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Research Paper

MAXIMUM LOADABILITY ESTIMATION FOR WEAK BUS IDENTIFICATION USING FAST VOLTAGE STABILITY INDEX IN A POWER TRANSMISSION SYSTEM BY REAL-TIME APPROACH

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This letter demonstrates the use of line stability index termed as Fast Voltage Stability Index (FVSI) in order to determine the maximum loadability in power system. Voltage stability analysis is conducted using line stability index indicated by FVSI to indicate the stressfulness of a line in a transmission system. The reactive power at a particular bus is increased until it reaches the instability point at bifurcation. At this instability point, the connected load at the particular bus is determined as the maximum loadability. The maximum loadability for every load bus will be sorted in ascending order with smallest value being ranked highest. The highest rank implies the weak bus in the system that has the lowest sustainable load. This technique is tested on the IEEE-30 bus system and a practical 24-bus system in Indian. The Weak area of the Practical system and the Ranking with overloading are found using FVSI.

Keywords: Maximum loadabilty maximum, Bifurcation, Voltage collapse, Stability index

INTRODUCTION

The slow variation in reactive power loading towards its maximum point causes the traditional load flow solution to reach its non convergence point. Beyond this point, the ordinary load flow solution does not converge, which in turn forces the system to reach the voltage stability limit prior to bifurcation in the system. The margin measured from the base case solution to the maximum convergence point in the load flow computation determines the loadability maximum at a particular bus in the system.Solvability of load flow can only be achieved before a power system network reaches its bifurcation point (Lof *et al.*, 1992a and 1992b; Chebbo *et al.*, 1992; Crisan and

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Liu, 1994; and Chiang and Jumeau, 1995). Sauer *et al.* (1990) determined loadability maximum through two basic constraints, i.e., the equality and inequality constraints. The equality constraint dealt with the Kirchoff's circuit laws, while the second one reflects physical limits such as thermal overload, critical voltage drop, and steady-state stability. Most literature agreed that loadability depends on the solvability margin of load flow (Gubina and Strmenik, 1995; Lof *et al.*, 1995a; Kessel and Glavitsch, 1996; and Musirin and Abdul, 2002) when the Jacobian matrix becomes singular.

In this letter, maximum loadability is estimated through voltage stability analysis (Voltage Stability of Power Systems: Concepts, Analytical Tools and Industry Experience, 1990) Voltage stability analysis (Loaf *et al.*, 1995b; and Van Custsem, 1995a and 1995b) is conducted using line stability index indicated by FVSI to indicate the stressfulness of a line in a transmission system. The reactive power at a particular bus is increased until it reaches the instability point at bifurcation. At the instability point, the connected load at the particular bus is determined as the loadability. The maximum loadabilty for each load bus will be sorted in ascending order with the smallest value being ranked highest. The highest rank implies the weak bus in the system that has the lowest sustainable load. This technique is tested on the IEEE-30 bus test system and 24- bus Indian system. The results show that it is able to estimate the loadability in a system. Comparisons are also conducted in verifying the proposed technique in determining critical line in the system. The critical line means the line which is close to its voltage stability limit.

RELATED RESEARCHES: A BRIEF REVIEW

Lof *et al.* (1992a) presented a paper on "Voltage stability indices for stressed power systems". This paper presents and discusses the use of static voltage stability indices based on a singular value decomposition of the power flow jacobian matrix and matrices divided from the jacobian matrix. The indices based on these matrices are useful for the system analyst in planning and operations planning it is shown that such indices, together with the singular vectors contain substantial and important information about the proximity to voltage instability point of view.

Loaf *et al.* (1992b) presented a fast method to calculate minimum singular value of the power flow jacobian and modified power flow Jacobian matrices as a static voltage stability index, including the distance between the studied operating point and steady state voltage stability limit. The magnitude of the MSV is a measure of the proximity of the system to the steady state voltage stability limit.

Chiang and Jumeau (1995) proposed a performance index that provides a direct relationship between its value and the load demand that the system can withstand before voltage collapse.

Gubina and Strmenik (1995) presents a 'phasor concept' of voltage collapse determination. The main idea proposed is that the voltage phasors contain enough information to detect the voltage stability margin.

Lof *et al.* (1995a) presents and studies a static model for synchronous generators with the voltage dependent reactive power limits.

The influence of voltage dependent reactive power limits is composed with fixed limits, by the use of minimum singular value of power flow jacobian matrix and related sub matrices as indicators of the static voltage limit.

Kessel and Glavitsch (1996) presented a paper on “Estimating the voltage stability of a power system”. This paper suggest, voltage stability index (L-Index) based in normal load flow solution for on-line applications varies from 0 (no load of system) to 1(voltage collapse).The bus with highest L-index value indicates the most vulnerable bus in the system and hence this method helps in identifying the weak areas in the system needing critical reactive power support.

Musirin and Abdul (2002), presented a paper on “Estimating Maximum Loadability for Weak Bus Identification using Fast Voltage Stability Index (FVSI)”. This paper demonstrates the use of line stability index termed as fast voltage stability index 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. It involves the experimental procedure of Voltage stability analysis and evaluation of line stability index based on the load variation. The point at which FVSI close to unity indicates the maximum possible connected load termed as maximum loadability at the point of bifurcations. Among the different indices for voltage stability and voltage collapse prediction it is seen that FVSI method gives fairly consistent results. The advantage of this method lies in the simplicity of numerical calculations and expressiveness of the results, in this project Fast Voltage Stability Index (FVSI) is used as a voltage stability indicator.

INDEX FORMULATION

The voltage stability index or proximity is the device used to indicate the voltage stability condition formulated based on a line or a bus. In this letter, the results of the proposed index (FVSI) are verified with the existing techniques proposed by Mohamed and Jammson (1989) and Mohavani and Omar (1998). The characteristics are the same, whether the quadratic equation discriminant is greater than or equal to zero. The maximum threshold is set at unity beyond which this limit system bifurcation will be experienced.

FVSI FORMULATION

The FVSI is derived from the voltage quadratic equation at the receiving bus on a two-bus system. The general two-bus representation is illustrated in Figure 1.

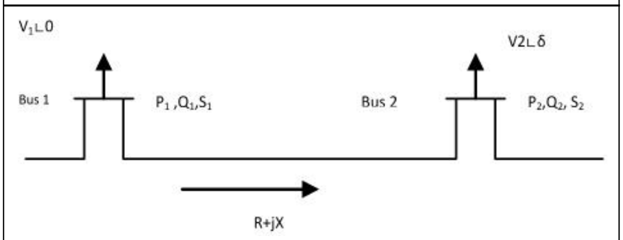
From the figure, the voltage quadratic equation at the receiving bus is written as

$$V_2^2 - \left[\frac{R}{x}\sin\text{¢} + \cos\text{¢}\right]V_1V_2 + \left(X + \frac{R^2}{x}\right)Q_2 = 0 \quad ...(1)$$

Setting the equation of discriminant be greater than or equal to zero yields

$$\left(\left[\frac{R}{x}\sin\text{¢} + \cos\text{¢}\right]V_1\right)^2 + 4\left(X + \frac{R^2}{x}\right)Q_2 \geq 0 \quad ...(2)$$

Figure 1: Two Bus Power System Model



Rearranging (2), we obtain

$$\frac{4_z^2 Q_2 X}{v_1^2 (R \sin ¢ + X \cos ¢)^2} < 1 \qquad ...(3)$$

Since "*i*"as the sending bus and "*j*" as the receiving end bus, Since ¢ is normally very small, then, $¢ \approx 0, R \sin ¢ \approx 0$ and $X \cos ¢ \approx X$. Taking the symbols *i* as the sending bus and *j* as the receiving bus, FVSI can be calculated

$$FVSI_{ij} = \frac{4z^2 Q_j}{V_i^2 X} \qquad ...(4)$$

where *z* and *X* is the line impedance and reactance, Q_j is the reactive power at the receiving end, and *V* is the sending end voltage.

LINE STABILTY INDEX

The line stability index symbolized by L_{mn} proposed by Mohavani and Omar (1998) is formulated based on a power transmission concept in a single line. The line stability index L_{mn} is given by

$$L_{mn} = \frac{4Q_r x}{[|V_s| \sin(¯ - ¢)]^2} \qquad ...(5)$$

where *x* is the line reactance, Q_r is the reactive power at the receiving end, V_s is the sending end voltage, ¯ is the line impedance angle, and ¢ is the angle difference between the supply voltage and the receiving end voltage. The value of L_{mn} must be lower than 1.00 to maintain a stable system.

LINE STABILITY FACTOR

Mohamed and Jammson (1989) derived four line stability factors based on a power transmission concept (Carson, 1994) in a single line. One of the factors termed LQP was used in the comparison since this factor is sensitive to change in reactive power. The formulation begins with the power equation in a power system and finally LQP is expressed as

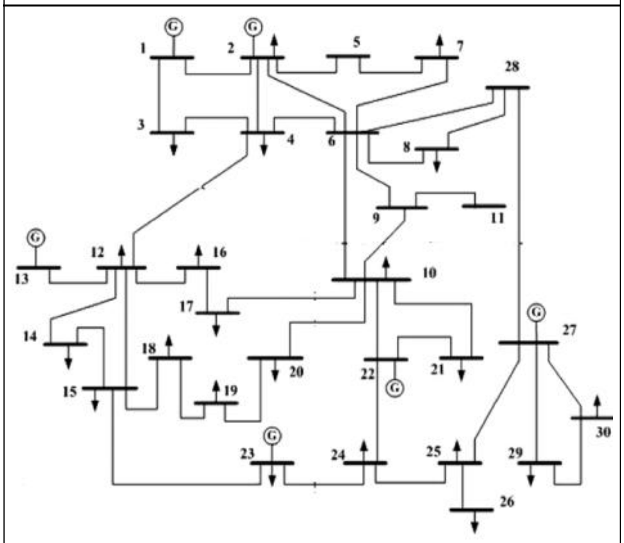
$$LQP = 4\left(\frac{x}{V_i^2}\right)\left(\frac{x}{V_i^2} P_i^2 + Q\right) \qquad ...(6)$$

where *x* is the line reactance, V_s is the sending end voltage, P_i is the sending end real power, and Q_j is the receiving end reactive power. LQP must be kept lower than 1.00 to maintain a stable system.

TEST SYSTEM

To validate the performance of the indicator, an IEEE 30-bus reliability (Hadi Saadat, 2002) test system is used. The single line diagram of the systemis shown in Figure 2. This system has six generator buses (PVs) and 24 load buses (PQ). In order to investigate (Kundur, 1993) the effectiveness of FVSI four load buses were selected in random. The reactive power at these buses is increased gradually one at a time.

Figure 2: IEEE 30 Bus System



DETERMINING THE MAXIMUM LOADABILTY FOR WEAK BUS DENTIFICATION

The following steps are implemented.

Step 1: Run the load flow program for the base case.

Step 2: Evaluate the FVSI value for every line in the system.

Step 3: Gradually increase the reactive power loading by 0.01 pu at a chosen load bus until the load flow solution fails to give results for the maximum computable FVSI.

Step 4: Extract the stability index that has the highest value.

Step 5: Choose another load bus and repeat steps 3 and 4.

Step 6: Extract the maximum reactive power loading for the maximum computable FVSI for every load bus. The maximum reactive power loading is referred to as the maximum loadability of a particular bus.

Step 7: Sort the maximum loadability obtained from step 6 inascending order. The smallest maximum loadability is ranked the highest, implying the weakest bus in the system.

Step 8: For verification purposes repeat steps 1 to 7 using Lmn and LQP.

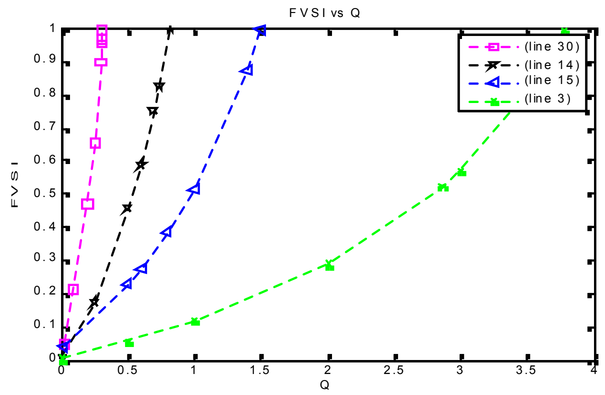
Figure 3 illustrates the response for FVSI versus Q. The individual FVSI curve is the most critical line referred to a bus. For instance, L4 (bus 3) means that line 4 is the most critical line with respect to bus 3. Similar meaning referred to other lines. The value of FVSI for each line is maximum at the loadability maximum of each individual load bus. The FVSI values at these points are close to unity indicating that the system has reached its stability limit.The bus ranking could be performed by sorting the maximum loadability in ascending order. The smallest maximum loadability will be ranked the highest and vice versa for largest loadability. The results for bus ranking are tabulated in Table 1. Bus 1 is ranked the highest with maximum loadability (Q_{max}) 0.35 p.u. indicating that this bus sustains the lowest load.

Practically, proper monitoring should be conducted (Moon *et al.*, 1999) on this bus so that the load connected to the respective bus will not exceed the maximum allowable load to maintain a stable system. On the other hand, bus 4 is ranked the lowest since it has the highest Qmax value, making it the most secure bus in the system. Table 1 also shows the results using Lmn, (Chiang and Jumeau, 1995) and LQP (Gubina and Strmenik, 1995). It shows that the results are very close to the results computed using FVSI. This implies that the proposed index is comparable to LQP techniques.

Table 1: Bus Ranking Comparision with Other Technique

Rank	Bus	Q_{max}	Volt	FVSI	L_{mn}	LQP
1	30	0.35	0.507	0.9336	0.9915	0.7964
2	14	0.70	0.837	0.8031	0.9535	0.3616
3	15	1.60	0.368	0.8686	0.9652	0.6985
4	3	3.45	0.709	0.9134	0.9850	0.8241

Figure 3: FVSI vs Reactive Load Variation Q (IEEE-30 Bus System)



CASE STUDY RESULTS (24 BUS INDIAN SYSTEM)

Table 2: For Bus No. 8 FVSI vs Voltage (PU)

Line No.	From To	Q = 400 MVAR	Q = 666.76 MVAR
8	2-8	0.7575	0.9999
Voltage		0.3552	0.6517

Table 3: For Bus No. 22 FVSI vs Voltage (PU)

Line No.	From To	Q = 400 MVAR	Q = 589.78 MVAR
22	8-22	0.2355	0.9905
Voltage		0.7946	0.4355

Table 4: For Bus No. 13 FVSI vs Voltage (PU)

Line No.	From To	Q = 400 MVAR	Q = 1000 MVAR
13	13-14	1.553	0.9945
Voltage		0.347	0.6835

Table 5: For Bus No.3 FVSI vs Voltage (PU)

Line No.	From To	Q = 400 MVAR	Q = 1198 MVAR
3	4-3	0.1953	0.9999
Voltage		0.9820	0.7839

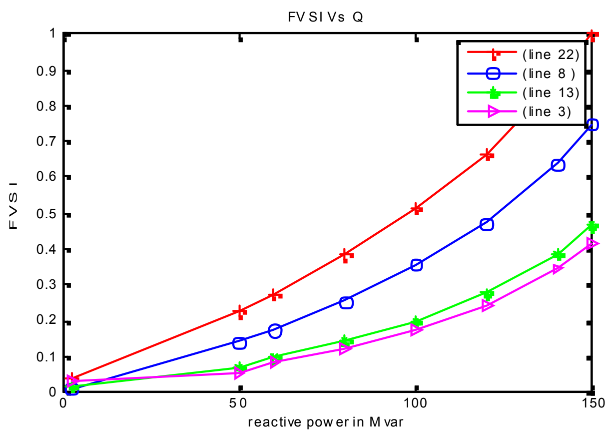
Table 6 clearly shows that the Weakest bus in the both IEEE 30 bus and Indian practical 24 bus system. The buses 30 and 22 are considered as the weakest buses and the respective lines 28-30, 8-22 are treated as Critical lines in IEEE 30 bus and 24 bus Indian system.

Table 6: Comparision of Weakest Bus in Test System

Case	Reactive Power Loadabilty		
	Q Value (MVAR)	Bus No.	Line No.
IEEE 30 Bus System	0.34	30	28-30
	0.72	14	12-14
	1.62	15	13-15
	3.40	13	11-13
Practical 24 Bus Indian System	0.58	22	8-22
	0.66	8	2-8
	1.00	13	13-14
	1.19	3	4-3

Figure 4 Illustrated the response for FVSI vs Q for Each line at the minimum loadabilty of each individual load bus. The FVSI of these points are close to unity indicating the system has reached the stability limit. The bus ranking could be performed by sorting the loadability in ascending order the smallest maximum loadabilty will be ranked the highest and vice

Figure 4: FVSI vs Reactive Load Variation Q (Practical 24-Bus Indian System)



versa for the largest maximum loadbailty. The result for bus ranking as shown in the table bus 22 is ranked the highest with maximum loadabilty (Q_{max}) 5.8 (PU) indicating the system sustains the load.so that proper monitoring suitable action should be initiated to prevent voltage collapse.

CONCLUSION

The work presents the successful analysis on Weakest bus in the IEEE 30 and a practical Indian 24 bus system. The FVSI determines the maximum load that is possible to be connected to a bus in order to maintain stability before the system reaches its bifurcation point. This point is determined as the maximum loadability of a particular bus which beyond this limit system violation will be experienced. The individual maximum loadability obtained from the load buses will be sorted in ascending order. The highest rank implies the weak bus in the system with low sustainable load and the bus which ranked highest may sustain higher load with broader stability margin. From this information, proper monitoring Indian 24 bus of a weak node can be conducted in maintaining a secure electric utility so that the load connected to the respective bus will not exceed the maximum allowable load to maintain a stable system.

REFERENCES

1. Carson W Taylor (1994), "Power System Voltage Stability", Tata-McGraw Hill.
2. Chebbo A M, Iriving M R and Stirling M J H (1992), "Voltage Collapse Proximity Indicator: Behaviour and Implications", *IEE Proc.C Generation, Transmission, Distrbution*, Vol. 139, pp. 241-252.
3. Chiang H D and Jumeau R J (1995), "Toward a Practical Performance Index for Determining Voltage Collapse in Electric Power Systems", *IEEE Transaction on Power Systems*, Vol. 10, No. 2, pp. 584-592.
4. Crisan O and Liu M (1994), "Voltage Collapse Prediction Using an Improved Sensitivity Approach", *Electric Power Systems Reasearch*, Vol. 28, No. 3, pp. 181-190.
5. Gubina F and Strmenik B (1995), "Voltage Collapse Proximity Index Determination Using Voltage Phasors Approach", *IEEE Transactions on Power Systems*, Vol. 10, No. 2, pp. 788-793.
6. Hadi Saadat (2002), "Power System Analysis", Tata McGraw-Hill Edition.
7. Kessel P and Glavitsch H (1996), "Estimating the Voltage Stability of a Power Systems", *IEEE Transactions on Power Delivery*, Vol. 1, No. 3, pp. 346-352.
8. Kundur P (1993), "Power System Stability and Control", McGraw-Hill, New York.
9. Lof P A, Andersson G and Hill D J (1992a), "Voltage Stability Indices for Stressed Power Systems", *IEEE Transaction on Power Systems*, Vol. 8, No. 1, pp. 326-335.
10. Loaf P A, Smed T, Andersson G and Hill D J (1992b), "Fast Calculation of a Voltage Stability Index", *IEEE Transaction on Power Systems*, Vol. 7, No. 1, pp. 54-63.
11. Lof P A, Andersson G and Hill D J (1995a), "Voltage Dependent Reactive Power Limits for Voltage Stability Studies", *IEEE Transactions on Power Systems*, Vol. 10, No. 1, pp. 220-228.

12. Loaf P A, Andersson G, Hill D J and Stefen Arnborg (1995b), "On Analysis of Long Term Voltage Stabilty", *International Journal of Electrical Power and Energy Systems*, Vol. 15, No. 4, pp. 229-237.

13. Melo A C G, Granville S, Mello J C O, Oliveira A M, Dornellas C R R and Soto J O (1999), "Assessment of Maximum Loadability in a Probabilistic Frame Work", *IEEE Power Eng. Soc. Winter Meeting*, Vol. 1, pp. 263-268.

14. Mohamed A and Jammson G B (1989), "Voltage Contingency Selection Techniquefor Security Assessment", *IEE Proc.*, Vol. 136, Pt C, pp. 24-28.

15. Mohavani M and Omar F M (1998), "Technique for Monitoring Contigencey Monitoring and Voltage Collapse Prediction", *IEEE Proc. Generation and Transmission and Distribution*, Vol. 145, pp. 634-640.

16. Moon Y-H, Chooi B K, Cho B H and Lee T S (1999), "Estimating of Maximum Loadability in Power System by Using Elliptic Properties of P-e Curve", *IEEE Power Eng. Soc. Winter Meeting*, Vol. 1, pp. 677-682.

17. Musirin T K and Abdul Rahman (2002), "Estimating Maximum Loadability for Weak Bus Identification Using Fast Voltage Stability Index (FVSI)", *IEEE Power Engineering Review*, November, pp. 50-52.

18. Sauer P W, Evans R J and Pai M A (1990), "Maximum Unconstrained Loadability of Power Systems", *IEEE Int.Symp.Circuits and Systems*, Vol. 3, pp. 1818-1821.

19. Van Custsem T (1995a), "A Method to Compute Reactive Power Margins with Respect to Voltage Collapse", *IEEE Transaction on Power Systems*, Vol. 6, No. 1, pp. 145-156.

20. Van Cutsem T (1995b), "An Approach to Corrective Control of Voltage Instability Using Simulation and Sensitivity", *IEEE Transactions on Power Systems*, Vol. 10, No. 2, pp. 616- 622.

21. "Voltage Stability of Power Systems: Concepts, Analytical Tools and Industry Experience", IEEE Special Publication, 90TH0358-2-PWR, 1990.