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Voltage Security Assessment of Power System

Amit Kumar Chowdhury[1,*], Surajit Mondal[2], S. K. Mehboob Alam[1], Jagadish Pal[1]

[1]Electrical Engineering Dept, IIEST, Shibpur, India

[2]University of Petroleum & Energy Studies, Dehradun, India

*E-mail address: amitchowdhury91@gmail.com

ABSTRACT

This paper deals with the security aspects of power system by evaluating the severity of transmission line outage. Voltage security assessment is made by determining the power flow in the line using load flow for each contingency. The severity of contingency is measured using a scalar index called Voltage performance index. 1P-1Q Method and Fast Decoupled load flow are used as approximate and exact load flow methods for Voltage security assessment respectively. Contingency analysis is carried out and ranked lists in the decreasing order of severity based on Voltage Performance Index values are prepared for standard test systems. The severity of line is evaluated and compared using these load flow methods.

Keywords**:** Voltage Collapse, Voltage Stability, 1P-1Q Method, Fast Decoupled Load flow, Voltage Performance index, Voltage insecurity

1. INTRODUCTION

Voltage security is defined as static voltage security, transient voltage security and dynamic voltage security according to the lasting time of disturbances. Voltage insecurity comprises of voltage instability or over voltage due to faults, loads increases or other kind of disturbances in the system. Masking better grid framework, better system operation and strengthening the control system will be helpful to improve voltage security. Analysis of voltage security in power industry is different from that in academic research institutions where off-line studies are carried out, while industrial analysis aims at doing it on-line.

The problem of voltage security has been an important factor of affecting power network security and limiting available power transmission capability. Recently many serious accidents of blackout around the world are relevant to the security of voltage and mostly due to voltage collapse. Voltage collapse typically occurs on power systems which are heavily loaded, weakened by transmission outages, or subjected to reactive power shortages. It is associated with reactive power deficiencies, and it may result in uncontrollable system-wide voltage collapse, loss of loads, and blackout. The prevailing practice in industry of avoiding voltage collapse is to maintain a deterministic reliability margin on bus voltages, reactive power requirements, transfer capabilities, or system loading levels such that the system can survive the collapse under any single component failure.

Voltage Collapse [1]

Voltage collapse is a system instability that involves several power system components failure simultaneously. It typically occurs on power systems that are heavily loaded, faulted and/or have reactive power shortages. Voltage collapse occurs since it is associated with the reactive power demands of loads not being met due to limitations on the production and transmission of reactive power. The production limitations include generator and SVC reactive power limits and the reduced reactive power produced by capacitors at low voltages. The primary limitations in transmission system are high reactive power losses on heavily loaded lines and line outages. Reactive power demands may also increase due to changes in the load such as, motor installing or increased proportion of compressor load.

Voltage collapse takes place on the different timescales ranging from sec-onds to hours, specially:

- Electromechanical transient (eg. generators, regulators, induction ma-chines) and power electronic (eg. SVC, HVDC) phenomena in the time range of seconds.
- Discrete switching devices, such as, load tap changers (OLTC) and excitation limiters acting at intervals of ten of seconds.
- Load recovery processes spanning several minutes.

There are numerous system events known to contribute to voltage col-lapse. Most of these changes have a large effect on reactive power production or transmission.

- Increase in loading.
- Generators or SVC reactive power limits.
- Action of tap changing transformers.
- Load recovery dynamics.
- Line tripping or generator outages.

Voltage Stability [2]

Voltage stability is concerned with the ability of a power system to maintain acceptable voltages at all buses under normal operating conditions and after being subjected to a disturbance. A system becomes unstable when a distur-bance (outage of generator, line, transformer, bus bar etc., increase in load, decrease in generation and/or weakening of voltage control) causes voltage to drop quickly or drift downward, and operators and automatic system controls fail to improve the voltage level. The main factor causing voltage instability is the inability of the power system to meet the demands for reactive power for maintaining desired voltages in the heavily stressed system. Other factors contributing to voltage instability are the generator reactive power limits, the load characteristics, the characteristics of the reactive power compensation devices and the action of the voltage control devices.

Voltage control and instability are local problems while consequences of voltage instability may have a widespread impact. Voltage collapse is the catastrophic result of a sequence of events leading to a very low voltage profile suddenly in a major part of the power system.

For the purpose of analysis voltage stability problems may be classified as small disturbance and large disturbance. Small disturbance voltage stability considers the power systems ability to control voltage after small distur-bances, e.g. load changes. Analysis of small disturbance voltage stability is done in steady state. In that case the power system can be linearized around the operating point and the analysis is typically based on eigen value and eigen vector techniques. Large disturbance voltage stability analyzes, the response of the power system to such disturbances for example faults, switching or loss of loads or loss of generation. Large disturbance voltage stability can be studied using non linear time domain simulations in the short-term time-frame and load flow analysis in long-term time-frame.

Static Voltage Security [2]

After the disturbance which causes voltage problem is died down and the steady state is reached, then the analysis is done to obtain the voltage profile of the system. Load flow is the tool to assess the voltage security of the system. Voltage magnitude for each outage (disturbance) at all the buses can be determined using load flow analysis. Voltage severity of the transmission line is determined using Voltage Performance Index PI_v. Higher the PI_v value, higher will be the voltage severity. The decreasing order of the voltage ranked list gives decreasing order of voltage severity of the line. Proper control action will be taken for the top harmful cases to bring back the normal voltage profile of the system. The voltage ranked list gives an idea for the operator in control center to initiate control action.

Voltage Performance Index [3]

Severity of line outage in respect of voltage security is measured with the help of the Performance Index for voltage magnitude, PI_v as given in equation

$$P_{IV} = \sum_{i=1}^{NB} \frac{W_{vi}}{2n} \left[\frac{|V_i| - |V_i^{SP}|}{\Delta V_i^{lim}} \right]^{2n}$$

$|V_i|$ = voltage magnitude at bus i (calculated). $|V_i^{sp}|$ = specified voltage magnitude at bus i.
ΔV_i^{lim} = voltage deviation limit.
NB = number of load buses in the system. n = exponent.
W_{Vi} = Weighting coefficient to reflect the importance of bus i.

In the present work the values of W_{Vi} , n and ΔV_i^{lim} are taken as 1.0, 1 and 0.075 p.u. respectively. Because of the non availability of specified (rated) voltage, ($|V_i^{sp}|$), the base case values obtained by running FDLF method are assigned for them.

The voltage deviation ΔV_i^{lim} represents the threshold above which volt-age level deviations are outside their limits, any contingency load flow with voltage levels outside this limit yields a high value of the index PI_V . When all the voltage level deviations from the rated voltage are within ΔV_i^{lim}, the voltage performance index PI_V is small. Thus, this index measures the sever-ity of the out-of-limit bus voltages, and for a set of contingencies, this index provides a direct means of comparing the relative severity of the different outages on the system voltage profile.

It is pertinent to note, that since the bus voltage levels depend mainly on the reactive power flows and therefore, on the reactive power production of the generators (and reactive power production units, e.g., synchronous con-densers), the performance index PI_V provides a good measure of the severity of abnormal voltages, as long as the generating units remain with in their reactive power limits. However, it is possible to encounter a contingency for which some generator reactive powers are driven to their limits. In this situation, the standard full AC load flow computes the bus voltage using the limiting reactive powers at generator buses as specified independent variable, and their voltages as dependent variables, as a consequence, there is a volt-age deviation from the scheduled voltage at the generator buses. Therefore, in order to reflect the reactive power capability constraints of the genera-tors in the contingency selection for voltage analysis, we define a generalized
voltage-reactive power performance index [8] by

$$P_{I_{VQ}} = \sum_{i=1}^{NB} \frac{W_{vi}}{2n} \left[\frac{|V_i| - |V_i^{iP}|}{\Delta V_i^{lim}} \right]^{2n} + \sum_{i=1}^{NG} \frac{W_{Qi}}{2n} \left[\frac{Q_i}{Q_i^{max}} \right]^{2n}$$

where,
Q_i = reactive power produced at bus i.
$Q^{max}{}_i$ = reactive power production limit.
NG = the number of generating (reactive production) units.
W_{Qi} = real non negative weighting factor.

The second summation, takes over all reactive production units, penal-izes any violations of the reactive power constraints. The reactive power weighting factors are set to zero if the effect of the reactive power deficit is not required. This perhaps important to emphasize here that the contin-gency selection procedure developed here is not concerned with computing the system performance index $PI_{V\,Q}$. The analysis deals with computing the voltage performance index (PI_V) and MW performance index (PI_{MW}) with respect to outages.

2. VOLTAGE SECURITY ASSESSMENT

Voltage Ranking of systems using 1P-1Q method [4]

As stated in chapter 2, 1P-1Q algorithm is the load flow solution of FDLF method for first iteration only. Using 1P-1Q algorithm voltage ranking of lines in standard 5, 6, IEEE-14 and IEEE-30 bus systems along with outage line number and its corresponding PI_V values are shown in the following tabular forms.

Ranking of standard 5 bus system:

Table 1. Voltage Ranking of standard 5 bus system using 1P-1Q method.

Rank	Line No.	From Bus to To Bus	PI_V
1	1	1-2	3.871338
2	5	2-5	1.142147
3	2	1-3	0.194431
4	4	2-4	0.047412
5	3	2-3	0.037579
6	7	4-5	0.010202
7	6	3-4	0.005400

Ranking of standard 6 bus system:

Table 2. Voltage Ranking of standard 6 bus system using 1P-1Q method.

Rank	Line No.	From Bus to To Bus	PI_V
1	9	3-6	1.098846
2	5	2-4	0.712250
3	2	1-4	0.145660
4	8	3-5	0.092044
5	3	1-5	0.064519
6	6	2-5	0.049441
7	7	2-6	0.036315
8	11	5-6	0.005972

9	10	4-5	0.001902
10	1	1-2	0.000103
11	4	2-3	0.000002

Voltage Ranking of IEEE-14 bus system:

Table 3. Voltage Ranking of IEEE-14 bus system using 1P-1Q method.

Rank	Line No.	From Bus to To Bus	PI_V
1	16	6-13	0.533000
2	14	6-11	0.136825
3	17	9-14	0.135441
4	12	7-9	0.135286
5	15	6-12	0.115881
6	13	9-10	0.064049
7	20	13-14	0.054500
8	1	1-2	0.044850
9	8	5-6	0.031594
10	18	10-11	0.024355
11	4	1-5	0.023332
12	3	2-4	0.023306
13	5	2-5	0.012935
14	7	4-5	0.010043
15	9	4-7	0.008214

16	2	2-3	0.005839
17	19	12-13	0.002023
18	6	3-4	0.001450
19	11	4-9	0.001311

Voltage Ranking of IEEE-30 bus system:

Table 4. Voltage Ranking of IEEE-30 bus system using 1P-1Q method.

Rank	Line No.	From Bus to To Bus	PI_V
1	1	1-2	6.753839
2	5	2-5	2.498179
3	6	2-6	2.247482
4	15	4-12	2.137817
5	36	28-27	2.097796
6	9	6-7	1.961527
7	2	1-3	1.942474
8	18	12-15	1.864922
9	4	3-4	1.840726
10	3	2-4	1.831095
11	38	27-30	1.817026
12	37	27-29	1.802708
13	25	10-20	1.797410
14	27	10-11	1.795194
15	19	12-16	1.778154

16	17	12-14	1.767301
17	22	15-18	1.765628
18	24	19-20	1.764812
19	41	6-28	1.763374
20	12	6-10	1.762551
21	30	15-23	1.760406
22	39	29-30	1.735897
23	35	25-27	1.724690
24	31	22-24	1.680212
25	26	10-17	1.674133
26	28	10-22	1.671998
27	21	16-17	1.671862
28	40	8-28	1.658438
29	14	9-10	1.620527
30	23	18-19	1.612969
31	32	23-24	1.610646
32	20	14-15	1.557299

(continued.......)

Rank	Line No.	From Bus to To Bus	PI_V
33	33	24-25	1.556389
34	29	21-22	1.516720
35	10	6-8	1.516024

36	7	4-6	1.456070
37	11	6-9	1.276885
38	8	5-7	1.058709

Voltage Ranking of systems using FDLF method [5]

Using FDLF algorithm voltage ranking of lines in standard 5, 6, IEEE-14 and IEEE-30 bus systems along with outage line number and its corresponding PI_Vvalues are shown in the following tabular forms.

Ranking of standard 5 bus system:

Table 5. Voltage Ranking of standard 5 bus system using FDLF method.

Rank	Line No.	From Bus to To Bus	PI_V
1	1	1-2	8.412059
2	5	2-5	2.419422
3	2	1-3	0.297620
4	3	2-3	0.258680
5	4	2-4	0.085794
6	7	4-5	0.033192
7	6	3-4	0.027571

Ranking of standard 6 bus system:

Table 6. Voltage Ranking of standard 6 bus system using FDLF method.

Rank	Line No.	From Bus to To Bus	PI_V
1	2	1-4	2.594501
2	3	1-5	2.186205

3	9	3-6	1.903658
4	5	2-4	0.909400
5	7	2-6	0.295928
6	6	2-5	0.101850
7	8	3-5	0.094679
8	11	5-6	0.005974
9	10	4-5	0.003247
10	4	2-3	0.002378
11	1	1-2	0.000358

Voltage Ranking of IEEE-14 bus system:

Table 7. Voltage Ranking of IEEE-14 bus system using FDLF method.

Rank	Line No.	From Bus to To Bus	PI_V
1	16	6-13	0.557213
2	8	5-6	0.379553
3	1	1-2	0.348232
4	12	7-9	0.243237
5	17	9-14	0.215973
6	15	6-12	0.174976
7	14	6-11	0.150691
8	13	9-10	0.133462
9	4	1-5	0.084310

10	3	2-4	0.072353
11	2	2-3	0.070462
12	7	4-5	0.070005
13	20	13-14	0.061953
14	5	2-5	0.050280
15	9	4-7	0.043754
16	18	10-11	0.036117
17	11	4-9	0.035919
18	19	12-13	0.025416
19	6	3-4	0.024128

Voltage Ranking of IEEE-30 bus system:

Table 8. Voltage Ranking of IEEE-30 bus system using FDLF method.

Rank	Line No.	From Bus to To Bus	PI_V
1	36	28-27	6.990140
2	11	6-9	2.726264
3	15	4-12	2.521516
4	9	6-7	2.246008
5	1	1-2	2.227146
6	37	27-29	2.004432
7	38	29-30	1.999195
8	8	5-7	1.910214
9	24	19-20	1.907808

10	39	29-30	1.902611
11	29	21-22	1.896554
12	33	24-25	1.895462
13	10	6-8	1.886528
14	32	23-24	1.866738
15	20	14-15	1.864514
16	21	16-17	1.863142
17	23	18-19	1.862495
18	26	10-17	1.854692
19	35	25-27	1.829236
20	7	4-6	1.814008
21	25	10-20	1.810655
22	4	3-4	1.806735
23	3	2-4	1.793179
24	31	22-24	1.790039
25	28	10-22	1.767801
26	40	8-28	1.761030
27	22	15-18	1.745831
28	30	15-23	1.736035
29	5	2-5	1.716901
30	6	2-6	1.705662
31	41	6-28	1.685715

32	19	12-16	1.643434
33	17	12-14	1.637855
34	2	1-3	1.603929
35	27	10-21	1.570518
36	12	6-10	1.540318
37	18	12-15	1.266729
38	14	9-10	1.078561

Comparison of Voltage Ranking between FDLF and 1P-1Q methods

Voltage ranking of IEEE-14 bus system obtained by FDLF and 1P-1Q meth-ods are compared. Ranking made from FDLF method is treated as ideal and exact ranking of line. Shifting of a particular line from the exact ranking is denoted by upward shift (US) or by downward shift (DS). Positional shift (PS) is expressed in number. If a line is found to appear in the same position as that of FDLF method, then it is said to be correctly ranked (CR).

Table 9. Comparison of Voltage ranking for IEEE-14 bus system.

Rank	FDLF	1P-1Q	P.S
1	16	16	CR
2	8	14	D_7
3	1	17	D_5
4	12	12	CR
5	17	15	U_2
6	15	13	$^{U}1$
7	14	20	U_5
8	13	1	$^{U}2$
9	4	8	D_2
10	3	18	D_2
11	2	4	D_5

12	7	3	$^{D}2$
13	20	5	U_6
14	5	7	$^{U}1$
15	9	9	CR
16	18	2	$^{U}6$
17	11	19	D_2
18	19	6	$^{U}1$
19	6	11	U_1

Control of Voltage Insecurity [6]

Control actions such as switching in shunt capacitors, blocking tap changing transformers, re-despatch of generation, rescheduling of generator and pilot bus voltages, secondary voltage regulation, load shedding and temporary reactive power over load of generators are counter measures against voltage collapse. Machine angles are typically also involved in the voltage collapse.

Thus, there is no sharp distinction between voltage collapse and classical transient instability. The differences between voltage collapse and classical transient instability are those of emphasis: voltage collapse focuses on loads and voltage magnitudes whereas transient instability focuses on generator angles. Also, voltage collapse often includes longer time scale dynamics and includes the effects of continuous changes such as load increases in addition to discrete events such as line outages.

Increasing voltage levels by supplying more reactive power generally im-proves the margin to voltage collapse. In particular, shunt capacitors become more effective at supplying reactive power at higher voltages. Increasing voltage levels by tap changing transformer action can decrease the margin to voltage collapse by in effect increasing the reactive power demand. Still, voltage levels are a poor indicator of the margin to voltage collapse while there are some relations between the problems of maintaining voltage levels and voltage collapse, they are best regarded as distinct problems since their analysis is different and there is only partial overlap in the control actions used to solve both problems.

3. CONCLUSIONS

Power system Voltage security assessment is important to maintain proper functioning of grid. Security assessment should be correct with ideal ranking algorithm. The results of security analysis will help the operators in power system control centers to take preventive control action. The results presented in this paper are based on traditional method of ranking algorithm are free from masking effect. Since masking effect is negligible in voltage security assessment, we should concentrate on developing control devices which improve voltage profile of the system

Ranking algorithms developed from the last decade yield good results for its own system. A unique ranking algorithm is not applicable for all the systems. An ideal power system security assessment can be done using advanced techniques like Artificial Neural Network (ANN), Artificial Intelligence etc.

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