Voltage Contingency Ranking for IEEE 39-Bus System using Newton-Raphson Method

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Abstract: - Steady state security assessment becomes a stringent need as it provides the knowledge about the state of the system following a contingency. This paper presents a Newton-Raphson load flow based method for voltage security assessment. A voltage performance index is computed firstly to classify contingencies in secure, insecure and critical classes and then to rank them in the decreased order of severity. The proposed approach is tested on the IEEE 39-bus system by performing (N-1) contingency for different load conditions.

Key-Words: - Classification, load flow, Newton-Raphson, (N-1) contingency, performance index, steady state security assessment.

1 Introduction

The secure power system operation is considered as an important challenge for electricity supply industry. Thus, the need for assessing the security of the system is increasingly insistent [1, 2]. The aim of security analysis is to have information about the state of the system in the event of an unscheduled contingency; therefore, control actions for keeping the system in secure operating limits can be taken immediately [3].

As a type of system security, steady state security assessment (SSA) is concerned with the screening of the steady state performance of the system after being subjected to a contingency, in terms of violation of any operating constraints as voltage limits [4]. The main function of the SSA is the analysis of the contingency which includes the definition, selection and ranking of the insecure contingencies according to their severity [5]. In the literature, various on-line ranking methods based on the estimation of the performance index (PI), have been put forward to measure the degree of severity of each contingency. However, the on-line application of these methods requires large computational time in addition to the high cost [6]. Wherefore, the offline method still has a great importance in power system security assessment.

Several works have been performed to tackle the issue of contingency assessing and ranking [6-8]. The authors in [9] evoked the issue of dynamic security assessment (DSA). They proposed an offline method based on numerical simulations analyses to compute two different severity indices. (N-1) contingency is performed on the IEEE 57-bus system to test the proposed method. A Newton-Raphson load flow method is proposed in [10] to rank line outage. Using a 5-bus test system, voltage performance and active power indices are computed for all the possible contingencies. This approach is also used in [11] for classifying line outage cases for two different test system. S. Gongada et al. [12] presented a fast decoupled load flow approach to measure the active power index and the voltage performance index. The sum of the two indices is used to order line contingencies based on their severity. Reference [13] deals with the analysis of the transient stability of the IEEE 14-bus system. The identification of the state of the system and the ranking of the contingencies are carried out by applying a heuristic method.

This paper deals with the static security assessment of power system. The proposed method is based on Newton-Raphson load flow to compute the voltage performance index. By performing (N-1) contingency on the test system IEEE 39-bus system, the PI index is tested for the classification of the voltage security level and the ranking of the contingencies in the decreased order of severity.

The remainder of the paper is organized as follow: section 2 presents the detailed methodology and the formulation of the PI. Section 3 details the Newton-Raphson load flow method. The case study and the simulations results are given in section 4. Finally, we summarize the main points of this paper in the conclusion.

2 Methodology

We propose an offline method to rank all the probable contingencies to identify those that may lead to insecure state. The approach is based on the resolution of the non-linear load flow equations to obtain the post-contingency buses voltages. These values are used for computing the performance index PI. A considerable number of operating conditions is generated by modifying the total load of the power system in large range and for each load pattern; a three-phase short circuit is applied at each transmission line using AC load flow. The contingencies are ranked in the decreased order of severity i.e., higher the PI severe is the contingency.

Table 1 shows the different classes of the contingencies corresponding to the PI range. When the PI value is below 0.2, the system is said in a secure state and the contingencies are the least severe. The second class corresponds to the insecure state where the PI value is above 0.8 and the contingencies are the most severe. While if 0.2 <PI<0.8, the state of the system is deemed critical [14].

Table 1
Classes of Voltage Performance Index

Class	Secure	Insecure	Critical
PI range	< 0.2	> 0.8	0.2 < PI< 0.8

2.1 The index of voltage performance

In this paper the performance index (PI), represented by equation (1), is used to classify the voltage security condition and to rank the contingencies from a well-defined list. Only the voltage violated buses are considered in the computation of the PI.

$$PI = \sum_{i \in S} \left(\frac{w_i}{M}\right)(f_i)^M \tag{1}$$

f_i is a function defined as follows:

$$f_i = \begin{cases} V_i - V_i^{\max}, \text{ for } V_i > V_i^{\max} \\ V_i^{\min} - V_i, \text{ for } V_i < V_i^{\min} \end{cases}$$

Where:

i : the number of the bus which belongs to the set of the violated buses only.

V_i : the post-contingency voltage at the ith bus.

$V_i^{\max}$: the upper limit of the voltage at the ith bus.

$V_i^{\min}$: the lower limit of the voltage at the ith bus.

M and w_i are the order of the exponent and the weighing coefficient respectively. We started the PI computation by arbitrary using w_i =1 and M=4. Taking into account that 0<PI<1, it was observed after repeated simulations, that the appropriate values of w_i and M to obtain reasonable results are: w_i =1 and M=6. Table 2 summarizes the main results of the simulations in the base case (no load increase).

Table 2
Index PI Value in Function of M

Transmission line	PI M=4	M=5	M=6
3-18	1.1093	0.6186	0.3778
16-19	1.4121	0.8446	0.5506
16-21	1.0095	0.5930	0.3818
16-24	1.4121	0.8446	0.5506
8-7	1.8374	1.2781	0.9465
18-17	1.3643	0.8079	0.5203
9-8	1.7909	1.2465	0.9225

2.2 Voltage contingency ranking

The following steps summarize the proposed method for voltage security ranking:

- Generate various operating conditions by perturbing the load of all the buses in wide range;
- For each case of load increase, perform (N-1) contingency for all the transmission lines by AC load flow;
- Compute the voltage PIs using equation (1) for all the contingencies;
- The contingencies having PI value <0.2 are not considered to be ranked;
- Rank the selected contingencies in the decreased order of severity.

3 Newton-Raphson Method

The Newton-Raphson method is the most used iterative algorithm for solving load flow problem. Based on Taylor's series, it approximates non-linear equations to linear equations. To express the process of the NR method, an n-bus system with bus 1 as a slack bus is considered [15-17].

The incoming current to a given bus i of a power system can be written as follows:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad \text{for } i = 1, 2, ..., n \tag{2}$$

Where:

I_i : the injected current at bus i ;

Y_{ij} : an element of the admittance matrix;

V_j : the injected voltage at bus j;

n: number of the buses in the system.

In polar form, the equation (2) can be expressed as follows:

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_i| \angle \theta_{ij} + \delta_j \tag{3}$$

Where:

θ_{ij} : the difference between voltage phase angles of buses i and j;

δ_j : voltage angle at bus j.

The complex power delivered to the bus i is given by equation (4):

$$P_i - jQ_i = V_i^* I_i \tag{4}$$

Where:

P_i : the injected active power at bus i;

Q_i : the injected reactive power at bus i;

V_i : the injected voltage at bus i.

By substituting the expression of I_i in equation (4), we obtain:

$$P_i - jQ_i = |V_i| \angle -\delta_i \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j \tag{5}$$

From equation (5), the real and reactive powers are given by:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{6}$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{7}$$

Equations (6) and (7) represent the nonlinear algebraic equations which depend upon the voltage $|V|$ and the phase angle δ . By expanding these two equations in Taylor's series concerning the initial estimate, we obtain the set of linear equations (8).

From equation (8), the Jacobian matrix presents a linearized relationship between on the one hand, the small changes in voltage magnitude $\Delta|V_i^{(k)}|$ and in voltage angle $\Delta\delta_i^{(k)}$ and on the other hand, the small changes in real and reactive power $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$. The Jacobian matrix elements, except for those of the slack bus which are known, are the partial derivatives of real and reactive power equations. In the matrix form, the equation (8) can be expressed as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{9}$$

The terms $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are called power residuals, they represent the difference between the calculated and the scheduled values and are expressed by equations (10) and (11).

$$\Delta P_i^{(k)} = P_i^{(sched)} - P_i^{(k)} \tag{10}$$

$$\Delta Q_i^{(k)} = Q_i^{(sched)} - Q_i^{(k)} \tag{11}$$

Where:

$P_i^{(sched)}$ and $Q_i^{(sched)}$: scheduled active and reactive power at bus i.

The estimates of the voltages and the phase angles are therefore written as follows:

$$|V_i^{(k+1)}| = |V_i^{(k)}| + \Delta|V_i^{(k)}| \tag{12}$$

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{13}$$

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2^k} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n^k} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2^k} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n^k} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ \frac{\partial Q_2^{(k)}}{\partial \delta_2^k} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n^k} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2^k} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n^k} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \begin{bmatrix} \Delta\delta_2^{(k)} \\ \vdots \\ \Delta\delta_n^{(k)} \\ \hline \Delta|V_2^{(k)}| \\ \vdots \\ \Delta|V_n^{(k)}| \end{bmatrix} \tag{8}$$

4 Case Study and Results

The proposed approach is tested for voltage contingency classification and ranking of IEEE 39-bus New England system [18]. This test system consists of 46 transmission lines, 12 transformers, 19 loads and it has 10 generators. 230 simulation cases were generated corresponding to 5 operating conditions: base case, 10%, 30%, 50% and 70% of load increase. A three-phase short circuit is considered as the contingency and is applied for each load pattern, at all the transmission lines with the following characteristics: fault resistance r_f = 0.01Ω and fault duration t= 100ms. In each case, the severity of the contingency is evaluated by computing the PI.

The test results of only some scenarios are shown in Tables 3 and 4, because of the limited space. Table 3 presents the classification of the contingencies in secure, insecure and critical classes. During the different load patterns, the PI value in case of a fault at line 1-39 is under 0.2, so the state of the system is classified as secure. However, a short-circuit at line 8-7 leads to insecure state. In other cases, for example line 14-15, the contingency is critical during the base case and 10% of load increase, but it belongs to insecure class under heavy load conditions.

The ranking phase considers only the contingencies belonging to insecure and critical classes. Thus, after assessing the PI value of all the 46 contingencies, it was found that the system operates in a secure manner for the following contingencies: line 1-39, line 9-39, line 11-12, line 26-29, line 13-12 and line 25-26. Therefore, these fault cases are filtered out from the list of credible contingencies i.e. are not considered to be ranked.

Table 4 shows the first ten most severe contingencies. The transmission lines 8-5, 8-7 and 9-8 gave the highest PI values and hence are deemed the most critical lines in the test system. However, lines 11-10, 16-24, 15-16 and 10-13 gave the least performance severity levels.

From the simulation results for all the load patterns, it is found that the proposed method is able to classify all the contingencies in three classes and to rank them according to their severities. However, a short-circuit at line 8-7 leads to insecure state. In other cases, for example line 14-15, the contingency is critical during the base case and 10% of load increase, but it belongs to insecure class under heavy load conditions.

Table 3
Contingency Classification for 5 Operating Conditions

Base case			10%			30%			50%			70%		
Line	PI	State	Line	PI	State	Line	PI	State	Line	PI	State	Line	PI	State
1-39	0.1225	S	1-39	0.1225	S	1-39	0.1225	S	1-39	0.1226	S	1-39	0.1226	S
9-39	0.1227	S	9-39	0.1229	S	9-39	0.1229	S	9-39	0.1233	S	9-39	0.1259	S
2-1	0.2445	C	2-1	0.2807	C	2-1	0.3038	C	2-1	0.3523	C	2-1	0.3728	C
14-15	0.6344	C	14-15	0.7013	C	14-15	0.8063	I	14-15	0.9270	I	14-15	0.9883	I
11-12	0.1227	S	11-12	0.1233	S	11-12	0.1442	S	11-12	0.1585	S	11-12	0.1694	S
25-37	0.2410	C	25-37	0.2565	C	25-37	0.2785	C	25-37	0.2934	C	25-37	0.3045	C
16-19	0.5506	C	16-19	0.5796	C	16-19	0.6357	C	16-19	0.6660	C	16-19	0.6949	C
3-2	0.4004	C	3-2	0.4093	C	3-2	0.4545	C	3-2	0.4799	C	3-2	0.4962	C
26-29	0.1741	S	26-29	0.1800	S	26-29	0.1834	S	26-29	0.1947	S	26-29	0.1951	S
13-12	0.1227	S	13-12	0.1233	S	13-12	0.1442	S	13-12	0.1585	S	13-12	0.1694	S
25-26	0.1741	S	25-26	0.1799	S	25-26	0.1834	S	25-26	0.1945	S	25-26	0.1951	S
6-5	0.9037	I	6-5	0.9206	I	6-5	0.9283	I	6-5	0.9079	I	6-5	0.8582	I
18-17	0.5203	C	18-17	0.5429	C	18-17	0.5880	C	18-17	0.6058	C	18-17	0.6261	C
7-6	0.8597	I	7-6	0.8878	I	7-6	0.8965	I	7-6	0.8594	I	7-6	0.8083	I
8-7	0.9465	I	8-7	0.8706	I	8-7	0.9502	I	8-7	0.9760	I	8-7	0.9365	I

S: Secure; C: Critical; I: Insecure

Table 4
Contingency Ranking for 5 Operating Conditions

Base case			10%			30%			50%			70%		
Rank	Line	PI	Rank	Line	PI	Rank	Line	PI	Rank	Line	PI	Rank	Line	PI
1	8-5	0.9467	1	6-5	0.9206	1	8-5 8-7 9-8	0.9502	1	9-8	0.9997	1	14-15	0.9883
2	8-7	0.9465	2	6-31 7-6	0.8878	2	6-5	0.9283	2	8-7	0.9760	2	8-5 8-7 9-8	0.9365
3	9-8	0.9225	3	9-8 8-5 8-7	0.8706	3	7-6 6-31	0.8965	3	8-5	0.9599	3	6-5	0.8582
4	6-5	0.9037	4	5-4	0.7347	4	14-15	0.8063	4	14-15	0.9270	4	6-31 7-6	0.8083
5	6-31 7-6	0.8597	5	4-14	0.7303	5	4-14 13-14	0.7844	5	6-5	0.9079	5	5-4	0.7727
6	5-4	0.7299	6	13-14	0.7017	6	5-4	0.7441	6	7-6 6-31	0.8594	6	13-14	0.7012
7	13-14 4-14	0.6928	7	14-15	0.7013	7	6-11	0.6788	7	13-14 4-14	0.8128	7	4-14	0.7004
8	14-15	0.6344	8	11-10	0.6396	8	11-10	0.6759	8	5-4	0.7118	8	15-16 16-19 16-24	0.6949
9	6-11	0.5991	9	6-11	0.6318	9	15-16 16-19 16-24	0.6357	9	15-16 16-19 16-24	0.6660	9	16-17	0.6264
10	11-10	0.5934	10	16-24 15-16	0.5805	10	10-13	0.6008	10	11-10	0.6571	10	18-17	0.6261

4 Conclusion

This paper has presented an offline method to rank selected contingencies in the decreased order of severity, in accurate manner. The approach is based on the computation of the voltage performance index PI using Newton-Raphson load flow method. The highest values of the index correspond to the most severe contingencies which lead to the violation of voltage limits. During the different load conditions, the ranking of the contingencies are the same, however, there are some misranking due to the fact that the PI values are so close and the variation degree is not always the same. Further works will introduce others methods for comparison purpose.

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