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Voltage Stability Based Collapse Prediction and Weak Cluster Identification

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Abstract: Voltage instability is a Phenomenon that could happen in a power system due to stressed condition. The result would be the occurrence of voltage collapse which leads to total blackout of the whole system. Therefore, voltage collapse prediction is important in power system planning and operation so that the occurrence of voltage collapse due to voltage instability could be avoided. Line outage in a power system could also, lead to the event of the voltage collapse which implies the contingency in the system. Contingency problem caused by line outage has been identified as one of the main reason to voltage instability in power system. This study presents, a new technique for contingency ranking based on voltage stability condition in power system. A new line stability index was formulated and used to identify the critical line outages and sensitive lines in the system. The line outage contingency ranking was performed on several loading condition in order to identify the effect of increase in loading to the critical line outages. Correlation study on the results obtained from contingency ranking and voltage stability analysis were also, conducted and it is found that line outages at the weak lines would cause voltage instability condition to a system. Subsequently, using the result from the contingency ranking weak areas in the system can be identified. The proposed contingency ranking technique was tested on IEEE reliability test system.

Key words: Voltage stability, sensitive lines, critical line outage, contingency ranking, voltage stability index, weak area cluster

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 (Chiang *et al*., 1990). This situation becomes worst 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 researches have shown that contingency analysis can be time consuming particularly for a bulk power system. For instance, if one minute is spent to analyse a single line outage, then the IEEE 30-bus system would require 41 min to simulate all the line outages. The computation burden can be alleviated by conducting contingency ranking that is normally carried out based on the severity of the line outages. This may reduce credible contingency set. This process is repeated for different cases in order to accurately rank the contingencies.

Many studies have discussed different techniques to simulate and rank the contingencies for example automatic contingency selection based on a pattern analysis as reported by Rodrigues *et al.* (1999). This technique is capable to identify the potential harmful contingencies. Voltage based contingency selection techniques reported in reference (Ekwue *et al*., 1998) is able to identify the 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 *et al.* (1999). Fast methods for contingency ranking techniques using the Jacobian matrix manipulation in the load flow study (Gubina *et al*., 1996; Mohamed *et al*., 1998) are alternative methods towards minimizing computation burden and the number of contingencies to be simulated. This study presents, a new contingency ranking technique using a line-based voltage stability index. The study involves voltage stability analysis and line outages 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.

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INDEX FORMULATION

Voltage stability index abbreviated by L_{ij} referred to a line is formulated in this study as the measuring unit in predicting the voltage stability condition in the system. The mathematical formulation is very simple that could speed up the computation. The L_{ij} is derived from the voltage quadratic equation at the receiving bus on a two-bus system (Musirin and Abdul Rehman, 2002). The general 2-bus representation is illustrated in Fig. 1.

From the Fig. 1, the voltage quadratic equation at the receiving bus is written as:

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

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

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

Rearranging Eq. 2, we obtain,

$$\frac{4Z^2Q_2X}{(V_1)^2(R\sin\delta + X\cos\delta)^2} \leq 1 \quad (3)$$

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

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

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.

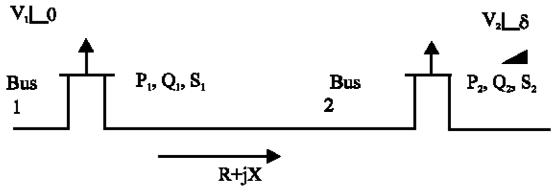

Fig. 1: Two-bus power system models

VOLTAGE STABILTY ANALYSIS

Voltage stability analysis is performed to predict the point of voltage collapse using the proposed L_{ij}. It is performed on IEEE 30-bus system. Initially 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 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 maximum permissible load characterizes the highest rank of bus which is the weakest one in the system. The bus which ranked lowest is the most secure bus in the system.

LINE OUTAGE CONTINGENCY ANALYSIS

In order to observe, the impact of line outage in the system, contingency analysis is performed on the system. Contingency analysis is conducted by removing the lines in the system in sequence for every pre determined case. The predetermined cases are as follows: Base case, Q_3 = 1.432 p.u., Q_{14} = 0.4115 p.u., Q_{15} = 0.7485 p.u. and Q_{30} = 0.155 p.u., the predetermined cases set at half of the maximum permissible load obtained from the VSA. The procedure for contingency analysis is almost similar to the one in voltage stability analysis. The only difference is that, load flow computation is done with a 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 highest rank is identified as the most critical outage and hence a list of critical contingencies can be identified.

RESULTS AND DISCUSSION

Voltage stability analysis: Result for the voltage stability analysis that aimed to determine the voltage stability condition, weak bus and load ranking in the system. Figure 2 illustrates the response for critical line on each bus against the reactive load variation. These lines are the dominating lines that exhibited the highest L_{ij} value for every tested bus. The line that exhibits the higher rate of

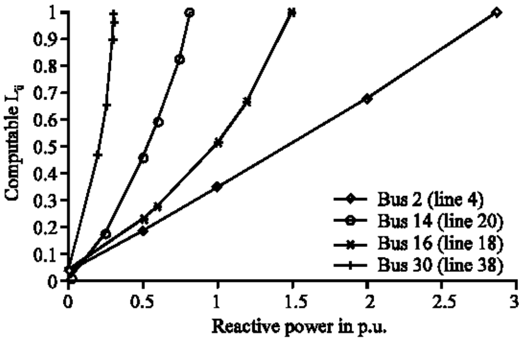

Fig. 2: L_{ij} Vs Reactive load variation (Q)

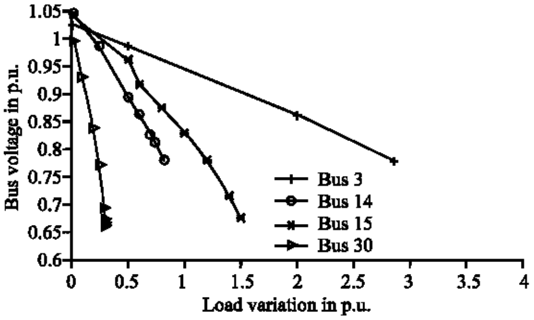

Fig. 3: Bus voltage against load variation

change of L_{ij} is considered as the critical line refer to a bus while the value closed 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 weak bus in the system. Weak bus is determined by looking at the maximum permissible load rather than the L_{ij} values, since beyond this limit system will be already 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 corresponds to any load change at bus 30. Bus 30 has the smallest maximum permissible load of 0.311 p.u. and it is ranked as the highest. On 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, a proper planning can be done according to the bus capacity in avoiding voltage collapse in the system. Figure 3 illustrates the voltage profile for critical line on each bus against the reactive load variation.

Line outage contingency analysis: The contingencies are ranked according to the severity of the index is tabulated in Table 2. While, analyzing the base case top 20 line outages are considered. From the Table 2, it is observed that lines 13, 16 and 34 are with highest index (unity). When Q_3 = 1.432 p.u., it is observed that lines 1, 4, 13, 16 and 34 are with highest index. When Q_{14} = 0.4115 p.u. it is observed that lines 13, 16, 17 and 34 are with highest index. When Q_{15} = 0.7485 p.u. it is observed that lines 13, 16, 18 and 34 are with highest index. When Q_{30} = 0.155 p.u. it is observed that lines 13, 16 and 34 are with highest index. This indicates that as the loading increased, the number of line outages which could cause voltage collapse also, increases and hence the risk for the system to experience voltage instability condition becomes higher. Results showed that ranking is consistent for all cases are 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 lines. 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.

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

Correlation between sensitive lines and critical lines outages: 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 Q_3 = 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, which are sensitive in terms of their voltage stability condition are also the critical lines i.e., if line outage occurs to any of these lines may lead the system into total voltage collapse.

Table 2: Result for contingency analysis

Line outage contingency analysis									
Base case		Q_3 = 1.432 p.u.		Q_{14} = 0.4115 p.u.		Q_{15} = 0.7485 p.u.		Q_{30} = 0.15545 p.u.	
Line	L_{ij}	Line	L_{ij}	Line	L_{ij}	Line	L_{ij}	Line	L_{ij}
13	1.0000	13	1.0000	13	1.0000	13	1.0000	13	1.0000
16	1.0000	16	1.0000	16	1.0000	16	1.0000	16	1.0000
34	1.0000	34	1.0000	34	1.0000	34	1.0000	34	1.0000
1	0.5628	38	0.7329	18	1.0000	17	1.0000	4	1.0000
5	0.2277	37	0.7030	1	0.6772	1	0.6305	1	1.0000
2	0.1695	39	0.6275	14	0.4933	20	0.6038	7	0.6840
4	0.1689	1	0.5842	15	0.4908	18	0.4231	3	0.5656
26	0.1635	33	0.3917	25	0.4598	14	0.3924	10	0.5329
25	0.1618	35	0.3627	24	0.4532	15	0.3859	6	0.5108
24	0.1578	5	0.3626	36	0.4531	4	0.3607	5	0.5053
14	0.1578	2	0.3624	26	0.4402	2	0.3607	14	0.5022
36	0.1572	4	0.3615	17	0.4378	25	0.3585	36	0.5017
7	0.1559	7	0.3567	32	0.4350	26	0.3582	8	0.4994
31	0.1505	31	0.3565	23	0.4313	24	0.3554	11	0.4983
35	0.1498	6	0.3548	7	0.4280	7	0.3549	25	0.4961
27	0.1493	30	0.3514	30	0.4267	11	0.3546	26	0.4958
12	0.1492	3	0.3511	12	0.4266	21	0.3526	24	0.4955
10	0.1476	18	0.3504	22	0.4256	5	0.3513	40	0.4933
28	0.1471	27	0.3494	20	0.4251	6	0.3506	12	0.4931
38	0.1464	32	0.3487	19	0.4023	36	0.3505	35	0.4916

Table 3: Sensitive lines and critical line outages at Q_3 =1.432 p.u.

	VSA		LOCA	
Rank	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

Table 4: Comparison between manual and automatic contingency ranking

		Computation time	
Test system	Loading condition	Manual	Automatic
IEEE 30 -bus	Base case	41 min	15 sec
	Q_3 =1.432 p.u.	41 min	15 sec

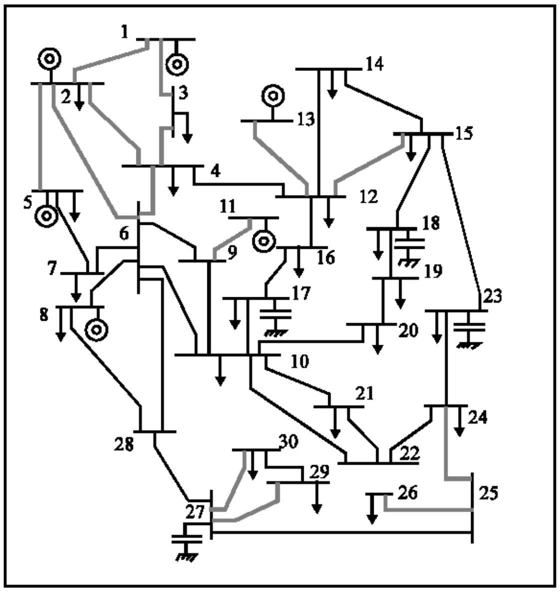

Fig. 4: Weak area cluster at Q_3 = 1.432 p.u.

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 cluster 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 1-6. 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 is also appeared along this path. Four other weak clusters are also identified, they are line 13 which is connecting a generator (buses 9 and 11), lines 16 and 18 which are 2 continuous lines connecting buses 12, 13 and 15. The lines 33 and

34 which are also 2 continuous lines connecting buses 24, 25 and 26 and the lines 37 and 38 which are also, 2 continuous lines connecting buses 27, 29 and 30. Therefore, the removal of any lines in the weak clusters must be avoided in maintaining 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 minimize the human error during the process.

CONCLUSION

Voltage collapse prediction is important information obtain from the voltage stability analysis performed on a power system. Hence, several control action can be taken in order to maintain a secure system. In this study, a voltage stability index L_{ij} referred to a line is presented. This index enables to identify the critical line in a system. A line is considered to be critical if the L_{ij} referred to this line is close to unity. This technique has successfully reduced the computation time for contingency analysis and ranking, which avoids the misranking due to long computation time and human factor constraint.

REFERENCES

Chiang, H.D., I. Dobson and R.J. Thomas, 1990. On voltage collapse in electric power systems. IEEE. Trans. Power Syst., 5 (2): 601-611.

Ekwue, A.O., A.M. Chebbo, M.E. Bradley and H.B. Wan, 1998. Experience of automatic contingency selection algorithms on the NGC system. IEEE. Power Eng. Rev., pp: 53-55.

Greene, S., I. Dobson and F.L. Alvarado, 1999. Contingency ranking for voltage collapse via sensitivities from a single nose curve. IEEE. Trans. Power Syst., 14 (1): 232-240.

Gubina, F., A. Debs and R. Golob, 1996. Improved adjoint network algorithm for on-line contingency analysis. Int. J. Elec. Power Syst. Res., 138: 161-168.

Mohamed, A., H. Shaaban and A. Kahla, 1998. A fast efficient accurate technique for circuit contingency evaluation. Int. J. Elec. Power Syst. Res., 45: 181-189.

Musirin, I. and T.K. Abdul Rahman, 2002. Estimating maximum loadability for weak bus identification using FVSI. IEEE. Power Eng. Rev., 22: 50-52.

Rodrigues, M.S., J.C.S. Souza, M.B. Do Coutto Filho and M. Th. Schilling, 1999. Automatic contingency selection based on a pattern analysis approach. Proc. IEEE. Int. Conf. Elec. Power Eng., Power Technol. Budapest, pp: 179.