Static Analysis of Vulnerability and Security Margin of the Power System

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***Abstract*--This paper introduces new concepts for evaluation of the power system steady state operations, namely the Vulnerability Index (*VI*) and Margin Index (*MI*). They provide quantitative vulnerability and security margin information about generation, transmission, load conditions and then the whole system. System operators can assess the system security and vulnerability information using the margin and vulnerability indices. Therefore, they can take some preventive and emergency control steps to keep the system operating at the secure level.**

***Index Terms*—Vulnerability Index, Security Analysis, Contingency Analysis, Power Flow**

I. Introduction

One of the most challenging problems for current power system operators in the highly competitive electricity market and complex, aging and stressed power system infrastructure is that they do not know the system security conditions very precisely. They may operate their system in the insecure state due to system events which are much different from what was predicted in the planning and other off-line studies. When unexpected things happen, the operators lack enough security information and confidence to take timely preventive and emergency control steps to keep the system secure. Several large area blackouts illustrate this clearly. For example, in July 1987 the system operators of TEPCO (Tokyo Electric Power Company) just watched their system voltage decreasing while the load was increasing fast till voltage collapse occurred after they run off their reactive power supply[1]. In August 1996, the BPA operators did not know that their system was insecure after a key transmission line was disconnected following several line outages in the Western Interconnection System[2] [3]. The post-blackout simulations show that if appropriate load shedding had been taken at the load area of Idaho for 30 minutes, the July 1996 large area blackout could have been prevented[2][4]. In August 2003 Northeastern blackout, the First Energy system operators did not know that they would run their system insecurely due to the next contingency. If the load shedding was taken at the Cleveland and Akron Area, the cascading outages could have been mitigated. With more system conditions awareness and associated control means taken, the catastrophic system loss could at least be mitigated if it could not be prevented [5].

Several promising ideas for dealing with system security analysis were proposed [6-9]. However, there is still a need for a technique that will give power system operators more precise information about the system operating conditions. Performance Index (PI) was first proposed to evaluate the line loading and voltage performance for the automatic contingency selection algorithm[6]. It is an important concept and method to evaluate system performance for contingency selection and security analysis. However, PI is not capable of representing the static security information for different system elements and the whole system in the dynamically evolving conditions. Besides the line overload and low/high bus voltage concerns, the loadbility, line distance relay performance, loss of generator and load, line outage, reactive power supply, etc., all need to be considered carefully.

This paper presents a novel and comprehensive concept of Vulnerability Index (*VI*) as well as Margin Index (*MI*) to give precise vulnerability and margin information for individual system element and the whole system performance. At the generator level, vulnerability indices for real power output, reactive power output and generation loss and margin indices for real and reactive power outputs will be considered. At the bus level, vulnerability indices for bus voltage performance, loadability and load loss and margin indices for bus voltage performance and loadability will be presented. Islanding and isolated buses due to the line outages will be considered in the load loss part. At the transmission line level, vulnerability indices for line real power, reactive power, line charging, line bus voltage angle difference, line distance relay performance, and line-off influence will be discussed. Similarly, the margin indices for line flow, line bus voltage angle difference and line distance relay will be analyzed. Different weights of different elements will be considered based on their importance and power system operating practice.

This paper introduces the Vulnerability Index and Margin Index concepts and the numerical results from the IEEE 39-bus New England system. In Section II, the Vulnerability Index and Margin Index equations and descriptions are provided. Numerical test results are presented in Section III. Conclusion and references are given in Section IV and V

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respectively.

II. THE APPROACH

Vulnerability Index (*VI*) and Margin Index (*MI*) are a good way to assess the vulnerability and security margin of the 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:

A. Vulnerability Index and Margin Index for generators

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

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

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

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

$$MI_{Pg,i} = 1 - \frac{Pg_i}{Pg_{i,\max}} \quad (5)$$

$$MI_{Qg,i} = 1 - \frac{Qg_i}{Qg_{i,\max}} \quad (6)$$

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

$MI_{Pg,i}$: *MI* of individual generator real power output

$MI_{Qg,i}$: M*I* of individual generator reactive power output

$W_{Pg,i}$: 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 and Margin Index for buses

$$VI_{V,i} = \frac{W_{V,i}}{2N}\left(\frac{V_i - V_i^{sche}}{\Delta V_{i,\lim}}\right)^{2N} \quad (7)$$

$$VI_{Loadab,i} = \frac{W_{Loadab,i}}{2N}(r_{Loadab,i})^{2N} \quad (8)$$

$$VI_{load\_loss,i} = W_{load\_loss,i} r_i \quad (9)$$

$$VI_{bus} = \sum_{i=1}^{n}(VI_{V,i} + VI_{Loadab,i} + VI_{load\_loss,i}) \quad (10)$$

$$MI_{V,i} = 1 - \left|\frac{V_i - V_i^{sche}}{\Delta V_{i,\lim}}\right| \quad (11)$$

$$MI_{Loadab,i} = 1 - r_{Loadab,i} \quad (12)$$

where,

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

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

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

VI_{bus}: total *VI* of all buses

$MI_{V,i}$: *MI* of individual bus voltage magnitude

positive if bus voltage is within limit; zero or negative if it is at or out of the limit

$MI_{Loadab,i}$: *MI* of individual load bus loadability

$W_{V,i}$: 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[10]. There are other loadability analysis methods [11] which users can also choose based on their own decision.

C. Vulnerability Index and Margin Index for branches

$$VI_{Pf,i} = \frac{W_{Pf,i}}{2N}\left(\frac{Pf_i}{S_{i,\max}}\right)^{2N} \quad (13)$$

$$VI_{Qf,i} = \frac{W_{Qf,i}}{2N}\left(\frac{Qf_i}{S_{i,\max}}\right)^{2N} \quad (14)$$

$$VI_{Qc,i} = \frac{W_{Qc,i}}{2N}\left(\frac{Qc_i}{Q_\Sigma}\right)^{2N} \quad (15)$$

$$VI_{line\_ang,i} = \frac{W_{line\_ang,i}}{2N}\left(\frac{La_i}{La_{i,\max}}\right)^{2N} \quad (16)$$

$$VI_{Relay,i} = \frac{W_{Relay,i}}{2N}((1/d_{sr,i})^{2N} + (1/d_{rs,i})^{2N}) \quad (17)$$

$$VI_{line\_off,i} = W_{line\_off,i} k_i \quad (18)$$

$$VI_{line} = \sum_{i=1}^{p} (VI_{Pf,i} + VI_{Qf,i} + VI_{Qc,i} + VI_{line\_ang,i} + VI_{Relay,i} + VI_{line\_off,i}) \quad (19)$$

$$MI_{Sf,i} = 1 - \frac{Sf_i}{S_{i,\max}} \quad (20)$$

$$MI_{line\_ang,i} = 1 - \frac{La_i}{La_{i,\max}} \quad (21)$$

$$MI_{Relay,i,sr} = d_{sr,i} - K_z \,|\sin(\pi/2 - \alpha + \theta_{d,sr})| \quad (22)$$

$$MI_{Relay,i,rs} = d_{rs,i} - K_z \,|\sin(\pi/2 - \alpha + \theta_{d,rs})| \quad (23)$$

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

$VI_{Relay,i}$: *VI* of individual line distance relay

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

VI_{line}: total *VI* of all lines

$MI_{Sf,i}$: *MI* of individual line flow

$MI_{line\_ang,i}$: *MI* of individual bus voltage angle difference

$MI_{Relay,i,sr}$, $MI_{Relay,i,rs}$: *MI* of individual line distance relay at sending and receiving ends, defined as the distance from apparent impedance seen by distance relay to relay protection zone circle, zero or negative values mean at or within the protection zone circle

$W_{Pf,i}$: 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, Sf_i: line real, reactive and apparent 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

$d_{sr,i}$, $\theta_{d,sr}$: magnitude and angle of normalized apparent impedance seen by distance relay from the sending end to receiving end of that line

$d_{rs,i}$, $\theta_{d,rs}$: magnitude and angle of normalized apparent impedance seen by distance relay from the receiving end to sending end of that line

α: line impedance angle

K_z: zone setting, i.e., define 2.4 as zone 3 setting

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

In this model, the line charging influence is considered for vulnerability index. Some lightly loaded lines and lines with high charging capacitance may contribute much to the reactive power supply and voltage support. Their outages may decrease the reactive power supply or 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 the study of others. For example, 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 line distance relay, if we use the series line model, we can find that normalized apparent impedance is only associated with the bus voltages along the line.

$$Z_{d,sr} = \frac{V_s}{I_{sr}} = \frac{V_s}{(V_s - V_r)/Z_{sr}} \quad (24)$$

$$\overline{Z}_{d,sr} = \frac{Z_{d,sr}}{Z_{sr}} = \frac{V_s}{V_s - V_r} = \frac{|V_s|}{|V_s - V_r|}\angle\theta_{d,sr} = d_{sr}\angle\theta_{d,sr} \quad (25)$$

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 the distance relay at no fault condition, the more possible the case that it may fall into the distance relay backup zone (zone 3 or zone 2 taken as backup). The smaller the apparent impedance, the more vulnerable the distance relay and the smaller the relay margin.

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

$$VI = W_{gen} VI_{gen} + W_{bus} VI_{bus} + W_{line} VI_{line} \quad (26)$$

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

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

III. Numerical Results

We use the standard IEEE 39-bus New England System to demonstrate our approach. The full AC power flow is run to get the steady state results, such as bus voltages, line flows and generator outputs. The detailed system data can be found at [12]. Fig. 1 gives the IEEE 39-bus system configuration.

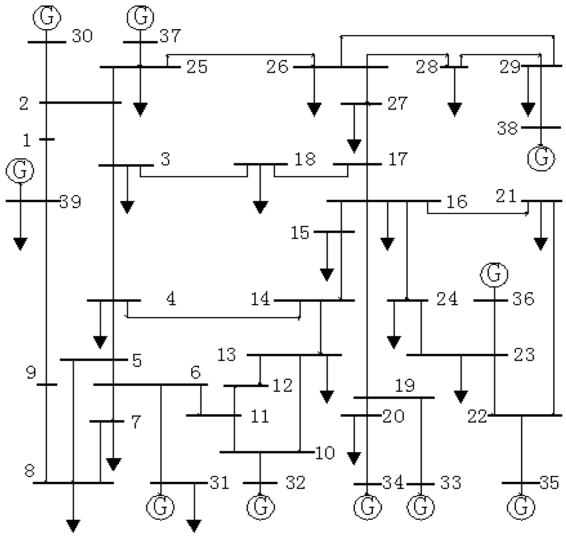

Fig. 1. IEEE 39-bus New England System

A. Vulnerability analysis for different loading conditions

We compare the vulnerability index (*VI*) values for the base load, 1.1 times the base load, and 1.2 times the base load with the generation increasing with the same ratio. Assign all weights as 1, line transfer limits as 10.0 p.u., voltage variance 0.075 p.u., line bus voltage angle difference limits as 40 degrees, PQ bus voltage magnitude limits as 1.0 p.u., then sum all individual Vulnerability Index values of generators, buses and lines and get the separate summary of *VI* values.

Tables I and II show the summary vulnerability index (*VI*) values. Columns 2-4 of Table I represent summary Vulnerability Index values at the buses, and columns 5-7 of Table I represent summary Vulnerability Index values at the generators. Columns 2-7 of Table II represent summary Vulnerability Index values at the lines.

TABLE I
VULNERABILITY INDEX VALUES OF SYSTEM, BUSES AND GENERATORS AT DIFFERENT LOADING CONDITIONS

	Total VI	V	load_ ability	Pg	Qg
Base load	10.212	2.856	0.948	2.347	0.675
1.1 load	11.227	2.105	1.159	2.842	1.010
1.2 load	12.868	1.701	1.396	3.384	1.460

TABLE II
VULNERABILITY INDEX VALUES OF LINES AT DIFFERENT LOADING CONDITIONS

	Pl	Ql	Qc	line_ ang	relay	line_ off
Base load	2.856	0.132	0.021	0.182	0.192	0
1.1 load	3.457	0.180	0.012	0.225	0.233	0
1.2 load	4.116	0.244	0.008	0.273	0.282	0

TABLE III
MARGIN INDEX VALUES OF TOP 6 LINES AT DIFFERENT LOADING CONDITIONS

Line No	base load		1.1 base load		1.2 base load	
	Relay	Flow	Relay	Flow	Relay	Flow
37(B6-31)	4.204	0.415	3.491	0.346	2.866	0.275
38(B10-32)	4.798	0.331	4.123	0.259	3.521	0.185
42(B23-36)	4.782	0.431	4.055	0.379	3.444	0.321
45(B29-38)	5.711	0.172	4.977	0.090	4.341	0.007
43(B25-37)	6.007	0.460	5.267	0.407	4.627	0.353
29(B24-23)	6.325	0.647	5.414	0.612	4.645	0.577

From Tables I and II we can see that the system is more vulnerable with the load increasing. Generators need to generate more real and reactive power to supply the load, especially the reactive power output. Line loadings are heavier than before. Line charging ratio at the reactive power supply is decreasing since generators are supplying more reactive power. The bus voltage angle differences at lines are also increasing. Relays see apparent impedances smaller than before. For the bus voltage magnitude performance, the reason that Vulnerability Index values of 1.1 and 1.2 times the base load are smaller than that of the base load condition is that the bus voltage magnitudes are higher at the base load condition and they decrease with the load increase. We just give equal weights to all the parameters to give a simple example. In practice, system operators may assign different weights to represent the varying importance of selected elements in the system.

Table III gives the margin indices of line distance relay and line flow. The top six most vulnerable lines are ranked by relay margin indices. They are much smaller than the average relay margin index 52.04. We can see that they are close to zone 3 circles even at the normal steady state. Thus, the distance relays at these lines need careful monitoring.

B. Vulnerability Analysis for Static N-1 contingency

We evaluate the system vulnerability by N-1 static contingency (line outage) analysis. For this small system, there are eleven single lines whose tripping result in islanding. They are L22(B19-16), L47(B20-19), and nine generator branches L37-L45 which connect G30-G38 respectively. For simple demonstration, here we only rank the non-islanding cases and give the Vulnerability Index values of the top six vulnerable line outages in Tables IV and V. We also check the relay margin and flow margin indices for those top six line outages. The top three most vulnerable relay margins and line flow margins of each line outage case are given in Table VI.

Columns 2-6 of Table IV represent summary vulnerability indices of the system, buses and generators respectively. Columns 2-7 of Table V represent summary vulnerability indices at the lines. Columns 2-4 of Table VI represent relay margin indices of most vulnerable lines 37, 38 and 42 for each line outage. Columns 5-7 represent flow margin indices of most vulnerable lines 45, 38 and 41 for each line outage.

TABLE IV
VULNERABILITY INDEX VALUES OF TOTAL SYSTEM, BUSES AND GENERATORS

Line Outage	Total VI	V	load_ ability	Pg	Qg
20(B16-15)	12.722	3.604	1.249	2.350	0.848
23(B21-16)	11.838	3.089	1.281	2.347	0.705
30(B26-25)	11.809	2.631	1.175	2.352	0.981
5(B4-3)	11.711	3.277	1.001	2.347	0.652
11(B7-6)	11.704	2.822	0.976	2.348	0.727
2(B39-1)	11.568	3.088	0.978	2.348	0.668

TABLE V
VULNERABILITY INDEX VALUES OF LINES

Line Outage	Pl	Ql	Qc	line_ ang	relay	line_ off
20	3.065	0.178	0.017	0.198	0.209	1.
23	2.882	0.140	0.020	0.180	0.190	1.
30	3.076	0.170	0.017	0.196	0.207	1.
5	2.867	0.166	0.019	0.185	0.194	1.
11	3.256	0.165	0.018	0.189	0.200	1.
2	2.955	0.131	0.016	0.185	0.195	1.

TABLE VI
RELAY AND FLOW MARGIN INDEX VALUES OF 6 LINES OUTAGES

Line Outage	Relay Margin			Flow Margin		
	37	38	42	45	38	41
20	3.991	4.680	4.842	0.172	0.305	0.367
23	4.186	4.789	4.905	0.172	0.328	0.330
30	3.987	4.779	4.717	0.169	0.326	0.316
5	4.102	4.747	4.783	0.171	0.318	0.325
11	4.135	4.788	4.775	0.172	0.328	0.324
2	4.180	4.795	4.782	0.172	0.330	0.325

Note: Line 37(B6-31), 38(10-32), 41(B22-35), 42(23-36), 45(B29-38)

From Table VI, we can see that for each of the 6 most vulnerable line outages, the most vulnerable distance relays are at lines 37, 38, and 42. For outages of lines 20, 23, and 11, the smallest flow margin lines are in the order of lines 45, 38 and 41. While for the other 3 line outages, they are in the order of lines 45, 41 and 38.

C. *Vulnerability Analysis for Static N-2 contingency*

We can also rank the system vulnerability by N-2 static contingency (2 line outages) analysis. For the 2-line outages, each of the single line combined with any other line can cause system islanding. There are also 30 pairs of lines whose outages can cause system islanding. For the simple demonstration, we only rank the non-islanding cases. Tables VII and VIII show the Vulnerability Index values of the top six pairs of line outages.

TABLE VI
VULNERABILITY INDEX VALUES OF TOTAL SYSTEM, BUSES AND GENERATORS

Line Outages	Total VI	V	load_ ability	Pg	Qg
5, 20	18.593	7.425	1.620	2.353	1.068
9,11	17.953	4.841	1.089	2.362	1.539
10,13	17.262	4.847	2.089	2.358	1.344
12,17	17.241	5.339	1.033	2.356	1.591
18,20	15.991	4.795	1.483	2.352	1.016
17,20	15.795	4.952	1.397	2.351	0.964

TABLE VII
VULNERABILITY INDEX VALUES OF LINES

Line Outages	Pl	Ql	Qc	line_ ang	relay	line_ off
5, 20	3.296	0.276	0.012	0.263	0.276	2.
9,11	5.170	0.386	0.008	0.266	0.290	2.
10,13	3.668	0.207	0.009	0.355	0.381	2.
12,17	3.466	0.495	0.008	0.464	0.486	2.
18,20	3.644	0.250	0.013	0.209	0.224	2.
17,20	3.441	0.234	0.014	0.211	0.227	2.

Note: Line 5(B4-3), 9(B6-5), 10(B8-5), 11(B7-6), 12(B11-6), 13(B8-7), 17(B13-10), 18(B14-13), 20(B16-15)

For the most vulnerable 2-line outage case, lines 5 and 20, the vulnerability index of bus voltage is very high. We choose 0.075 p.u. as voltage variance limit. When checked with the margin index of the bus voltage, the voltage margin indices are 0.040, 0.099 and –0.479 at buses 3, 14 and 15 respectively. Their voltage magnitudes are 0.928, 0.932 and 0.889 p.u. respectively. For the second most vulnerable 2-line outage case, lines 9 and 11, the vulnerability index of the line flow is very high. When checked with the margin index of the line flow, the line flow margin indices are -0.014, -0.189 and –0.237 at lines 8 (B14-4), 17 and 18 respectively. Their line flows are all overloaded showing 10.144, 11.888 and 12.372 p.u. respectively. For the third most vulnerable 2-line outage case, lines 12 and 17, the vulnerability index of the line distance relay is very high. When checked with the margin index of the line distance relay, the line distance relay margin indices are 0.236 and 0.249 at lines 35 (B12-11) and 18 (B12-13) respectively. This means that the apparent impedances seen by these two distance relays are very close to their zone 3 circles at the post-contingency steady state. For this case, the vulnerability index of the bus voltage is also high. When checked with the voltage margin, their indices are –0.928 and –0.140 at buses 12 and 13 respectively. Their bus voltage magnitudes are 0.855 and 0.915 p.u. respectively.

IV. CONCLUSION

This paper introduces a novel and comprehensive concept of Vulnerability Index and Margin Index. Different security related factors are considered and modeled in this method, such as bus voltage magnitude, bus loadability, load loss, generator real and reactive power output, generation loss due to outage, line real and reactive power, line charging, bus voltage angle difference at the line, apparent impedance seen by distance relay, line outage, etc. Line charging, bus voltage angle difference, and relay performance are considered and modeled in this method. Vulnerability Index and Margin Index are combined together to give both the vulnerability and security information of the system and individual element. Thus, the system operators can evaluate their system operation quantitatively and know the vulnerability and security information of the system. The impacts on the system security by different system events can be analyzed and the system operators can take some preventive or emergency control steps to increase the security level. The full AC power flow method is used to calculate the Vulnerability Index and Margin Index values.

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VI. Biographies

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