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Stability Index Based Voltage Collapse Prediction and Contingency Analysis

C. Subramani†, **Subhransu Sekhar Dash***, **M. Jagdeeshkumar**** and **M. Arun Bhaskar****

Abstract – Voltage instability is a phenomenon that could occur in power systems due to stressed conditions. The result would be an occurrence of voltage collapse leading to total blackout of the system. Therefore, voltage collapse prediction is an important part of power system planning and operation, and can help ensure that voltage collapse due to voltage instability is avoided. Line outages in power systems may also cause voltage collapse, thereby implying the contingency in the system. Contingency problems caused by line outages have been identified as one of the main causes of voltage instability in power systems. This paper presents a new technique for contingency ranking based on voltage stability conditions in power systems. A new line stability index was formulated and used to identify the critical line outages and sensitive lines in the system. Line outage contingency ranking was performed on several loading conditions in order to identify the effect of an increase in loading to critical line outages. Correlation studies on the results obtained from contingency ranking and voltage stability analysis were also conducted, and it was found that line outages in weak lines would cause voltage instability conditions in a system. Subsequently, using the results from the contingency ranking, weak areas in the system can be identified. The proposed contingency ranking technique was tested on the IEEE reliability test system.

Keywords: Critical line outage, Contingency ranking, Sensitive lines, Voltage Stability Index, Weak area cluster

1. Introduction

Continuing interconnections of bulk power systems brought about by economic and environmental pressures has led to an increasingly complex system which must be operated closer to the limits of stability [1]. This situation is worse when contingencies occur in the stressed network. Contingencies caused by line, generator and transformer outages are identified as the most common contingencies that could violate the voltage stability condition of the entire system. Past research has shown that contingency analysis can be time consuming, particularly for bulk power systems. For instance, if one minute is spent analyzing a single line outage, then the IEEE 30-bus system would require 41 minutes to simulate all line outages. The computation burden can be alleviated by conducting contingency ranking normally carried out based on the severity of the line outages. This may reduce the credible contingency set. This process is repeated for different cases in order to accurately rank the contingencies.

Many papers have discussed different techniques to simulate and rank contingencies, such as automatic contingency selection based on a pattern analysis as reported by Rodrigues [2]. This technique is capable of identifying potential harmful contingencies. Voltage based contingency selection techniques reported in reference [3] are able to identify critical line outages. The change in load margin between nominal and contingency based on voltage collapse can also be identified via sensitivities obtained from the single nose of a PV curve as reported by Greene [4]. Fast methods for contingency ranking techniques using the Jacobian matrix manipulation in the load flow study [5], [6] are alternative methods for minimizing the computation burden and the number of contingencies to be simulated. This paper presents a new contingency ranking technique using a line-based voltage stability index. The study involves voltage stability analysis and line outage simulation, which subsequently derived the correlation between critical line outages and sensitive or weak lines. The results have shown that there is a correlation between critical line outages and sensitive lines obtained from voltage stability analysis. The technique was tested on the IEEE Reliability Test System and the results from this study could also identify the weak cluster in a power system network.

2. INDEX FORMULATION AND METHODOLOGY

The Voltage Stability Index abbreviated by L_{ij} and referred to a line is formulated in this study as the measuring

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† Corresponding Author : Dept. of Electrical and Electronics Engineering, Velammal Engineering College, Chennai India (csmsrm@gmail.com)

* Dept. of Electrical and Electronics Engineering, SRM University, Chennai, India(munu_dash_2k@yahoo.com)

** Dept. of Electrical and Electronics Engineering, Velammal Engineering College, Chennai, India(mpjagadeesh@yahoo.com, m.arunbhaskar@gmail.com)

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unit in predicting the voltage stability condition in the system. The mathematical formulation to speed up the computation is very simple. The L_{ij} is derived from the voltage quadratic equation at the receiving bus on a two-bus system [7]. The general two-bus representation is illustrated in Fig. 1.

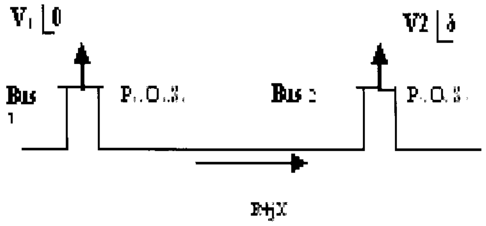

Fig. 1. Two-bus power system models

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

$$\left[V_2^2 - \left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1 V_2 + \left(X + \frac{R^2}{X}\right)Q_2 = 0\right] \tag{1}$$

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

$$\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_2 \geq 0 \tag{2}$$

Rearranging Eq. 2, we obtain:

$$\frac{4Z^2 Q_2 X}{\left(V_1\right)^2 \left(R\sin\delta + X\cos\delta\right)^2} \leq 1 \tag{3}$$

Taking the symbols 'i' as the sending bus and 'j' as the receiving bus, L_{ij} can be defined by:

$$L_{ij} = \frac{4Z^2 Q_j X}{V_i^2 (R\sin\delta + X\cos\delta)^2} \tag{4}$$

Where:

Z = line impedance
X = line reactance,
Q_j = reactive power at the receiving end
V_i = sending end voltage

Any line in a system that exhibits L_{ij} closed to unity indicates that the line is approaching its stability limit and hence may lead to system violation. L_{ij} should always be less than unity in order to maintain a stable system.

3. VSA AND LOCA

Voltage Stability Analysis (VSA) is performed to predict the point of voltage collapse using the proposed L_{ij}. It is performed on an IEEE 30–bus system. Initially, a load flow program was developed to obtain the power flow solution. The results are used to calculate the L_{ij} for each line in the system. The load flow analysis is performed from base case to convergence. All load buses in the system are consecutively tested in order to determine the overall system performance accurately. Results from this experiment indicate the point of voltage stability, weak bus and critical lines in the system. The critical line refers to a particular bus and is determined by the L_{ij} value close to 1.00, while the weak bus is determined by the maximum permissible load for the individual bus in the system. Load ranking is done by sorting the maximum permissible load in ascending order. The lowest value of the maximum permissible load characterizes the highest rank of the bus, which is the weakest one in the system. The bus that ranked lowest is the most secure in the system.

In order to observe the impact of line outage in the system, line outage contingency analysis (LOCA) is performed on the system. Contingency analysis is conducted by removing the lines in the system in sequence for every predetermined case. The predetermined cases are as follows: (i) base case, (ii) Q_3 = 1.432 p.u., (iii) Q_{14} = 0.4115 p.u., (iv) Q_{15} = 0.7485 p.u. and (v) Q_{30} = 0.155 p.u., with the predetermined cases set at half of the maximum permissible load obtained from the VSA. The procedure for contingency analysis is similar to the one in the voltage stability analysis. The only difference is that load flow computation is done with one line removed at a time, and there is no need to increase the reactive power load in the system. The line outage contingency is simulated by removing each line at a time. L_{ij} was computed for each line in the system for every line outage. The highest L_{ij} value from every line outage was extracted and sorted in descending order. The line outage with the highest rank is identified as the most critical outage, and hence a list of critical contingencies can be identified.

4. RESULTS AND DISCUSSION

4.1 Voltage Stability Analysis

Results for voltage stability analysis aiming to determine the voltage stability condition, weak bus and load ranking in the system. Fig. 2 illustrates the response for the critical line on each bus against the reactive load variation. These lines are the dominating lines exhibiting the highest L_{ij} value for every tested bus. The line that exhibits the higher rate of change of L_{ij} is considered as the critical line and refers to a bus, while the value closest to 1.00 is assigned as the maximum permissible load. The critical lines extracted from every load bus are plotted together on the same graph in order to identify a weak bus in the system. A weak bus is determined by looking at the maximum permissible load rather than the L_{ij} values since beyond this limit the system will already be unstable.

The result for bus ranking based on maximum loadability is tabulated in Table 1. It is obvious that the line index increases as the reactive power loading is increased. Line 38 is the most critical line and corresponds to any load change at bus 30. Bus 30 has the smallest maximum permissible load of 0.311 p.u. and is ranked as the highest. On the other hand, line 4 is the most critical line which corresponds to load change at bus 3. Since bus 3 has a maximum permissible load of 2.864 p.u., it is the most secure bus in the system. From this result, proper planning can be done according to the bus capacity in order to avoid voltage collapse in the system. Fig. 2 illustrates the voltage profile for critical line on each bus against the reactive load variation.

Table 1. Bus ranking based on maximum loadability using L_{ij}

Rank	Bus	Load (p.u)	Voltage (p.u)	Line No	L_{ij}
1	30	0.311	0.6597	38	0.9962
				39	0.5748
2	14	0.823	0.7784	17	0.8264
				20	0.9998
3	15	1.497	0.6747	18	0.9998
				20	0.7462
				22	0.4663
				30	0.4147
4	3	2.864	0.7755	2	0.5239
				4	0.9997

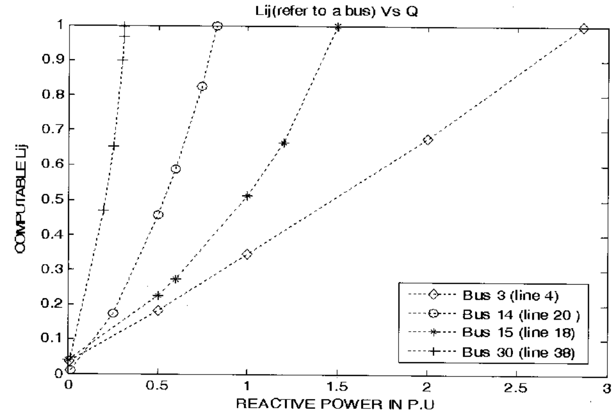

Fig. 2. L_{ij} Vs Reactive load variation (Q).

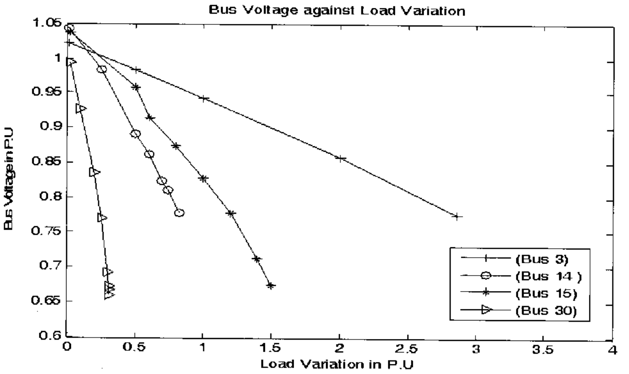

Fig. 3. Bus voltage against load variation.

4.2 Line Outage Contingency Analysis

The contingencies are ranked according to the severity of the index and are tabulated in Table 2. While analyzing, the base case top 20 line outages are considered. From the table, it is observed that lines 13, 16 and 34 have the highest index (unity). When Q_3 = 1.432 p.u, it is observed that lines 1, 4, 13, 16 and 34 have the highest index. When Q_{14} = 0.4115 p.u, it is observed that lines 13, 16, 17 and 34 have the highest index. When Q_{15}= 0.7485 p.u., it is observed that lines 13, 16, 18 and 34 have the highest index. When Q_{30} = 0.155 p.u. it is observed that lines 13, 16 and 34 have the highest index. This indicates that as the loading increased, the number of line outages that could cause voltage collapse also increases and hence the risk for the system to experience voltage instability conditions becomes higher. Results showed that ranking is consistent for all cases and is accurately done. For instance, lines 13, 16 and 34 are ranked the highest for all cases, which implies that these lines are the most critical. These lines become very sensitive because the removal of lines 13 and 16 could cause the generators floating at bus 11 and 13, respectively, and may lead the system into total voltage collapse.

4.3 Correlation between VSA and LOCA

The correlation between the critical line outage obtained from the contingency ranking and weak lines from the voltage stability analysis was observed by comparing both results. VSA was conducted on the system by evaluating L_{ij} for each line. The analysis was conducted at the operating condition Q3 = 1.432 p.u. The values of L_{ij} obtained from the voltage stability analysis were sorted in descending order and the top 20 lines with high L_{ij} were tabulated in Table 3. These lines were recognized as the sensitive lines in the system. In order to identify the weak cluster, correlation between sensitive lines and critical line outages are done. Similar loading conditions were retabulated in Table 3. From Table 3, lines 1, 2, 3, 4, 5, 6, 7, 13, 16, 18, 33, 34, 37 and 38 belonged to both categories. This implies that the lines sensitive in terms of their voltage stability condition are also the critical lines i.e., if line outage occurs to any of these lines, it may lead the system into total voltage collapse.

4.4 Weak Cluster Identification

The results obtained from the contingency ranking were further used to identify weak clusters in the system. Illustrating the results obtained from the contingency ranking of the test system shows some of the weak clusters in the system. The results from Table 3 are illustrated in Fig. 4 and weak clusters are identified. The lines which caused critical contingencies are highlighted and a continuous path is observed from bus 1 to bus 6. It is identified as the major weak cluster based on critical line outages.

Removal of any one of these lines along this path would violate the system stability and could possibly cause cascaded blackout in the system. A radial distribution network also appears along this path. Four other weak clusters are identified: these are line 13 ,which connects a generator (buses 9 and 11); and lines 16 and 18, which are two continuous lines connecting buses 12, 13 and 15.

Table 2. Result for Contingency Analysis

LINE OUTAGE CONTINGENCY ANALYSIS									
Base case		Q_3 =1.432p.u		Q_{14} = .4115p.u		Q_{15}=0.7485p.u		Q_{30}=0.15545p.u	
line	L_{ij}	line	L_{ij}	line	L_{ij}	line	L_{ij}	line	L_{ij}
13	1.000	13	1.000	13	1.000	13	1.0000	13	1.0000
16	1.000	16	1.000	16	1.000	16	1.0000	16	1.0000
34	1.000	34	1.000	34	1.000	34	1.0000	34	1.0000
1	0.562	38	0.732	18	1.000	17	1.0000	4	1.0000
5	0.227	37	0.703	1	0.677	1	0.6305	1	1.0000
2	0.169	39	0.627	14	0.493	20	0.6038	7	0.6840
4	0.168	1	0.584	15	0.490	18	0.4231	3	0.5656
26	0.163	33	0.391	25	0.459	14	0.3924	10	0.5329
25	0.161	35	0.362	24	0.453	15	0.3859	6	0.5108
24	0.157	5	0.362	36	0.453	4	0.3607	5	0.5053
14	0.157	2	0.362	26	0.440	2	0.3607	14	0.5022
36	0.157	4	0.361	17	0.437	25	0.3585	36	0.5017
7	0.155	7	0.356	32	0.435	26	0.3582	8	0.4994
31	0.150	31	0.356	23	0.431	24	0.3554	11	0.4983
35	0.149	6	0.354	7	0.428	7	0.3549	25	0.4961
27	0.149	30	0.351	30	0.426	11	0.3546	26	0.4958
12	0.149	3	0.351	12	0.426	21	0.3526	24	0.4955
10	0.147	18	0.350	22	0.425	5	0.3513	40	0.4933
28	0.147	27	0.349	20	0.425	6	0.3506	12	0.4931
38	0.146	32	0.348	19	0.402	36	0.3505	35	0.4916

Table 3. Sensitive Lines and Critical Line Outages at Q_3=1.432 p.u

Rank	VSA		LOCA	
	Line	L_{ij}	Line	L_{ij}
1	4	0.4908	13	1.0000
2	3	0.2256	16	1.0000
3	13	0.2149	34	1.0000
4	2	0.1825	38	0.7329
5	16	0.1526	37	0.7030
6	7	0.1345	39	0.6275
7	11	0.1309	1	0.5842
8	8	0.1075	33	0.3917
9	6	0.1043	35	0.3627
10	36	0.0811	5	0.3626
11	1	0.0668	2	0.3624
12	34	0.0561	4	0.3615
13	38	0.0558	7	0.3567
14	5	0.0534	31	0.3565
25	18	0.0469	6	0.3548
16	33	0.0463	30	0.3514
17	10	0.0437	3	0.3511
18	14	0.0424	18	0.3504
19	12	0.0391	27	0.3494
20	37	0.0384	32	0.3487

Lines 33 and 34, which are also two continuous lines connecting buses 24, 25 and 26, and lines 37 and 38, which are also two continuous lines connecting buses 27, 29 and 30. Therefore, the removal of any lines in the weak clusters must be avoided in order to maintain a secure power delivery.

The results of comparative studies between the manual contingency ranking and automatic contingency can be observed in Table 4. It is obvious that the automatic contingency analysis and ranking technique is much faster than the conventional method which in turn minimizes human error.

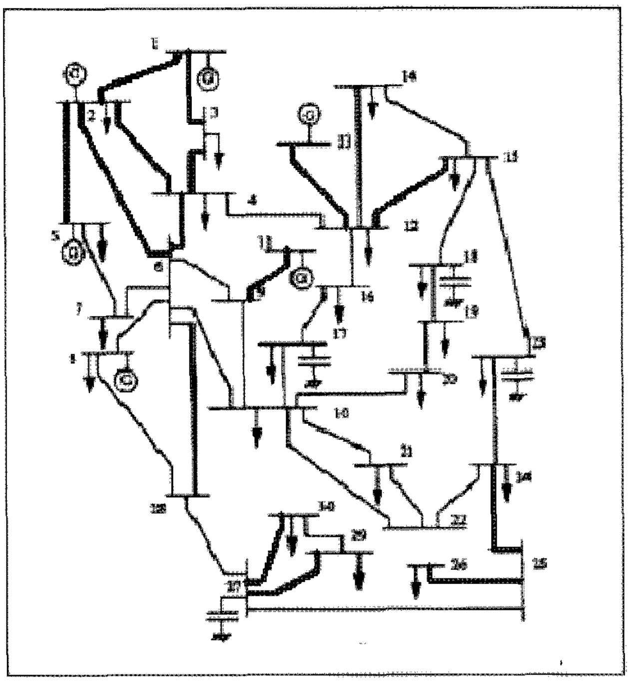

Fig. 4. Weak Area Cluster at Q_3 = 1.432 p.u

Table 4. Comparison between Manual and Automatic Contingency Ranking

Test System	Loading Condition	Computation Time	
		Manual	Automatic
IEEE 30 - bus	Base case	41 min	15 sec
	Q_3=1.432 p.u	41 min	15 sec

5. CONCLUSION

Voltage collapse prediction is important information obtained from the Voltage Stability Analysis performed on a power system. Hence, several control actions can be taken in order to maintain a secure system. In this paper, a Voltage Stability Index L_{ij} referred to as a line is presented. This index enables the critical line in a system to be identified. A line is considered to be critical if the L_{ij} referred to in this line is close to unity. This technique has successfully reduced the computation time for contingency analysis and ranking, thus avoiding misranking due to a long computation time and human factor constraints.

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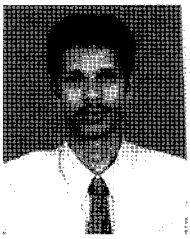
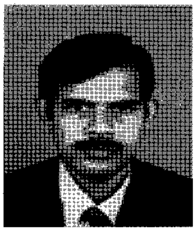
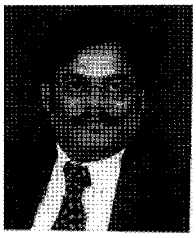


C. Subramani is a senior lecturer in the Dept. of EEE at Velammal Engineering College, Chennai, Tamilnadu, India. He is currently pursuing his research at SRM University, Chennai, India, in the area power system voltage stability. His areas of interest are power system stability, power system control and FACTS.



Subhransu Sekhar Dash is a Professor and Head of the Dept. of EEE at SRM University, Chennai, Tamilnadu, India. He has guided more than 20 PG students, and is currently guiding 15 research scholars. His areas of interest are power system operation, control and stability, power quality and FACTS.



M. Jagadeeshkumar is an Asst. Professor in the Dept. of EEE at Velammal Engineering College, Chennai, Tamilnadu, India. He is currently pursuing his research at SRM University, Chennai, India, in the area of power system voltage stability. His areas of interest are power system stability, power system control and FACTS.

M. Arun Bhaskar is a senior Lecturer in the Dept. of EEE at Velammal Engineering College, Chennai, Tamilnadu, India. He is currently pursuing his research at SRM University, Chennai, India, in the area of power system stability improvement. His areas of interest are power system stability, power system control and FACTS.