Line Stability Indices and Contingency Screening by Sensitivity Factors Based Static Voltage Stability Study

Rinkesh A. Jain and Darshan B. Rathod

Abstract Due to ever increasing load demand, currently, power system has become stressful in context with reactive power management and voltage control which may in turn lead to voltage instability problems in electrical power system. If the voltage stability is not evaluated and the problems occurred are not attended timely, sequential outages of components of power system may occur and this may lead to voltage collapse or blackout. Therefore, detect voltage collapse point, voltage stability is needed. Several voltage stability indices have been suggested in the literature to assess static and dynamic voltage stability of power system based on power flow through transmission line. In the present work, three voltage stability indices, i.e., Line Stability Index (L_{mn}), Fast Voltage Stability Index (FVSI), and Voltage Collapse Proximity Index (VCPI) have been used to detect voltage stability status. Contingency screening has been carried out using Linear Sensitivity Factors (LSFs) based on Z-bus. Voltage stability indices and contingency screening results have been obtained on IEEE 14-bus test system.

Keywords Linear Sensitivity Factors (LSFs) · Voltage stability indices · Z-bus method

Acronyms

VCPI	Voltage collapse proximity index
L_{mn}	Line stability index
LODF	Line outage distribution factor
θ	Impedance angle

R. A. Jain (✉) · D. B. Rathod
PG Student, Electrical Engineering, Shantilal Shah Engineering College, Bhavnagar, Gujarat, India
e-mail: rinkeshjain72@yahoo.com

D. B. Rathod
e-mail: darshanbr2012@gmail.com

D. Deb et al. (eds.), *Innovations in Infrastructure*, Advances in Intelligent Systems and Computing 757, https://doi.org/10.1007/978-981-13-1966-2_11

varphi Power factor angle

1 Introduction

Voltage stability is the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition [1]. Nowadays, voltage instability is a challenging problem in a power system. Insufficient of supply and unnecessary absorption of reactive power cause voltage instability in a power system. Voltage instability may result in the voltage collapse if necessary actions are not taken immediately to restore the system voltage within limits.

Voltage stability study has been classified into static and dynamic analysis. For static voltage stability study, algebraic equations are solved. Therefore, static voltage stability analysis is computationally less complex than dynamic analysis [2]. In this paper, static voltage stability analysis has been carried out to identify voltage stability status.

Static voltage stability analysis is to be done with various methods such as PV and QV curves [3], reduced Jacobian matrix based modal analysis [4] but these methods are time consuming for interconnected system network. Nowadays, numbers of voltage stability indices such as VCPI, L_{mn}, FVSI, Line Stability Factor (LQP), and New Voltage Stability Index (NVSI) have been used to assess system voltage stability status [5]. In the present paper, simulation and result analysis of L_{mn}, FVSI, and VCPI are carried out for static voltage stability study. To identify the distance from the particular current operating point to the point of voltage collapse, these all indices are used.

Contingency means unpredictable event/outage and it may be caused by line outage or change in generation in the system which could lead the voltage instability. Contingency analysis can be done using different methods such as AC power flow, LSFs [6], line stability indices [7], various artificial intelligence techniques, etc. In the present paper, contingency analysis has been carried out using LSFs based on Z-bus method. From the contingency analysis, power system operator can know about the effect on power system when an outage of any particular line or generator occurs.

2 Indices Formulation

2.1 Line Stability Index (L_{mn})

Moghavemmi [8] has expressed L_{mn} by analyzing power flow in a single transmission line. The L_{mn} index is detected the distance from current operating point to the point of voltage collapse. The L_{mn} value is 0 in no load condition and 1 in collapse condition. L_{mn} is given by Eq. (1)

$$\mathrm{L}_{mn} = \frac{4x\,Q_{\mathrm{r}}}{[V_{\mathrm{s}}\sin(\theta - \delta)]^2} \tag{1}$$

where θ is impedance angle, Q_{r} is the receiving bus reactive power flow in pu, x is line reactance in pu, δ is angular difference between sending end and receiving end bus voltage, and V_{s} is sending end bus voltage in pu.

2.2 Fast Voltage Stability Index (FVSI)

Musirin [9] has used the same concept of power flow through a single transmission line and the derived FVSI can be given by Eq. (2)

$$\mathrm{FVSI} = \frac{4|\mathrm{Z}|^2 Q_{\mathrm{r}}}{|V_{\mathrm{s}}|^2 x} \tag{2}$$

where Z is the line impedance in pu.

FVSI can be calculated based on the above equation which depends on the reactive power flow through transmission line. The line has index value is close to 1 indicates that line goes into instability condition and may cause voltage collapse.

FVSI can also use to identify weak bus based on a maximum allowable load on the bus in a system. The weakest bus in the system is considered as a bus which has minimum the value of maximum allowable reactive load in the whole system.

2.3 Voltage Collapse Proximity Index

Moghavvemi [8] has expressed VCPI index for the investigate voltage stability of each line based on the same concept power transfer through the line. VCPI is given by Eq. (3)

$$\mathrm{VCPI(P)} = \frac{P_{\mathrm{r}}}{P_{\mathrm{r(max)}}} \tag{3}$$

where P_{r} is the active power flow at the receiving end bus in pu and $P_{\mathrm{r(max)}}$ is the maximum active power transferred through the line in pu is given by Eq. (4).

$$P_{\mathrm{r(max)}} = \frac{V_{\mathrm{s}}^2}{\mathrm{Z}} \cdot \frac{\cos\varphi}{4\cos^2\left(\frac{\theta-\varphi}{2}\right)} \tag{4}$$

where $\varphi = \tan^{-1}\frac{Q_{\mathrm{r}}}{P_{\mathrm{r}}}$ = power factor angle.

With the increasing power transfer through a line, VCPI index value is increased when the VCPI reaches to 1, and the system voltage collapses. VCPI is adequate for indicating voltage collapse in the line.

3 Linear Sensitivity Factors (LSFs)

There are thousands of possible outages on a daily basis. It is difficult to solve the outage with less time in a power system. With the help of LSFs, it is possible to get the quick and fast solution of possible overloads [6]. These factors give approximate change in line flow with the change in generation or outage of any line. These factors are basically two types:

- Line Outage Distribution Factor (LODF)
- Generation Shift Factor (GSF)

In this paper, only LODF is used for contingency screening.

3.1 LODF Using Z-Bus Element

When the transmission circuit is lost, the LODF is used to verify the overload of the line [10]. It is given by Eq. (5),

$$L_{ij,mn} = -\frac{Z_a}{Z_c}\left[\frac{(Z_{im} - Z_{in}) - (Z_{jm} - Z_{jn})}{Z_{th,mn} - Z_a}\right] \tag{5}$$

where mn = outage line, ij = ne whose post-outage power flow is to be checked, Z_a = impedance of outage line, Z_c = impedance of line under consideration, $Z_{im}, Z_{in}, Z_{jm}, Z_{jn}$ = off-diagonal elements of Z-bus.

$$Z_{th,mn} = Z_{mm} + Z_{nn} - 2 * Z_{mn} \tag{6}$$

where Z_{mm}, Z_{nn} = diagonal elements of Z-bus.

Post-outage power flow in line *i*–*j* due to outage of line *m*–*n* is given by Eq. (7),

$$P'_{ij} = P_{ij} + L_{ij,mn}P_{mn} \tag{7}$$

where I_{ij} = pre-outage power flow in line *i*–*j*, I_{mn} = pre-outage power flow in line *m*–*n*.

4 Test Result and Discussion

In order to demonstrate the effectiveness of voltage stability indices and LSFs numerical analysis have been made for the IEEE 14-bus test system.

4.1 Base Case Loading

Base loading means that load at all buses to prespecified load of IEEE 14 bus test system [11]. Lines with smaller voltage stability indices have much more voltage stability margin whereas larger voltage stability indices indicate that lines are heavily stressed condition and further addition of load line goes into voltage collapse condition.

Different voltage stability indices have been calculated for IEEE 14 bus system are presented in Table 1. It is observed from this Table 1 that line 7–8 has the highest index value compared to another line because compensator is connected to bus 8. In base case loading, no one line becomes stressful. Therefore, more reactive power can supply in base the case.

4.2 Global Load Increase

Global load increase, it means that equal percentage of active, reactive or apparent load are increased on all buses. Loading means increased active or reactive load on the load bus of IEEE 14 bus test system from its base loading.

From Table 2, it is observed that L_{mn} and FVSI have a similar result for all types of loading for 20 and 40% loading. If the load is increased, the indices value is increased in all three cases but L_{mn} and FVSI gives system status when reactive load increases.

Table 1 Voltage stability indices for IEEE 14—bus test system with base case loading

Line	L_{mn}	FVSI	VCPI
1–2	0.0688	0.0645	0.0451
1–5	0.0203	0.0184	0.0275
2–4	0.0227	0.0211	0.02
3–4	0.0365	0.0377	0.0252
4–7	0.0901	0.0899	0.045
5–6	0.0767	0.0759	0.038
6–13	0.0388	0.0381	0.0252
7–8	0.111	0.111	0.0557
9–14	0.0431	0.0424	0.0281
13–14	0.0228	0.0224	0.0148

Table 2 Indices result of line 13–14 for global loading

	20% loading			40% loading		
Types of loading	L_{mn}	FVSI	VCPI	L_{mn}	FVSI	VCPI
Reactive	0.0373	0.0367	0.0821	0.052	0.0512	0.0924
Active	0.0267	0.0261	0.0864	0.0314	0.0307	0.1011
Apparent	0.0449	0.044	0.0984	0.061	0.0597	0.1211

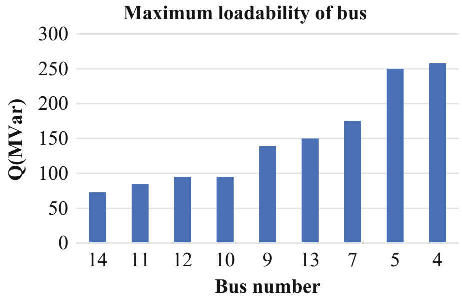

Fig. 1 Maximum loadability of load buses in IEEE 14 bus system

VCPI is more suitable for active and apparent loading condition. In all these buses, the voltage is more than 0.9 pu in all cases so that the system voltage remains in stable condition. Table 2 shows that in power system, till 40% load increase, no lines become critical because the voltage stability index for 40% loading is less than one. So for global loading, system maintain stability for up to 40% or more loading.

Voltage stability indices can also determine the weakest bus in the system and it is based on the maximum loadability of a bus. Arrange maximum loadability of the bus in ascending order and lowest maximum loadability of bus is considered as the weakest bus.

From Fig. 1, it is shown that bus 14 has the less reactive loading. So, bus 14 is considered as the weakest bus in the system and this bus is also far away from the generator so less active power reach to bus 14. Bus 4 is the largest loadability compared to all load buses. So, this bus is the strongest bus in the system and bus 4 is near to generator so it contains large active power from the generator.

Table 3 shows the voltage stability indices for maximum loading condition of load bus and it shows that line 9–10 and 10–11 are having largest indices value for loading on bus 10. So, these lines become critical for loading on bus 10 (Fig. 2).

Figure 3 shows that line 6–13 is the critical line for loading on bus 13 and when this load is 240 MVAR, this line achieves FVSI value near to unity.

The chart presented in Fig. 4 shows the value of VCPI in each variation of reactive load for bus 13. Line 13–14 needs some higher value of reactive loading to attain unity value of VCPI index.

Table 3 Line stability indices for IEEE 14 test system

Load (MVAR)	Line	L_{mn}	FVSI	VCPI
Q10 = 94.8	9–10	0.5269	0.5301	0.5217
	10–11	0.5411	0.5346	0.5095
Q11 = 85	6–11	0.8089	0.8244	0.7647
	10–11	0.5431	0.606	0.5801
Q14 = 72.8	9–14	0.833	0.8837	0.7971
	13–14	0.7924	0.8193	0.7439
Q4 = 250	3–4	0.4648	0.4925	0.4445
	2–4	0.4215	0.4017	0.4941
Q13 = 150	6–13	0.5866	0.6186	0.5391
	12–13	0.4389	0.4914	0.3035
Q7 = 175	7–8	1.0139	1.0139	0
	4–7	0.3784	0.3773	0.4022
Q12 = 95	12–13	1.0579	0.8722	0.2544
	6–12	0.6019	0.6413	0.1337
Q5 = 258	5–6	0.5992	0.59	0.726
	2–5	0.4528	0.4406	0.3654

Fig. 2 L_{mn} versus reactive load variation for bus 13

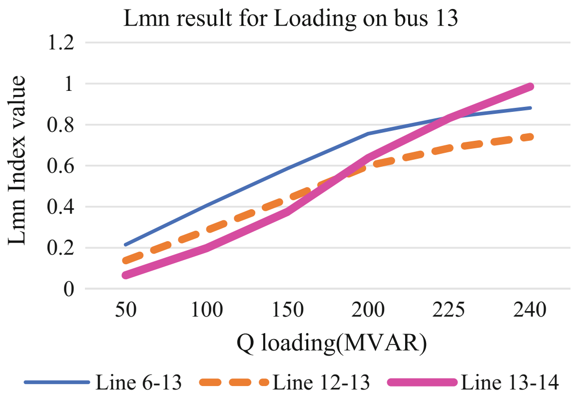

Table 4 shows that lines which have L_{mn} value is near to unity for maximum reactive loading and these all lines are considered as the most critical line for individual bus loading.

Fig. 3 FVSI versus reactive load variation for bus 13

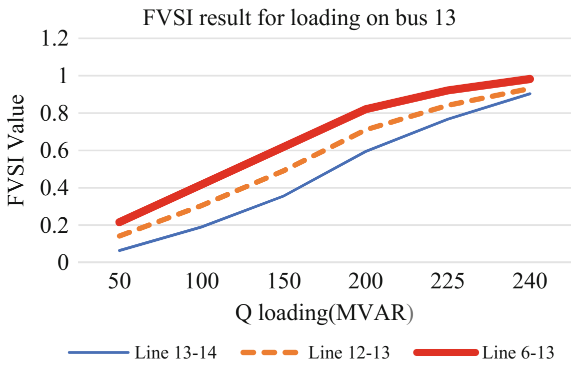

Fig. 4 VCPI versus reactive load variation for bus 13

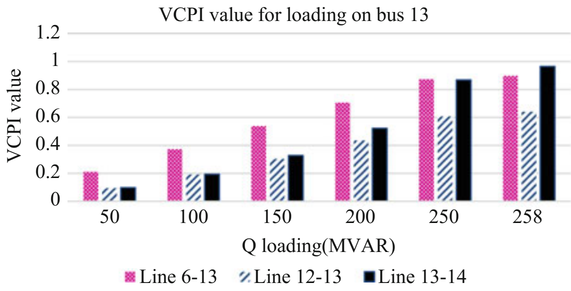

Table 4 Critical line for individual bus loading based on L_{mn}

Bus	Maximum reactive load	Critical line
14	120	13–14
13	240	13–14
12	90	12–13
10	148	10–11
7	175	7–8
11	195	6–11
5	340	5–6
4	440	4–7

5 Contingency Screening

Steps to follow for performing contingency screening by using LSFs based on Z-bus method.

Step 1. Obtain Z-bus for IEEE 14 bus test system using MATLAB coded program.
Step 2. Calculate pre-outage power flow for all lines.
Step 3. Find out LSFs from Z-bus element for particular line outage.
Step 4. Calculate post-outage power flow using LSFs.
Step 5. Compare post-outage power flow with MW limit of line.

Table 5 Contingency screening of IEEE 14 bus system using LSFs

Contingency (outage)	Most severe line	Rank	Power in pu
2–1	5–1	1	2.1885
5–1	2–1	2	2.1885
6–5	2–1	3	1.5017
11–6	2–1	4	1.4803
13–6	2–1	5	1.4796
14–13	2–1	6	1.4794
12–6	2–1	7	1.4782
13–12	2–1	8	1.4780
8–7	2–1	9	1.4779
11–10	2–1	10	1.4767
10–9	2–1	11	1.4758
14–9	2–1	12	1.4751
9–4	2–1	13	1.4745
7–4	2–1	14	1.4697
9–7	2–1	15	1.4696
4–3	2–1	16	1.4277
4–2	5–4	17	1.3278
3–2	2–1	18	1.3327
5–2	2–1	19	1.3303
5–4	2–1	20	1.2977

Step 6. Extract lines which exceed its MW limit and choose one line which is maximum MW overloading margin from MW limit. Consider this line is the most stressed line for particular line outage.
Step 7. Repeat steps 1–6 for all line outages.
Step 8. Arrange the line with MW margin in descending order.
Step 9. Top order outage is considered as the most critical line outage.

Table 5 shows that in most of the line outage case, line 2–1 becomes most critical line because this line is directly connected to a bus where large generator connected. So, that for every outage, most of active power supply by generator is flowing through line 2–1 so this line is the most stressful line.

6 Conclusion

This paper presents a comparative study and analysis of the different voltage stability indices for static voltage stability assessment. Voltage collapse occurs when system is heavily loaded, the voltage magnitude decreases. These indices can predict voltage stability of power system under all operating condition. These indices can be used to identify critical lines and weakest bus in the system. Based on simulation result, it can be concluded that to identify voltage stability status, VCPI gives accurate result when active power change in the system while L_{mn} and FVSI gives accurate for reactive power change in the system. From the contingency screening, it can be concluded that line 1–2 is a most severe line and which is overloaded in all the line outages and line 1–2 is most severe outage in the system.

References

1. Hill, J.P., David, P.Kundur: Definition and classification of power system stability. IEEE Trans. Power Syst. **19**(2), 1387–1401 (2004)
2. Reis, C., Barbosa, F.P.M., Member, S.: Line indices for voltage stability assessment. In: IEEE Bucharest Power Tech Conference, pp. 1–6 (2009)
3. Chiang, H., Jumeau, R.J.: Toward a practical performance index for predicting voltage collapse in electric power systems. IEEE Trans. Power Syst. **10**(2), 584–592 (1995)
4. Ayasun, S., Nwankpa, C.O., Kwatny, H.G.: Voltage stability toolbox for power system education and research. **49**(4), 432–442 (2006)
5. Yari, S.: Assessment of line stability indices in detection of voltage stability status. pp. 7–11 (2017)
6. Wood, B.F.W., Allen, J.: Power Generation, Operation, and Control. Wiley
7. Tiwari, R., Niazi, K.R., Gupta, V.: Electrical power and energy systems line collapse proximity index for prediction of voltage collapse in power systems. Elsevier Electr. Power Energy Syst. **41**(1), 105–111. Oct, 2012
8. Moghavvemi, F.M.O.M.: Technique for contingency monitoring and voltage collapse prediction. In: IEEE Proceedings—Generation Transmission and Distribution, vol. 145, no. 6 (1998)
9. Musirin S.K.N.A., Zin, A.M., Khairuddin, A.: A comparison of voltage stability indices 1. IEEE 8th International Conference on Power and Energy Engineering Conferences, pp. 30–34. March, 2014
10. Grainger, W.D.S.J.J.: Power System Analysis. McGraw-Hill (1994)
11. https://www2.ee.washington.edu/research/pstca/pf14/pg_tca14bus.htm