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Static Security Analysis based on Vulnerability Index (VI) and Network Contribution Factor (NCF) Method

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***Abstract*--This paper introduces a new approach of power system static security analysis based on the Vulnerability Index (*VI*) and Network Contribution Factor (NCF) method. Vulnerability Index method provides quantitative vulnerability information about generation, transmission, load condition, and the whole system. NCF method gives fast approximate power flow results due to parameter change (contingency) based on the base load flow condition and network information. The contingency list can be chosen based on NCF method and VI evaluation. Comparison with the full AC power flow method shows that this approach is promising for fast and accurate static security analysis.**

***Index Terms*—Power System Security, Contingency Analysis, Vulnerability Index, Performance Index, Static Security Analysis**

I. Introduction

Power system security analysis, including both static and dynamic, is very important for assuring reliable power system operation. Contingency analysis is a critical part of the power system static security analysis for steady state operation. In general, there are two types of contingency analysis methods: a) contingency ranking method based on Performance Index (PI) [1-2] and b) contingency screening method based on a fast and approximate network solution [3-4]. A hybrid method covering the two was also proposed to achieve both the speed and accuracy goals [5]. There are other approaches, such as pattern recognition, neural network, genetic algorithm, etc [6~7]. For the final selected contingency list, the full AC power flow is run to check whether there are security constraints violations or not. Normally, branch overload and bus voltage limit violation are the major concern. Such conditions can be modeled in the Performance Index (PI) method to give the numerical values to represent the system severity information. However, current power system operation is becoming more and more complex due to deregulation and imposing stress on the aging power system infrastructure. Overload and low/high voltage concerns are not enough to represent the power system security analysis. Loadability, transferability, relay problems(i.e., hidden failure), and other similar events, also need to be considered.

This paper proposes the Vulnerability Index (*VI*) method to give comprehensive vulnerability information about individual power system component and the whole power system conditions. It considers vulnerability in three parts: generators, buses and transmission lines. For the generator part, real and reactive power outputs and generation loss due to outage are considered. For the bus part, bus voltage, loadability and load loss are modeled. For the transmission line part, vulnerability indices of transmission line real power, reactive power, line charging, line bus voltage angle difference, line distance relay performance and line-switching influence will be given. Different weights of various elements will be considered comprehensively based on their importance and power system operating practices.

Network Contribution Factor (NCF) method has been proposed to help relieve the overload and low voltage problems [8]. It finds the most contributing parameter which can relieve the line overload or improve the bus voltage by using the base flow condition and network information. Line on/off switching, line parameter change due to TCSC insertion, and bus shunt capacitor/reactor on/off switching, can all be considered. Not only single parameter but also multi-parameter analysis and control can be achieved. Final results are verified by the full AC load flow. NCF method is demonstrated to be fast and accurate.

This paper introduces a new approach for power system static security analysis based on Vulnerability Index (*VI*) and Network Contribution Factor (NCF) method. In Section II, the Vulnerability Index equations and descriptions are provided. In Section III, Network Contribution Factor (NCF) method for single and multiple parameter analysis is outlined. Numerical test results are presented in Section IV. Conclusion and references are given in Section V and VI respectively.

II. Vulnerability Index

Vulnerability Index (*VI*) is a good way to assess the vulnerability of individual element and the whole system. Given a system with m generators, n buses, p lines and q loads, we define the comprehensive Vulnerability Index (*VI*) sets as follows:

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A. Vulnerability Index for generators

$$VI_{Pg,i} = \frac{W_{Pg,i}}{2N}\left(\frac{Pg_i}{Pg_{i,\max}}\right)^{2N} \quad (1)$$

$$VI_{Qg,i} = \frac{W_{Qg,i}}{2N}\left(\frac{Qg_i}{Qg_{i,\max}}\right)^{2N} \quad (2)$$

$$VI_{gen\_loss,i} = W_{gen\_loss,i} k_i \quad (3)$$

$$VI_{gen} = \sum_{i=1}^{m} (VI_{Pg,i} + VI_{Qg,i} + VI_{gen\_loss,i}) \quad (4)$$

where,

$VI_{Pg,i}$: VI of individual generator real power output

$VI_{Qg,i}$: VI of individual generator reactive power output

$VI_{gen\_loss,i}$: VI of individual generator loss

VI_{gen} : total VI of all generators

$W_{Pg,i}$: weight of individual generator real power output

$W_{Qg,i}$:weight of individual generator reactive power output

$W_{gen\_loss,i}$: weight of individual generator loss influence

Pg_i , Qg_i : individual generator real, reactive power output

$Pg_{i,\max}$: maximum real power output of generator

$Qg_{i,\max}$: maximum reactive power output of generator when Qg_i is positive; minimum reactive power output of generator when Qg_i is negative

k_i : 1 when generator is off, 0 when generator is on

N: 1 in general

Different weights are chosen based on the system operating practice. For example, large capacity generators and important reactive power supply generators in the load area can be assigned larger values of $W_{gen\_loss,i}$.

B. Vulnerability Index for buses

$$VI_{V,i} = \frac{W_{V,i}}{2N}\left(\frac{V_i - V_i^{sche}}{\Delta V_{i,\lim}}\right)^{2N} \quad (5)$$

$$VI_{Loadab,i} = \frac{W_{Loadab,i}}{2N}(r_{Loadab,i})^{2N} \quad (6)$$

$$VI_{load\_loss,i} = W_{load\_loss,i} r_i \quad (7)$$

$$VI_{bus} = \sum_{i=1}^{n} (VI_{V,i} + VI_{Loadab,i} + VI_{load\_loss,i}) \quad (8)$$

where,

$VI_{V,i}$: VI of individual bus voltage magnitude

$VI_{Loadab,i}$: VI of individual load bus loadbility

$VI_{load\_loss,i}$: VI of individual load bus load loss

VI_{bus} : total VI of all buses

$W_{V,i}$: weight of individual bus voltage influence

$W_{Loadab,i}$: weight of individual bus loadability

$W_{load\_loss,i}$: weight of individual bus load loss influence

$r_{Loadab,i}$: bus loadability

$$r_{Loadab,i} = \frac{Z_{th,i}}{Z_{L0,i}}$$

$Z_{th,i}$: Thevenin equivalent system impedance

$Z_{L0,i}$: equivalent load impedance at steady state

V_i : bus voltage magnitude

V_i^{sche} : scheduled bus voltage magnitude

$\Delta V_{i,\lim}$: voltage variance limit

r_i : load loss ratio, 0~1, 0: no loss; 1: completely loss

N: 1 in general

In this method, loadability is considered by using Thevenin equivalent impedance method [9]. There are other loadability analysis methods which the user can also choose based on their own decision [10].

C. Vulnerability Index for branches

$$VI_{Pf,i} = \frac{W_{Pf,i}}{2N}\left(\frac{Pf_i}{S_{i,\max}}\right)^{2N} \quad (9)$$

$$VI_{Qf,i} = \frac{W_{Qf,i}}{2N}\left(\frac{Qf_i}{S_{i,\max}}\right)^{2N} \quad (10)$$

$$VI_{Qc,i} = \frac{W_{Qc,i}}{2N}\left(\frac{Qc_i}{Q_\Sigma}\right)^{2N} \quad (11)$$

$$VI_{line\_ang,i} = \frac{W_{line\_ang,i}}{2N}\left(\frac{La_i}{La_{i,\max}}\right)^{2N} \quad (12)$$

$$VI_{\mathrm{Re}lay,i} = \frac{W_{\mathrm{Re}lay,i}}{2N}((1/d_{sr,i})^{2N} + (1/d_{rs,i})^{2N}) \quad (13)$$

$$VI_{line\_off,i} = W_{line\_off,i} k_i \quad (14)$$

$$VI_{line} = \sum_{i=1}^{p} (VI_{Pf,i} + VI_{Qf,i} + VI_{Qc,i} + VI_{line\_ang,i} + VI_{\mathrm{Re}lay,i} + VI_{line\_off,i}) \quad (15)$$

where,

$VI_{Pf,i}$: VI of individual line real power

$VI_{Qf,i}$: VI of individual line reactive power

$VI_{Qc,i}$: VI of individual line charging

$VI_{line\_ang,i}$: VI of individual bus voltage angle difference at each line

$VI_{\mathrm{Re}lay,i}$: VI of individual line distance relay

$VI_{line\_off,i}$: VI of individual line outage influence

VI_{line} : total VI of all lines

$W_{Pf,i}$: weight of individual line real power influence

$W_{Qf,i}$: weight of individual line reactive power influence

$W_{Qc,i}$: weight of individual line charging influence

$W_{line\_ang,i}$: weight of individual line bus angle difference

$W_{Relay,i}$: weight of individual line distance relay

$W_{line\_off,i}$: weight of individual line off influence

Pf_i , Qf_i : individual line real and reactive power

$S_{i,\max}$: individual line transmission limit, which can be either thermal limit or transfer limit due to security constraints

Qc_i : individual line charging

Q_Σ : total reactive power output of all generators, or total reactive power of the whole system

La_i : individual bus voltage angle difference at each line

$La_{i,\max}$: bus voltage angle difference limit at each line

$d_{sr,i}$: normalized apparent impedance seen by distance relay looking from the sending end to the receiving end of that line

$d_{rs,i}$: normalized apparent impedance seen by distance relay looking from the receiving end to the sending end of that line

k_i : 1 when line is off, 0 when line is on

In this model, the line charging influence is considered. Some lightly loaded lines and lines with high charging capacitance may contribute significantly to the reactive power supply and voltage support. Their outages may decrease the reactive power supply and increase the need for generators to generate more reactive power.

The bus voltage angle difference at each line is also an important signal which was ignored in previous studies. From the simplest lossless series line model (without charging capacitance), we know that larger bus voltage angle difference means larger power transfer through that line and smaller normalized apparent impedance seen by the line distance relay. Therefore, the line distance relay may misoperate during the overload and low voltage conditions.

For the apparent impedance seen by the transmission line distance relay, if we use the short line model, we can find that the normalized apparent impedance is only associated with the bus voltages along the line.

$$Z_{d,ij} = \frac{V_i}{I_{ij}} = \frac{V_i}{(V_i - V_j)/Z_{ij}} \quad (16)$$

$$\overline{Z}_{d,ij} = \frac{Z_{d,ij}}{Z_{ij}} = \frac{V_i}{V_i - V_j} = \frac{|V_i|}{|V_i - V_j|} \angle\theta_{d,ij} \quad (17)$$

For the more accurate Π line model, we can use accurate parameters to calculate the normalized apparent impedance. The smaller the normalized apparent impedance seen by distance relay at no fault condition, the more possible case that it may fall into the distance relay backup zone (zone 3 or zone 2 taken as backup).

The aggregate system Vulnerability Index (*VI*) can be presented by

$$VI = W_{gen}VI_{gen} + W_{bus}VI_{bus} + W_{line}VI_{line} \quad (18)$$

This leads to the following conclusion: the larger the *VI* value, the more vulnerable the system condition.

From different *VI* values for various system conditions, we can know more about the whole system security level as well as the performance of individual system elements.

III. NETWORK CONTRIBUTION FACTOR (NCF) METHOD

The NCF method was first proposed in [8]. Now we revisit and expand it for multi-parameter variance analysis.

A. Line parameter variance

Given an n-bus-l-branch system, A is the node-branch incidence matrix, Y_p is the primitive branch admittance matrix, Y_{bs} is the node shunt capacitance matrix,

$$Y_p = diag[y_1 \quad \ldots \quad y_l] \quad (19)$$

$$Y_{bs} = diag[y_{s1} \quad \ldots \quad y_{sn}] \quad (20)$$

$$A_{ij} = \begin{cases} 1 & \text{i is the sending node of branch j} \\ -1 & \text{i is the receiving node of branch j} \\ 0 & else \end{cases} \quad (21)$$

From the fast decouple power flow (FDPF), we know the approximate real power equation,

$$\frac{P}{E} = B'\theta \quad (22)$$

where, P, E, θ are the node real power injection, magnitude and angle of the bus voltage respectively. Assign

$$Y_1 = -imag(Y_p) \quad (23)$$

Approximate line real power flow,

$$P_{line} \cong Y_1 A^T (E\theta) \quad (24)$$

Node real power injection,

$$P_{node} \cong AP_{line}$$

Bus voltage angle variance due to line parameter variance,

$$\Delta\theta = -(A(Y_1 + \Delta Y_1)A^T)^{-1}(A\Delta Y_1 A^T)\theta \quad (25)$$

Rewrite as

$$\Delta\theta = -X_1(A\Delta Y_1 A^T)\theta \quad (26)$$

where

$$X_1 = (A(Y_1 + \Delta Y_1)A^T)^{-1} \quad (27)$$

for single parameter variance,

$$\Delta Y_1 = diag[0 \quad .. \quad \Delta y_i \quad .. \quad 0]$$

for multi-parameter variance, here only assume at line i and j, more variances are similar,

$$\Delta Y_1 = diag[0 \quad .. \quad \Delta y_i \quad .. \quad \Delta y_j \quad .. \quad 0]$$

Line real power flow variance,

$$\Delta P_{line} = \Delta Y_1 A^T (E\theta) + (Y_1 + \Delta Y_1)A^T (E\Delta\theta) \quad (28)$$

For single line i parameter variance,

(a) For the line k, $k \neq i$, real power flow change,

$$\Delta P_{line-k} = -[A_{1k} \quad \ldots \quad A_{nk}]X_1 K_i (y_k \Delta y_i) \quad (29)$$

where

$$K_i = [A_{1i} \quad .. \quad A_{ii} \quad .. \quad A_{ni}]^T \sum_{j=1}^{n} A_{ji} E_j \theta_j \quad (30)$$

(b) For the line i real power flow change,

$$\Delta P_{line-i} = (\sum_{j=1}^{n} A_{ji} E_j \theta_j / y_i' - [A_{1i} \quad \ldots \quad A_{ni}]X_1 K_i)(y_i' \Delta y_i) \quad (31)$$

For single line outage, simply assign

$$\Delta P_{line-i} = -P_{line-i} \tag{32}$$

For multi-parameter variance, assume line i, j for simple example,

(a) For line k, $k \neq i, j$, real power flow change,

$$\Delta P_{line-k} = -[A_{1k} \quad ... \quad A_{nk}]X_1(K_i\Delta y_i + K_j\Delta y_j)y_k \tag{33}$$

where

$$K_i = [A_{1i} \quad .. \quad A_{ii} \quad .. \quad A_{ni}]^T \sum_{l=1}^{n} A_{li}E_l\theta_l \tag{34}$$

$$K_j = [A_{1j} \quad .. \quad A_{jj} \quad .. \quad A_{nj}]^T \sum_{l=1}^{n} A_{lj}E_l\theta_l \tag{35}$$

(b) For the line i, j real power flow change,

$$\Delta P_{line-i} = \sum_{l=1}^{n} A_{li}E_l\theta_l(\Delta y_i) - [A_{1i} \quad ... \quad A_{ni}]X_1(K_i\Delta y_i + K_j\Delta y_j)y_i \tag{36}$$

$$\Delta P_{line-j} = \sum_{l=1}^{n} A_{lj}E_l\theta_l(\Delta y_j) - [A_{1j} \quad ... \quad A_{nj}]X_1(K_i\Delta y_i + K_j\Delta y_j)y_j \tag{37}$$

for lines i, j outages, simply assign

$$\Delta P_{line-i} = -P_{line-i} \tag{38}$$

$$\Delta P_{line-j} = -P_{line-j} \tag{39}$$

B. Bus parameter variance

By the fast decoupled power flow (FDPF),

$$\frac{\Delta Q}{E} = B^{"}\Delta E \tag{40}$$

$$\Delta E = (B^{"})^{-1}\frac{\Delta Q}{E} = X_2\Delta B_s E \tag{41}$$

where

$$X_2 = (B^{"})^{-1} \tag{42}$$

$$\Delta Q = \Delta B_s E^2 \tag{43}$$

for single bus parameter variance at bus i,

$$\Delta B_s = [0 \quad .. \quad \Delta y_{bs,i} \quad .. \quad 0]^T$$

bus k voltage variance,

$$\Delta E_k = X_{2,ki}E_k\Delta y_{bs,i} \tag{44}$$

for bus multi-parameter variance at bus i, j

$$\Delta B_s = [0 \quad .. \quad \Delta y_{bs,i} \quad .. \quad \Delta y_{bs,j} \quad .. \quad 0]^T$$

bus k voltage variance,

$$\Delta E_k = X_{2,ki}E_k\Delta y_{bs,i} + X_{2,kj}E_k\Delta y_{bs,j} \tag{45}$$

C. FNCF and VNCF

For single line i parameter variance,

$$\Delta P_{f,k} = N_{f,k}y_k\Delta y_i \tag{46}$$

Flow Network Contribution Factor (FNCF), for line k, $k \neq i$

$$N_{f,k} = -[A_{1k} \quad ... \quad A_{nk}]X_1K_i \tag{47}$$

for line k, $k = i$

$$N_{f,k} = \sum_{j=1}^{n} A_{ji}E_j\theta_j / y_i - [A_{1i} \quad ... \quad A_{ni}]X_1K_i \tag{48}$$

For single bus i parameter variance,

$$\Delta E_k = N_{v,ki}E_k\Delta y_{bs,i} \tag{49}$$

Voltage Network Contribution Factor (VNCF), for bus k,

$$N_{v,ki} = X_{2,ki} \tag{50}$$

where

K_i, X_1, X_2 in (30),(27),(42).

for fast approximation, we can use base network matrix

$$X_1 = (AY_1A^T)^{-1} \tag{51}$$

For multi-parameter variance, here only take 2 parameters variance as simple example,

For line i, j parameter variance,

$$\Delta P_{f,k} = N_{f,k}y_k(\Delta y_i + \frac{K_j}{K_i}\Delta y_j) \tag{52}$$

For bus i, j parameter variance,

$$\Delta E_k = N_{v,ki}E_k\Delta y_{bs,i} + N_{v,kj}E_k\Delta y_{bs,j} \tag{53}$$

IV. Numerical Results

We use the IEEE One Area RTS-96 24-bus system as the study system [11]. Fig. 1 gives the system configuration. Table I gives the base flow condition.

For the contingency analysis, the contingencies can be classified into three groups: contingency causing nonlinearity (Class A), contingency causing discontinuity (Class B), and others (Class C) [5]. For the Class A and Class B contingencies, full AC power flow needs to be run to get the accurate results. In this paper, we only compare the results of NCF method with those of full AC power flow method for Class C contingency analysis.

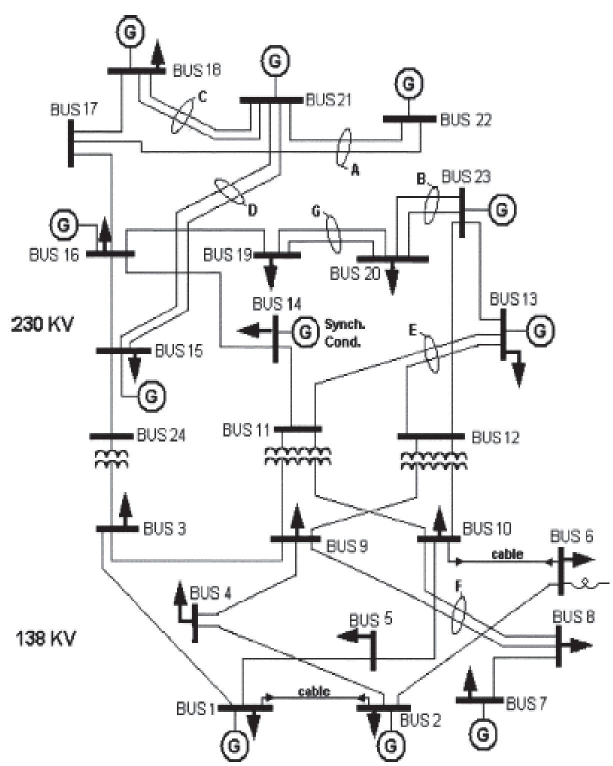

Fig. 1. IEEE One Area RTS-96 system

TABLE I
BASE FLOW CONDITION (PD, QD, BS, PG: MVA; V: P.U.)

Bus	Pd	Qd	Bs	Pg	V
1	108.00	22.00	0.	172.00	1.035
2	97.00	20.00	0.	172.00	1.035
3	180.00	37.00	0.	0.00	0.983
4	74.00	15.00	0.	0.00	0.997
5	71.00	14.00	0.	0.00	1.017
6	136.00	28.00	-100.	0.00	1.010
7	125.00	25.00	0.	240.00	1.025
8	171.00	35.00	0.	0.00	0.992
9	175.00	36.00	0.	0.00	1.000
10	195.00	40.00	0.	0.00	1.025
11	0.00	0.00	0.	0.00	0.991
12	0.00	0.00	0.	0.00	1.002
13	265.00	54.00	0.	187.44	1.020
14	194.00	39.00	0.	0.00	0.980
15	317.00	64.00	0.	215.00	1.014
16	100.00	20.00	0.	155.00	1.002
17	0.00	0.00	0.	0.00	1.033
18	333.00	68.00	0.	400.00	1.050
19	181.00	37.00	19.	0.00	1.014
20	128.00	26.00	0.	0.00	1.035
21	0.00	0.00	0.	400.00	1.050
22	0.00	0.00	0.	300.00	1.050
23	0.00	0.00	0.	660.00	1.050
24	0.00	0.00	0.	0.00	0.979

For the Vulnerability Index calculation, we just assign all weights as 1, line power transfer limits as 3.0 p.u., the line bus voltage angle difference limits as 40 degrees, PQ bus voltage magnitude limits as 1.0 p.u.. Then we sum all individual Vulnerability Index values of generators, buses and lines and get the separate summary of Vulnerability Index values.

A. Vulnerability Analysis for N-1 contingency analysis

We list the top 10 most vulnerable line outages selected by the NCF method and full AC power flow method. Tables II and III show the summary vulnerability index (*VI*) values obtained by the NCF method. Column 1 in all tables represent outage lines. '10' is the line number and 'B6-10' represents from Bus 6 to Bus 10. Columns 2-6 of Table II represent summary vulnerability index values of the total, at the buses and generators. Vulnerability index values of load loss at buses and vulnerability index values of generation loss at generators are not listed because they are all zeros. Columns 2-7 of Table III represent summary vulnerability index values at the transmission lines. Tables IV and V show the summary vulnerability index (*VI*) values obtained by the full AC power flow method. The meanings of each column are similar as in Tables II and III.

TABLE II
VULNERABILITY INDEX VALUES OF TOTAL, BUS PART AND GENERATOR PART DUE TO LINE OUTAGES OBTAINED BY NCF METHOD

Line Outage	Total	V	load_ ability	Pg	Qg
10(B6-10)	14.906	0.399	0.597	2.898	1.674
22(B13-23)	14.791	0.399	0.481	2.898	1.674
7(B3-24)	14.587	0.461	0.481	2.898	1.690
26(B15-21)	13.698	0.397	0.485	2.898	1.685
27(B15-24)	13.265	0.395	0.453	2.898	1.700
20(B12-13)	13.073	0.399	0.478	2.898	1.674
21(B12-23)	13.068	0.395	0.774	2.898	1.679
28(B16-17)	12.898	0.399	0.450	2.898	1.674
25(B15-21)	12.898	0.399	0.450	2.898	1.674
24(B15-16)	12.791	0.393	0.446	2.898	1.689

TABLE III
VULNERABILITY INDEX VALUES OF LINE PART DUE TO LINE OUTAGES OBTAINED BY NCF METHOD

Line Outage	Pl	Ql	Qc	line_ ang	relay	line_ off
10(B6-10)	6.640	0.494	0.090	0.554	0.558	1.0
22(B13-23)	6.737	0.500	0.090	0.501	0.508	1.0
7(B3-24)	6.546	0.477	0.089	0.467	0.475	1.0
26(B15-21)	5.950	0.423	0.089	0.379	0.389	1.0
27(B15-24)	5.425	0.490	0.087	0.403	0.411	1.0
20(B12-13)	5.204	0.494	0.090	0.413	0.421	1.0
21(B12-23)	5.021	0.488	0.090	0.355	0.366	1.0
28(B16-17)	5.207	0.470	0.090	0.349	0.359	1.0
25(B15-21)	5.207	0.470	0.090	0.349	0.359	1.0
24(B15-16)	5.062	0.505	0.086	0.349	0.360	1.0

TABLE IV
VULNERABILITY INDEX VALUES OF TOTAL, BUS PART AND GENERATOR PART DUE TO LINE OUTAGES OBTAINED BY AC POWER FLOW METHOD

Line Outage	Total	V	load_ ability	Pg	Qg
10(B6-10)	16.262	0.669	0.604	2.898	3.235
22(B13-23)	15.405	1.570	0.501	2.898	1.817
26(B15-21)	14.726	0.896	0.502	2.898	1.810
7(B3-24)	13.404	0.550	0.485	2.898	1.823
27(B15-24)	13.396	0.458	0.456	2.898	2.037
20(B12-13)	13.304	0.386	0.449	2.898	2.378
25(B15-21)	13.304	0.386	0.449	2.898	2.378
24(B15-16)	13.112	0.435	0.480	2.898	1.903
21(B12-23)	12.765	0.454	0.558	2.898	2.047
18(B11-13)	12.714	0.570	0.757	2.898	1.479

TABLE V
VULNERABILITY INDEX VALUES OF LINE PART DUE TO LINE OUTAGES OBTAINED BY AC POWER FLOW METHOD

Line Outage	Pl	Ql	Qc	line_ ang	relay	line_ off
10(B6-10)	6.282	0.441	0.045	0.535	0.549	1.0
22(B13-23)	6.246	0.353	0.051	0.471	0.496	1.0
26(B15-21)	6.246	0.353	0.052	0.471	0.496	1.0
7(B3-24)	5.635	0.184	0.070	0.372	0.382	1.0
27(B15-24)	5.358	0.304	0.061	0.406	0.416	1.0
20(B12-13)	5.126	0.281	0.079	0.347	0.357	1.0
25(B15-21)	5.126	0.281	0.079	0.347	0.357	1.0
24(B15-16)	5.152	0.326	0.062	0.420	0.432	1.0
21(B12-23)	4.615	0.339	0.078	0.381	0.393	1.0
18(B11-13)	4.954	0.252	0.079	0.354	0.366	1.0

From Tables II, III, IV and V we can see that the NCF method is very promising for N-1 contingency ranking and evaluation. For the top 10 line outages, 9 of them are ranked both by NCF and power flow methods. Line 18 (Bus 11-13) outage is ranked by power flow method as the 10th vulnerable while it is ranked by NCF method as 13rd. Line 28 (Bus 16-17) outage is ranked by power flow method as the 11st vulnerable while it is ranked by NCF method as 8th.

B. Vulnerability Analysis for N-2 contingency analysis

For the N-2 contingency analysis, the Class A and B contingencies, that is, some combinations of 2 line outages causing the system islanding and nonlinearity, need to be considered and modified in full AC power flow method.

For the simple demonstration, we give the comparison of NCF method and AC power flow method for ranking Class C contingencies.

TABLE VI
COMPARISON OF TOP 10 PAIRS N-2 CONTINGENCY RANKING OBTAINED BY NCF METHOD AND POWER FLOW METHOD

NCF line 1	NCF line 2	PF line 1	PF line 2
7	12	10	24
10	24	7	12
10	28	1	12
10	22	10	22
10	29	10	29
10	30	10	27
10	23	10	26
10	26	10	23
10	18	10	16
10	27	10	15

TABLE VII
COMPARISON OF TOP 11-20 PAIRS N-2 CONTINGENCY RANKING OBTAINED BY NCF METHOD AND POWER FLOW METHOD

NCF line 1	NCF line 2	PF line 1	PF line 2
10	20	10	20
1	12	10	18
10	17	10	17
10	25	10	30
10	16	10	19
8	12	10	32
10	32	8	12
13	14	10	21
10	19	9	12
10	15	2	12

Tables VI and VII give top 10 and top 11-22 most vulnerable N-2 contingency ranking lists obtained by the NCF method and power flow method respectively. From Table I, line outage combinations of lines 10&30, 10&20, and 10&18 are ranked by NCF method while they are not ranked by power flow (PF) method. Line outage combinations of lines 1&12, 10&16, and 10&15 are ranked by PF method while they are not ranked by NCF method. Combined with Table VII for the contingency ranking list of the top 20 most vulnerable N-2 contingencies, line outage combinations of lines 10&28, 10&25, and 13&14 are ranked by NCF method while they are not ranked by PF method. However, they do appear as 24th, 26th and 30th in the PF ranking list. Line outage combinations of lines 10&21, 9&12, and 2&12 are ranked by PF method while they are not ranked by PF method. They appear as 21st to 23rd in the NCF ranking list.

For this IEEE RTS-96 system, the line 10 (from bus 6 to bus10) is a special cable with large capacitance. There is a 100Mvar reactor connected at bus 6 to compensate the capacitance. When the line 10 is switched off, if the reactor is not switched off, there will be some voltage problem. This is the reason why there are so many vulnerable combinations between line 10 and other lines.

From Tables VI and VII, we can see that NCF method gives good approximation for N-2 contingency analysis.

IV. Conclusion

This paper proposes the Vulnerability Index method to give a comprehensive representation of power system vulnerability information. Different security related factors are considered and modeled in Vulnerability Index method. The Network Contribution Factor (NCF) method is used for the fast contingency analysis. Numerical results demonstrate that the proposed methods are very promising. With the aid of these tools, the system operators can clearly learn the system security conditions and have enough confidence to take associated control to operate the system securely and economically.

V. References

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VI. Biographies

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