \frac{V_r^2+PR+QX}{V_sV_r} \quad (5)$$

$$\cos\theta_2 = \frac{V'_r+\frac{P'R+Q'X}{V'_r}}{V_s} = \frac{V'^2_r+P'R+Q'X}{V_sV'_r} \quad (6)$$

Rewrite equation 6 yields to:

$$\cos(\theta_1+\Delta\theta) = \frac{(V_r+\Delta V_r)^2+(P+\Delta P)R+(Q+\Delta Q)X}{V_s(V_r+\Delta V_r)}$$

$$\cong \cos\theta_1\cos\Delta\theta - \sin\theta_1\sin\Delta\theta \quad (7)$$

For small change of angle θ, the following assumption are made:

$\cos\Delta\theta \approx 1$, and $\sin\Delta\theta \approx \Delta\theta$

Equation 7, can be put in the form

$$V_sV_r\left(\frac{V_r^2+PR+QX}{V_rV_s}\right)+V_s\left(\frac{V_r^2+PR+QX}{V_sV_r}\right)\Delta V_r - V_sV_r\sin\theta_1\Delta\theta - V_s\sin\theta_1\Delta\theta\Delta V_r$$

$$\cong V_r^2+2V_r\Delta V_r+PR+R\Delta P+QX+X\Delta Q \quad (8)$$

Equation 8 can be put in the form:

$$(-V_r^2+PR+QX)\Delta V_r - V_sV_r^2\sin\theta_1\Delta\theta = V_rR\Delta P + V_rX\,\Delta Q + V_rV_s\sin\theta_1\Delta\theta\Delta V_r \quad (9)$$

such that

$$\sin\theta_1 = \frac{XP-RQ}{V_sV_r} \quad (10)$$

$$\sin\theta_2 = \frac{XP'-RQ'}{V_sV_r} \quad (11)$$

Equation 11 can be put in the form:

$$\sin(\theta_1+\Delta\theta) = \frac{X(P+\Delta P)-R(Q+\Delta Q)}{V_s(V_r+\Delta V_r)} \quad (12)$$

where:

$\sin(\theta_1+\Delta\theta) = \sin\theta_1\cos\Delta\theta + \cos\theta_1\sin\Delta\theta$
For incremental change of θ, we get
$\sin\Delta\theta \cong \Delta\theta$, *and* $\cos\Delta\theta \cong 1$
Therefore, equation 12 can be put in the form

$$\frac{X(P+\Delta P)-R(Q+\Delta Q)}{V_s(V_r+\Delta V_r)} = \sin\theta_1 + \cos\theta_1\Delta\theta \quad (13)$$

Rewrite equation 13 gives:

$$V_s\sin\theta_1\Delta V_r + V_sV_r\cos\theta_1\Delta\theta = X\Delta P - R\Delta Q - V_s\cos\theta_1\Delta\theta\Delta V_r \quad (14)$$

From equations 9 and 14, we can get the following relation

$$\begin{bmatrix} V_s\sin\theta_1 & V_sV_r\cos\theta_1 \\ -V_r^2+PR+QX & -V_sV_r^2\sin\theta_1 \end{bmatrix}\begin{bmatrix}\Delta V_r \\ \Delta\theta\end{bmatrix} = \begin{bmatrix} X & -R \\ RV_r & XV_r\end{bmatrix}\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} + \begin{bmatrix}-V_s\cos\theta_1 \\ V_sV_r\sin\theta_1\end{bmatrix}\Delta\theta\Delta V_r \quad (15)$$

We can assume that $\Delta\theta\Delta V_r \approx 0$, therefore equation 15 yields to:

$$\begin{bmatrix} V_s\sin\theta_1 & V_sV_r\cos\theta_1 \\ -V_r^2+PR+QX & -V_sV_r^2\sin\theta_1 \end{bmatrix}\begin{bmatrix}\Delta V_r \\ \Delta\theta\end{bmatrix} = \begin{bmatrix} X & -R \\ RV_r & XV_r\end{bmatrix}\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} \quad (16)$$

Equation 16 gives a new formula to calculate the change of voltage and its angle based on change of active and reactive power of loads. Also, this equation depends on the base case load flow and network data. Therefore, the repeated load flow in each case of change active and reactive power is not required.

VI. CASE STUDY

To test the capability of the proposed method the following applications are made.

D. Two bus system

The pu data of the system under studying are given in pu:

Vs = 1.05
P = 0.3
Q = 0.2
R = 0.083
X = 0.31

In this system the following applications are made

1) System under Condition of Power Factor4

In this case the active and reactive power are change to get constant power factor. The test results are demonstrated as follows

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a) L- indicator (VCPI)

From Fig. 6 it is noted that the system under study is stable when the active power P and reactive power Q reach the values 1.38 pu and 0.92 pu. Respectively. Otherwise the system collapse to unstable region when the active power P and reactive power Q greater than the above values.

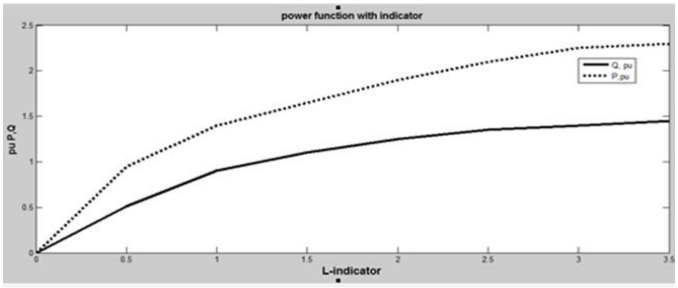
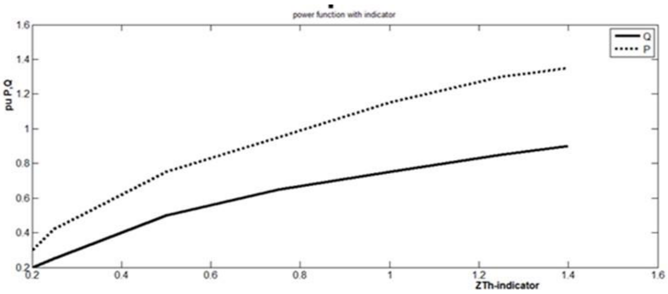


Fig. 6 Active and reactive power in pu relation with L-inductor at constant pf

b). FVSI indicator

It can be noted that from figure 7 the system under study is stable when the active power P is vary up to the value of.2 pu and the reactive power Q is vary up to the value of 0.8 pu. The system behavior is changed to unstable when the active power P and reactive power Q greater than 1.2and 0.8 pu



respectively.

Fig 7 Active and reactive power in pu relation with FVSI-indicator at constant pf

c). Thevennin's impedance indicator

In this case it is noted that from figure 8 the system under study is stable when the active P is varying up to the value of 1.2 pu and the reactive power Q is varying up to the value of 0.8 pu, otherwise the system is unstable. The system behavior is changed to unstable when the active power P reaches 1.21 pu and the reactive power Q reaches 0.8067pu.

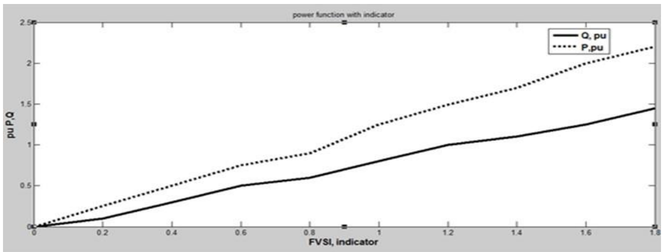


Fig. 8 Active and reactive power in pu relation with ZTh-inductor at constant pf

2). System under Condition of Constant Active Power P

In this case $\Delta P = 0$, and the applications are made as shown below.

a) L-indicator (VCPI)

Figure 9 show that the system under study is stable when the reactive power Q is vary up to the value of 1.1196 pu and the angle Ø is vary up to 1.309 rad., the system behavior is changed to the unstable when the reactive Q reaches 1.7014 pu and the angle Ø reaches 1.3963 rad.

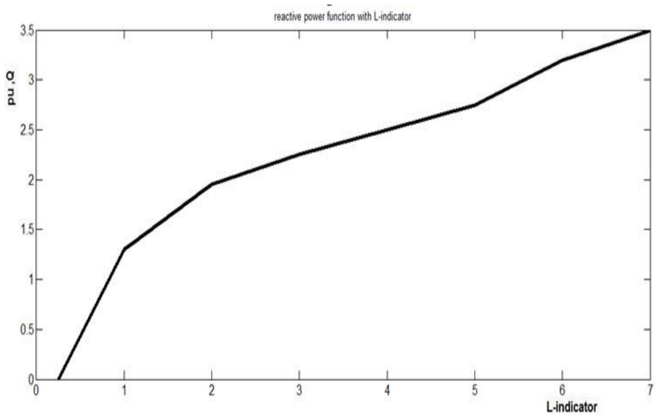


Fig. 9 Reactive power relation with L-inductor at constant P

b) FVSI indicator

It is noted that from figure 10, the system under study is stable when the reactive power Q is varying up to the value of 0.8242 pu and the angle Ø is vary up to 1.2217. The system behavior is changed to the unstable when the reactive power Q reaches 1.1196 pu and the angle Ø reaches 1.309 pu.

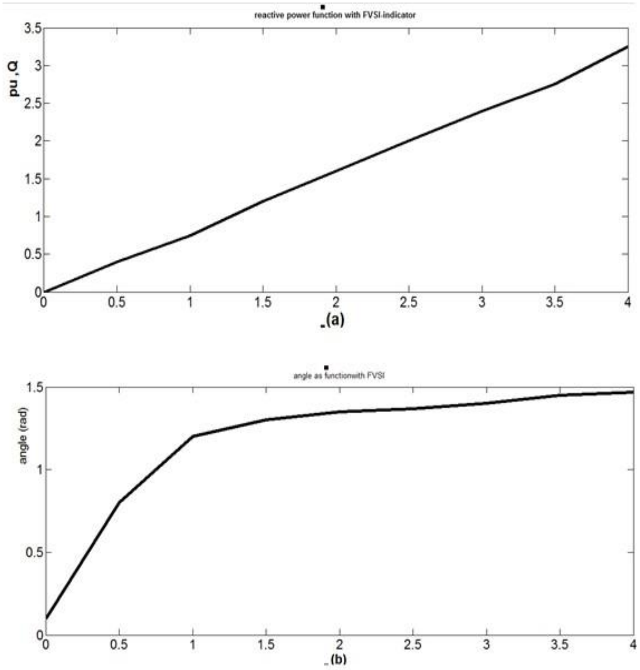


Fig. 10 (a) Variation of reactive power with FVSI inductor
(b) Variation pf angle with FVSI inductor

c) Thevennin's impedance indicator

Figure 11 shows that the system under study is stable when the reactive power Q is vary up to the value of 0.8242 pu and the angle is vary up to 1.2217, the system behavior is changed to the unstable when the reactive power Q reaches 1.1196 pu and the angle Ø reaches 1.309 rad.

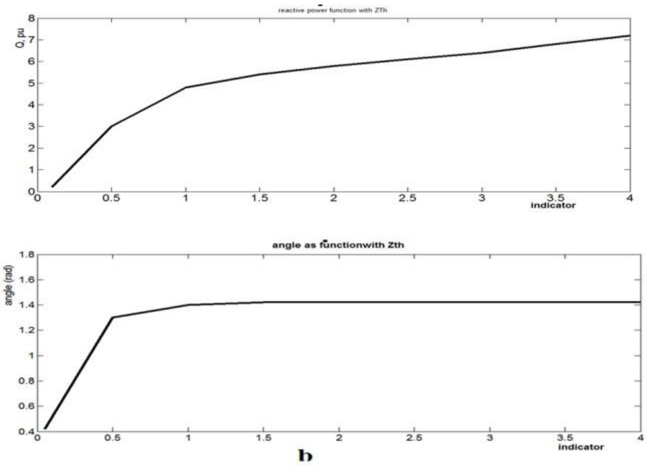


Fig. 11(a) Change of reactive power with ZTh-inductor at constant power
(b) Change of Power Factor angle ZTh-inductor at constant power

3) System under Condition of Constant Reactive Power Q

In this case ΔQ = 0, and the applications are made as shown belowز

a) L-indicator (VCPI)

The system under study shown in figure 12 is stable when the active power P is varying up to the value of 2.286 pu and the angle Ø is varying up to 0.0873. the system behavior is changed to the unstable when the reactive power P reaches 5.7273 pu and the angle Ø reaches 0.0349 rad.

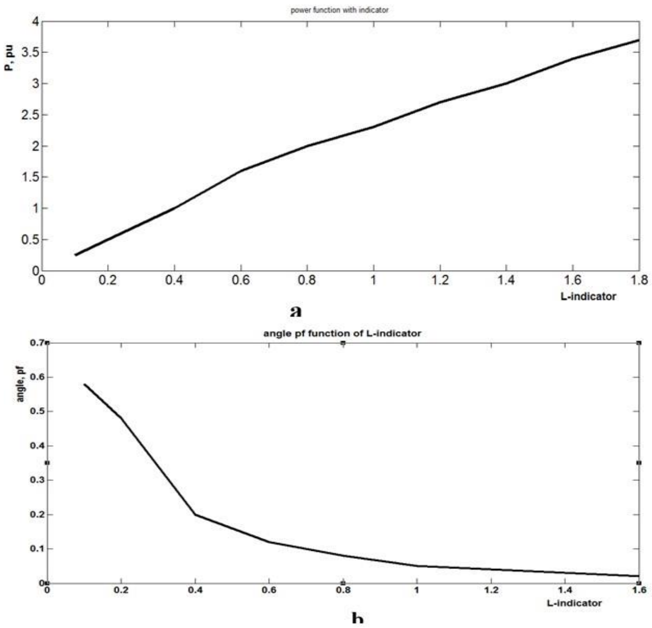


Fig. 12 (a) Change of reactive power with ZTh-inductor at constant power
(b) Change of Power Factor angle ZTh-inductor at constant power

b) FVSI indicator

We can note that the function between active power and FVSI indicator is constant function because the FVSI indicator depends on the reactive power Q, such that ΔQ = 0 and there is the same function between angle Ø and FVSI indicator

c). Thevennin's impedance indicator

From figure 13 it is noted that

i) The system under study is stable when the active power P is varying up to the value of 2.286 pu and the power factor angle is varying up to 0.0873 rad.

ii) The system behavior is changed to the unstable when the active power P reaches 2.8601 pu and the power factor angle Ø reaches to 0.698 rad.

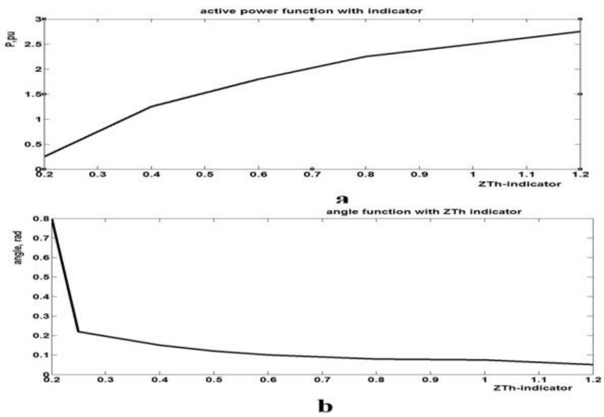


Fig. 13 (a) Active power as a function with ZTh-inductor at constant Q
(b) Power Factor as a function with ZTh-inductor at constant Q

VII. APPLICATION ON IEEE 6-BUS POWER SYSTEM NETWORK

Figure 14 shows the configuration of IEEE 6-bus network power system. This figure includes base case load flow. In this section the stability index under base case condition is made and the effect of load change on the stability index is also investigated.

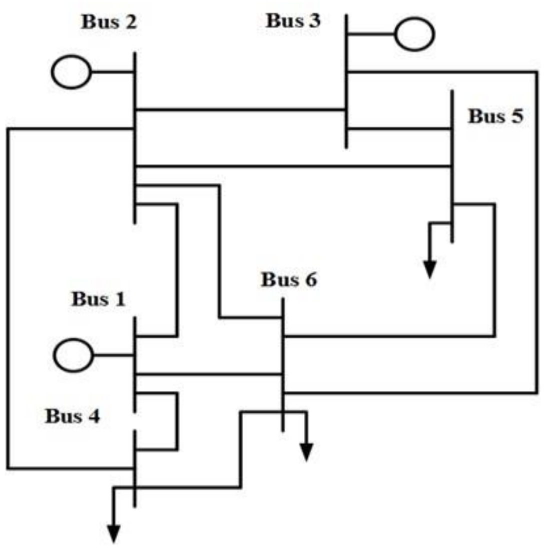


Fig. 14 IEEE 6=bus power system network

a). Base Case results

TABLE 1 SHOWS THE SYSTEM IS STABLE BASED ON THE BASE CASE

Bus number	L-indicator	Z_{Th}- indicator
4	0.093	0.0692
5	0.1143	0.0793
6	0.0956	0.0824

1) *Change in Bus 4*

The effect of load change on bus 4 at constant P, Q and power factor on the stability are studied and shown in Table 2. It is noted that the system is stable at all condition

TABLE 2: L AND ZTH INDICATORS AT CONSTANT P, Q AND POWER FACTOR WITH CHANGES AT BUS 4

Constant active power P							Constant reactive power Q							Constant power factor (pf)							
Q	L-indicator			Z_{Th} indicator			P	L-indicator			Z_{Th} indicator			P	Q	L-indicator			Z_{Th} indicator		
	buses			buses				buses			buses					buses			buses		
	4	5	6	4	5	6		4	5	6	4	5	6			4	5	6	4	5	6
0.8	0.108			0.075			0.8	0.087			0.099			0.8	0.496	0.055			0.107		
1	0.138			0.088			1	0.077			0.091			1	0.619	0.064			0.138		
1.2	0.168			0.108			1.2	0.066			0.082			1.2	0.744	0.073			0.17		
1.4	0.198			0.123			1.4	0.055			0.073			1.4	0.868	0.082			0.204		
1.6	0.228			0.142			1.6	0.044			0.063			1.6	0.991	0.091			0.24		
1.8	0.261			0.169			1.8	0.033			0.055			1.8	1.11	0.099			0.278		
2	0.295			0.209			2	0.021			0.047			2	1.24	0.109			0.319		

2) *Change in bus 5*

The effect of load change on bus 5 at constant P, Q and power factor on the stability are studied and shown in Table 3. It is noted that the system is stable at all condition of studies.

TABLE 3: L AND ZTH INDICATORS AT CONSTANT P, Q AND POWER FACTOR WITH CHANGES AT BUS 5

Constant active power P							Constant reactive power Q							Constant power factor (pf)							
Q	L-indicator			Z_{Th} indicator			P	L-indicator			Z_{Th} indicator			P	Q	L-indicator			Z_{Th} indicator		
	buses			buses				buses			buses					buses			Buses		
	4	5	6	4	5	6		4	5	6	4	5	6			4	5	6	4	5	6
0.8		0.13			0.086		0.8		0.108			0.112		0.8	0.496		0.074			0.121	
1		0.162			0.102		1		0.097			0.097		1	0.619		0.084			0.156	
1.2		0.195			0.126		1.2		0.086			0.088		1.2	0.744		0.094			0.193	
1.4		0.228			0.143		1.4		0.074			0.079		1.4	0.868		0.103			0.232	
1.6		0.263			0.167		1.6		0.062			0.068		1.6	0.991		0.112			0.274	
1.8		0.302			0.199		1.8		0.05			0.059		1.8	1.11		0.121			0.319	
2		0.349			0.249		2		0.037			0.05		2	1.24		0.131			0.368	

3) *Change in Bus 6*

The effect of load change on bus 6 at constant P,Q and power factor on the stability are studied and shown in Table 4. It is noted that the system is stable at all condition of studied

TABLE 4: L AND ZTH INDICATORS AT CONSTANT P, Q AND POWER FACTOR WITH CHANGES AT BUS 6

Constant active power P							Constant reactive power Q							Constant power factor (pf)							
Q	L-indicator			Z_{Th} indicator			P	L-indicator			Z_{Th} indicator			P	Q	L-indicator			Z_{Th} indicator		
	buses			buses				buses			Buses					buses			Buses		
	4	5	6	4	5	6		4	5	6	4	5	6			4	5	6	4	5	6
0.8			0.108			0.09	0.8			0.091			0.133	0.8	0.496			0.061			0.123
1			0.135			0.106	1			0.082			0.096	1	0.619			0.07			0.157
1.2			0.161			0.131	1.2			0.072			0.089	1.2	0.744			0.078			0.193
1.4			0.189			0.15	1.4			0.062			0.079	1.4	0.868			0.086			0.232
1.6			0.222			0.174	1.6			0.051			0.071	1.6	0.991			0.094			0.273
1.8			0.264			0.209	1.8			0.04			0.064	1.8	1.11			0.101			0.316
2			0.343			0.262	2			0.029			0.055	2	1.24			0.109			0.363

It is noted that from Table 2,3, and 4 the changes in active and reactive power at any conditions the voltage stability indicators L-indicator and Z_{Th} indicator are increase and the stability of the system are decrease.

VIII. CONCLUSION

A method for computation static voltage collapse proximity indicator VCPI, FVSI and Z_{Th} indicator are presented. Some case studies conducted on typical power networks have also been presented. These networks represented by two buses connected by transmission line and IEEE 6-buses system. This paper presented a new formula to get change in voltage and its angles based on the change on active and reactive powers.

This formula is used to calculate L-index, FVSI- index and Z_{Th}- index directly without need to compute load flow in each time. Therefore, this formula depends only to compute base case load flow for one time to find the initial steady state condition. This study is important to prevent a possible voltage collapse with simple calculations of voltage stability indicator.

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APPENDIX

Bus	V (kV)
1	$241.5\angle 0^o$
2	$241.6\angle -3.1^o$
3	$246.1\angle -3.3^o$
4	$227.6\angle -4.2^o$
5	$226.7\angle -5.3^o$
6	$231\angle -5.9^o$

Generator	P (Mw)	Q (Mvar)
1	107.9	16
2	60	74.4
3	60	89.6

load	P (Mw)	Q (Mvar)
4	70	70
5	70	70
6	70	70