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Effective Contingency Ranking Based on Composite Indices

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Abstract: Contingency ranking in power system transient stability is a complicated and time consuming task. To prevail over this difficulty, various indices are used. These indices are based on the concept of coherency and three dot products of the system variables. It is well known that some indices work better than others for a particular power system. This paper introduces an innovative composite severity index for power system transient stability. In this paper two composite indices are presented and compared. One of them is based on Least Mean Square (LMS) and the other based on summing up indices by evenly balanced weights. To illustrate the effectiveness of the developed severity indices, they have been tested for two real practical power systems. Numerical simulations of the developed index, demonstrate that composite index with LMS method is more effective than other indices.

Key-words: dynamic security, transient stability, combination of indices, severity indices

1 Introduction

In recent years, power systems have been operated under more stressed conditions and close to their stability limits. Due to recent blackouts, power system security has become a major concern. Under these circumstances, an important problem that is frequently considered for secure operation is the severity of transient stability. This concerns the maintenance of synchronism between generators following a severe disturbance. The analysis of contingency is performed by using the indices obtained from time domain simulation. Indices that report how much of a contingency is stable or instable in an electrical power system have been the object of several studies in the last decades.

Many researchers have worked on this area of contingency screening. Fouad [1] determined an index by evaluating the individual machine energy function along the system trajectory generated by the time domain simulation method. Haque [2] suggested the hybrid method to find the stability margin, but only one of the machines in the system is considered. Padilha [3] tested a hybrid method using time domain simulation and the individual machine energy function. Fu and Bose[4] have compared three different screening methods, which are based on the concepts of coherency, transient energy conversion between kinetic energy and potential energy, and three dot products of the system variables. In that work, each index is assigned the same weight to test the overall performance of all indices and composite index have been computed by tuning the weights for a particular power system. Chan [5] estimated dynamic stability by using hybrid transient energy function and clustering analysis. Bettiol [6] used an artificial neural network filter for selecting severe cases on the ranking list. This may be achieved by computing the values of the performance index for each line outage and subsequently, ranking the contingencies from the most important (largest value of performance index) to the least important (smallest value of the performance index). Lee et.al. [7] developed an index based on the angle variation of each generator for fast contingency screening. This method evaluates the first swing stability of a large number of contingencies in a short time. The maximum amplitude of a rotor angle swing in the post-contingency period can be used as a measure of the transient severity of a contingency. Utility operational guidelines usually recommend that large rotor swings should be avoided to maintain security of operation. For this reason the maximum rotor swing amplitude was used as the transient stability index [8-9]. All researches [1-3, 5-9] present an index for security analysis and in [4] five indices is presented and composite index is obtained by adding these indices with equal weights. In this paper a novel severity index for contingency ranking in power system stability analysis is presented that is based on combination of five indices. This index assigns different weights to each individual index based on LMS method and adds them together. As shown in next section this index provides a better ranking for severely unsecured cases in test systems. The developed method demonstrates that combination of indices provide better ranking than a single index. This paper is organized as follows: section 1 presented the motivation and justification of the developed scientific research work. Section 2 describes the formulation of the indices. In section 3 numerical results are presented.

2 Indices

The purpose of contingency filtering is to identify, usually from a very large list of probable contingencies, the severe ones (or potentially severe) that should be analyzed thoroughly in order to assess system security after the occurrence of a large disturbance. The effects of possible contingencies are presented by, a severity or Performance Index (PI). The calculated performance indices are then sorted in such a way to provide an ordered list of contingencies according to their severity.

The index in [9] is based on critical clearing time and generation margin as well as considering coherency concept. The following performance indices are defined based on coherency concept [10]:

$$PI_1 = \max\left\{\max\delta_i(t) - \min\delta_i(t)\right\} \quad (1)$$

$$PI_2 = \max\left\{\max(\delta_i(t) - \delta_i^0)\right\} \quad (2)$$

$$for: i = 1,2,......., NG$$

$$and: t_{cl} \le t \le t_{cl} + T$$

where:

δ_i: generator rotor angle relative to Center Of Inertia (COI).

NG : total number of generators.

t_{cl} : fault clearance time.

T: length of short period after fault clearing(0.5-0.6 second).

δ_i^0: rotor angle in beginning of the fault.

By defining new angles and speeds relative to center of inertia, the state equations become :

$$\frac{d\delta_i}{dt} = \omega_i \quad (3)$$

$$\frac{d\omega_i}{dt} = \frac{P_{mi} - P_{ei}}{M_i} - \frac{P_{COI}}{M_t}$$

The swing equation then becomes:

$$M_i \frac{d^2\delta_i}{dt^2} = P_{mi} - P_{ei} - \frac{M_i}{M_t} P_{COI} \quad (4)$$

A dot product was defined for detecting the exit point. The exit point is characterized by the first maximum of transient potential energy with respect to the post-fault network.

$$f = \begin{bmatrix} P_{m1} - P_{e1} - \frac{M_1}{M_t} P_{COI} \\ .... \\ P_{mNG} - P_{eNG} - \frac{M_{NG}}{M_t} P_{COI} \end{bmatrix} \quad (5)$$

$$\omega = [\omega_1, ..., \omega_{NG}]^T \quad (6)$$

The dot product is presented as :

$$dot_1 = \sum_{i=1}^{NG} f_i \omega_i$$

$$f_i = P_{mi} - P_{ei} - \frac{M_i}{M_t} P_{COI} \quad (7)$$

$$P_{COI} = \sum_{i=1}^{NG} (P_{mi} - P_{ei})$$

$$for: i = 1, ..., NG$$

where:

f_i :accelerating power of generator i referred to the center of inertia.

M_i :inertia constant of each generator.

M_t : total inertia constant of all generators.

P_{mi} : mechanical power input for each generator.

P_{ei} : electrical power output for each generator.

ω_i : rotor speed with respect to COI.

The dot product can give the amount of total accelerating power and the power system response to this accelerating power, thus it could be an acceptable index for ranking contingencies. The rotor angle and speed are significant measures, thus the following two dot products are defined:

$$dot_2 = \sum_{i=1}^{NG} f_i \delta_i \qquad (8)$$

$$dot_3 = \sum_{i=1}^{NG} \omega_i (\delta_i - \delta_i^{cl}) \qquad (9)$$

where:

δ_i^{cl} : rotor angle at fault clearing time for generator i.

There are three indices defined from the concept of these three dot products:

$$\begin{aligned} PI_3 &= \max dot_1(t) - \min dot_1(t) \\ PI_4 &= \max dot_2(t) - \min dot_2(t) \\ PI_5 &= \max dot_3(t) - \min dot_3(t) \end{aligned} \qquad (10)$$

$$for: t_{cl} \le t \le t_{cl} + T$$

Transient energy function is probably the best known direct method for fast transient stability assessment. The total kinetic energy (Vke) is given by:

$$V_{ke} = \frac{1}{2} \sum_{i=1}^{NG} M_i \omega_i^2 \qquad (11)$$

The total potential energy is defined as:

$$V_{pe} = \sum_{i=1}^{NG} \int_{\delta_i^s}^{\delta_i} (P_{mi} - P_{ei} - \frac{M_i}{M_T} P_{COI}) d\delta_i \qquad (12)$$

$$V_{cl} = V_{pe} + V_{ke} \qquad (13)$$

$$\Delta V = V_{cr} - V_{cl}$$

where:

δ_i^s : post fault steady state value of δ_i

V_{cr} represent the value of potential energy on the boundary and V_{cl} represent the value of energy at the instant of fault clearing time. Both the kinetic and potential energies calculated numerically using the data generated directly from a time domain simulation. The direct method of transient stability based on the transient energy function (TEF), can provide a stability index of power system. All indices are calculated in the same time and ΔV is used as a benchmark to compare the results to other performance indices. Indices PI_1 to PI_5 may not reliably capture all the severely unsecured outages. Each index can't rank the severity of contingencies for different systems under various conditions. The composite index can surely provide a global evaluation of the different power system factors. This index assigns different weights to each individual index and adds them together. As shown in next section this index will provide a better ranking for severely unsecured cases in test systems.

The purpose of the combination of indices is to take advantage of the slightly different characteristics of the five indices to find the best index for contingency ranking. Usually, indices PI_1, PI_2 and PI_5 have better behavior and due to this a weighted combination of indices is suggested to take advantage of those indices that work better for a particular power system.

In this paper unequal weights composite index (CI) is presented and compared to other equal weights. The composite index is determined by Least Mean Square algorithm (LMS). The LMS algorithm is an adaptation scheme widely used in practice due to its simplicity. The linear relation between indices and variation of rotor angles dose not exist. If it is supposed ideally any n-input, 1-output linear system with n unknown parameters X :

$$AX = Y \qquad (14)$$

where :

A : indices matrix

X : weight coefficient vector

Y : output vector (here vector of CI)

In order to determine the X, one can construct the following matrix relation:

$$A\hat{X} = \hat{Y} \qquad (15)$$

where:

$$A = \begin{bmatrix} PI_{11} & PI_{12} & \cdots & PI_{1n} \\ PI_{21} & PI_{22} & \cdots & PI_{2n} \\ \vdots & \vdots & \vdots\vdots\vdots & \vdots \\ PI_{m1} & PI_{m2} & \cdots & PI_{mn} \end{bmatrix}$$

$$X = [X_1, ..., X_n]^T$$

and $Y = [Y_1, ..., Y_n]^T$

A, is a matrix containing input values PI_1 to PI_5 and Y, is a vector containing the calculated out.Note that the number of calculated values (m) is greater than (or equal to) the number of unknown parameters (n). In order to determine the vector of weight cofficients (X) we can determine a nearest value of it as $\hat{X}$, such as:

$$\min J = \left\| Y - \hat{Y} \right\|_2 \qquad (16)$$

where:

J : objective function

The goal in LMS algorithm is to minimize the square of errors, thus by algebraic manipulations we have:

$$J = \left\| Y - \hat{Y} \right\|_2 = (Y - \hat{Y})^T (Y - \hat{Y}) \qquad (17)$$

Substituting eqn.(13) and (15) in eqn.(17) and rewriting it, the result is:

$$\begin{aligned} J &= (AX - A\hat{X})^T.(AX - A\hat{X}) \\ J &= (Y - A\hat{X})^T.(Y - A\hat{X}) \\ J &= (Y^T - \hat{X}^T.A^T).(Y - A\hat{X}) \\ J &= Y^T.Y - Y^T.A\hat{X} - \hat{X}^T A^T Y + \hat{X}^T A^T A\hat{X} \end{aligned} \qquad (18)$$

To minimize objective function, gradient of J must be zero. Thus:

$$\frac{\partial J}{\partial \hat{X}} = 0 \Rightarrow \hat{X} = (A^T A)^{-1} A^T Y \qquad (19)$$

Substituting $\hat{X}$ in eqn.(15), $\hat{Y}$ will be calculated, which is a reasonable estimate of final combination of indices.

3 Numerical results

Three systems were used for testing the developed indices: IEEE 9-bus test system, Sistan 9-bus 230 kV and Khorasan 400 kV power systems in Iran. Data for these systems are constructed based on PSS/E raw data format.

Three-phase short circuit fault was applied on the selected bus in all the systems and then removed after 8 cycles (0.16 second). To study the stability of the above test systems, the generator's rotor angle, electrical power, mechanical power and speed of the rotor were obtained through PSS/E simulator, then performance indices PI_1 to PI_5 were calculated by IPLAN programs and finally by applying LMS algorithm to these performance indices, composite index was obtained.

Transient energy function index ΔV is used as a benchmark to compare and demonstrate the effectiveness of the composite index. As shown by simulation results (Tables 1-3), ranking using CI is very similar to those of ΔV. For the three sample power systems, initially line outage contingency ranking is obtained based on ΔV for each outage and then PI_1 to PI_5 are calculated separately.

3.1 IEEE 9-bus test system

IEEE 9-bus test system has three generators of GENROE and three exciter of IEEET1 type. The above procedure is carried out on this power system. Table 1 shows the line outage ranking results in descending order (the worst outage has the highest value in the table) and demonstrates that contingency ranking using PI_1 to PI_5 have properly pointed out severity of the first two outages only and rest of them are incorrectly ranked. Similarly, CI with equal weighting factors of 0.2 (ref. [4] method) determined the first two contingency ranking appropriately. But the proposed method, has correctly pointed out the contingencies up to fourth order. Fig. 1 and 2 shows indices, composite index and (TEF) or ΔV for contingencies. As seen in figures composite index is very similar to ΔV in ranking of contingencies (Note that values is normalized and then plotted).

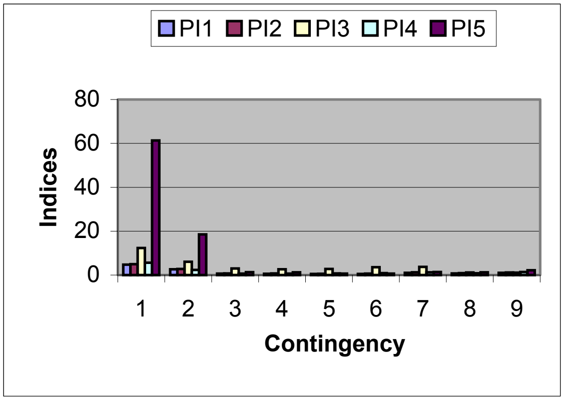

Fig.1 Ranking contingencies with PI1 to PI5 indices in IEEE 9-bus test system

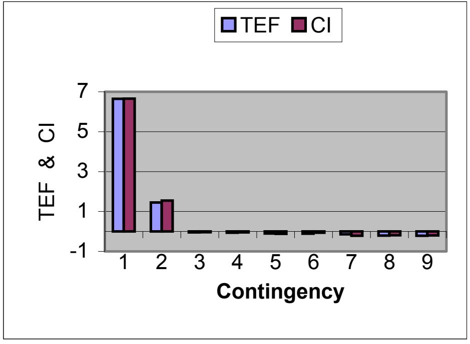

Fig.2 performance of CI and ΔV in IEEE 9 bus system.

3.2 Practical power systems

The Sistan 9-bus power system has three generators of GENCLS type (constant internal voltage generator model).This system has 10 transmission lines in which outage of four lines cause instability in the system. Table-2 show the results of simulations for different indices. As mentioned earlier, CI using the developed LMS method has computed more accurate contingency ranking order. Similarity Fig. 3 and 4 shows indices, composite index and (TEF) or ΔV for contingencies. As seen in figures composite index is very similar to ΔV in ranking of contingencies (Note that values is normalized and then plotted). The Khorasan 18-bus power system has four generators of GENCLS type. Table 3 demonstrates that contingency ranking using PI_1 to PI_5 have properly pointed out severity of the first one outages only and rest of them are incorrectly ranked. Similarly, CI with equal weighting factors of 0.2 (ref. [4] method) determined the first one contingency ranking appropriately. But the proposed method, has correctly pointed out the contingencies up to fifth order.

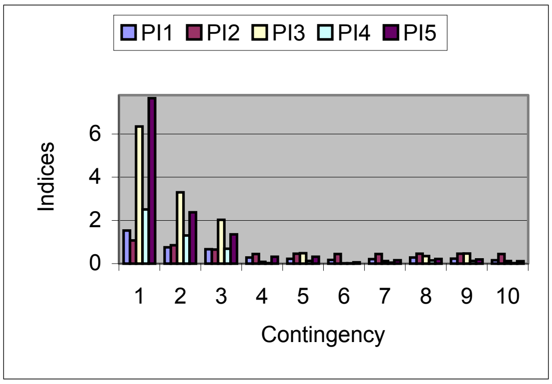

Fig. 3 Ranking contingencies with PI1 to PI5 indices in Sistan power system.

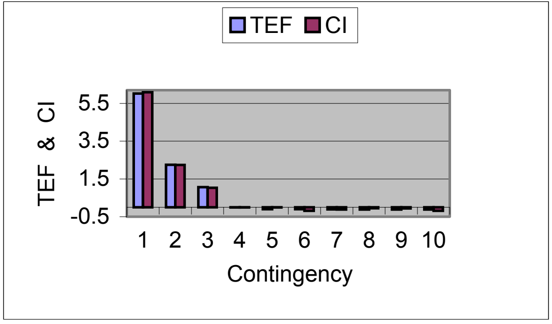

Fig. 4 Performance of CI and ΔV in Sistan power system

4 Conclusions

Contingency ranking methods play an important role during power system operation and the needed speed forces the use of performance indices. Any single index can not rank the severity of each outage properly. This paper proposed a novel algorithm to combine various indices to establish a new composite index that is more accurate and precise. The presented method is based on LMS technique. The simulation results validate the developed algorithm and show that they are very close to the benchmark values.

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Table -1 Ranking result of IEEE 9-bus power system with fault clearance time=0.36

Line tripped	PI_1	PI_2	PI_3	PI_4	PI_5	CI with equal weights	CI with LMS	ΔV
2-7*	4.75	4.98	12.33	5.579	61.34	17.758	-34268	-34285.26
3-9*	2.63	2.76	6.059	2.3	18.52	6.453	-7512	-7457.27
1-4*	0.62	0.756	2.966	0.629	1.293	1.252	189	238.8
4*-5	0.6	0.757	2.63	0.657	1.207	1.17	238	336.118
4*-6	0.529	0.573	2.74	0.708	0.65	0.986	637	539.61
8*-9	0.51	0.68	3.58	0.854	0.66	1.2568	328	594.06
7*-8	1.01	1.24	3.75	1.24	1.362	1.502	1112	743.82
6*-9	0.76	0.84	1.16	0.789	1.246	0.959	1008	1073.3
5*-7	1.0	1.15	1.13	1.4	2.22	1.38	1029	1117.2

*(faulted bus)

Table -2Ranking result of Sistan 230 kV power system with fault clearance time=0.36

Line tripped	PI_1	PI_2	PI_3	PI_4	PI_5	CI with equal weights	CI with LMS	ΔV
1740*-1741	1.53	1.077	6.35	2.51	7.66	3.82	-13812	-13786.43
4231-4230*	0.756	0.847	3.3	1.3	2.37	1.71	-5081	-5144.21
1811-1810*	0.667	0.654	2.03	0.69	1.35	1.07	-2337	-2435.69
1810*-1830	0.279	0.44	0.083	0.023	0.316	0.228	17.1	14.3
1740*-4230	0.227	0.457	0.48	0.124	0.319	0.321	24	226.19
4230*-3720	0.169	0.442	0.017	0.018	0.0619	0.141	425	236.64
1810*-1740	0.207	0.441	0.117	0.043	0.155	0.192	280	250.05
1740*-3540	0.28	0.457	0.345	0.153	0.22	0.291	121	256.47
1740*-3720	0.23	0.457	0.469	0.124	0.197	0.295	143	266.16
1810*-3540	0.158	0.44	0.118	0.022	0.114	0.17	428	279.16

Table 3 Ranking result with Khorasan 400 kV power system with fault clearance time=0.36

Line tripped	PI_1	PI_2	PI_3	PI_4	PI_5	CI with equal weights	CI with LMS	ΔV
3570*-3571	7.57	7.22	63.76	23.9	201.69	60.82	-545870	-549025.0
3550*-3551	5.7	5.35	47.33	14.72	133.55	41.33	-378670	-381065.0
4060*-4061	7.05	1.97	55.48	21.19	156.023	48.34	-341750	-340385.0
3540*-3541	5.679	5.55	40.19	14.43	102.45	33.65	-200980	-194553.0
3570*-4060	2.56	1.99	0.574	0.806	36.14	8.4	-52220	-57139.0
3550*-4130	2.099	1.92	0.731	0.315	28.12	6.63	-44030	-38710.0
3570*-3580	2.04	1.876	1.717	0.408	27.23	6.65	-45740	-37241.0
3550*-3560	2.04	1.8	0.9	0.238	26.98	6.39	-43130	-37114.0
3550*-3570	2.03	1.92	0.84	0.255	27.35	6.47	-45080	-37091.0
3520*-4130	2.02	1.59	2.173	1.03	22.2	5.8	-13180	-25201.0
3530*-3550	1.78	1.66	0.883	0.27	17.857	4.49	-10300	-14490.0
2520-3520*	1.62	1.535	2.94	0.565	16.27	4.496	-15010	-12440.0
3570*-4380	1.78	1.66	1.83	0.45	16.98	4.54	-7860	-12234.0
3520*-4060	1.64	1.5	2.76	0.59	16.09	4.51	-11690	-11719.0
3540*-3580	1.56	1.43	1.23	0.129	14.754	3.82	-8970	-9809.0
3540*-3560	1.52	1.39	1.22	0.138	13.59	3.57	-4890	-7082.0
3540*-4310	1.313	1.166	1.34	0.128	8.71	2.53	8900	3603.0
3510*-3540	1.12	1.02	1.19	0.109	6.9	2.067	9780	4402.0