Effective transient stability assessment based on composite indices

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Abstract: This paper presents a new composite index to analyze power system transient stability. 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, transient energy conversion between kinetic and potential energy 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 along with test results using two practical 230 kV Sistan and 400 kV Khorasan power system in Iran, and 9 bus IEEE test system demonstrates that combination of indices provides better ranking than a single one. In this paper two composite indices (CI) is presented and compared. One composite index is based on Least Mean Square algorithm (LMS) and other based on summing indices by equal weights. Numerical simulations of the developed index, demonstrate that composite index is more effective than other indices.

Keywords: composite index, transient stability, energy margin.

1 Introduction

In recent years, power systems have been operated under more stressed conditions close to their stability limits. Also for 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 problem of transient stability. This concerns the maintenance of synchronism between generators following a severe disturbance.

In system operation, dynamic security analysis encompasses a large class of problems, such as finding the security levels of the power system, the power transfer limit in a transmission line, the worst contingency in some specified area of the system, etc. Dynamic Security Analysis (DSA) is the evaluation of the ability of the system to withstand contingencies by surviving the transient conditions to acceptable steady-state operation and gives indications about the remedial actions when necessary. These studies provide necessary information to select the proper set of relays and circuit breakers such that a fault is cleared in time without losing system stability. Two of the main features of the DSA function are:

- Contingency screening: to rank a large number of contingencies and select those, which are likely to cause dynamic security violations.
- Contingency evaluation: to carry out time domain simulation based transient and dynamic stability assessment, and, if necessary, to propose preventive/remedial actions to improve system security according to the contingency severity.

For large complex power systems, it is impractical and unnecessary to perform full detail analysis on the influence of every contingency. This is because of time consuming process associated with the detail analysis.

Therefore, a screening algorithm that filters out very stable cases and selects more severe contingencies, has been adopted as a key function in the transient stability monitoring. Accurate but fast contingency screening indices can be used to reduce the computation burden on the computer. For successful screening, the indices should be a good measure of system severity in the transient condition.

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. This method requires the computation of corrected kinetic energy. 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. The method outlined by Chan classifies contingencies into four categories and ranking contingencies with a descending system severity index.

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The four categories are transiently unstable, oscillatory unstable, stable but poorly, and stable and well damped. 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] and [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 indices is presented. 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 insecure cases in test systems. This paper also shows that combination of indices provide better ranking than a single index. This paper is organized as follows. Section 1 presents the motivation and justification of the developed scientific research work. Section 2 describes the formulation of problem. In section 3 numerical results and effect of load variation, change of network configuration and type of generator in transient stability indices is presented.

2 Problem formulation

In the operation of a modern electric power system, a contingency filtering and ranking analysis should be carried out.

The purpose of this study is to identify, usually from a very large list of probable contingencies, the severe ones (or potentially severe) that should be analyzed in details in order to assess system security after the occurrence of a large disturbance. The mathematical model of a multimachine power system for transient stability analysis consists of non-linear differential equations and algebraic equations. The differential equations describe the time varying properties of all generator variables, which account for both fast dynamics and slow dynamics, while the algebraic equations incorporate the power flow equations of the transmission networks and loads as well as the generator static equations. 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 with considering coherency concept. The coherency concept is stated as follows: for very stable cases, the angle of each machine will move coherently with the Center Of Inertia (COI). For unstable cases, there are some machines whose angles will move from the COI . The following performance indices are defined based on coherency concept [10].

$$PI_1 = max\{max\,\delta_i(t) - min\,\delta_i(t)\} \tag{1}$$

$$PI_2 = max\{max\,\delta_i(t) - \delta_i^0\} \tag{2}$$

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

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

where:

δ : generator rotor angle relative to 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 COI reference, the state equations become:

$$\frac{d\delta_i}{dt} = \omega_i \tag{3}$$

$$\frac{d\omega_i}{dt} = \frac{P_{mi} - P_{ei}}{M_i} - \frac{P_{COI}}{M_t} \tag{4}$$

The swing equation then becomes:

$$M_i \frac{d^2\delta_i}{dt^2} = P_{mi} - P_{ei} - \frac{M_i}{M_t} P_{COI} \tag{5}$$

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.

$$f = \begin{bmatrix} P_{m1} - P_{e1} - \frac{M_1}{M_t} P_{COI} \\ .... \\ P_{mNG} - P_{eNG} - \frac{M_{NG}}{M_t} P_{COI} \end{bmatrix} \tag{6}$$

$$\omega = [\,\omega_1......\omega_{NG}\,]^T \tag{7}$$

The dot product is presented as:

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

$$f_i = P_{mi} - P_{ei} - \frac{M_i}{M_t} P_{COI} \tag{8}$$

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

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

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 measure of total accelerating power and the power system response to this accelerating power, thus it could be a good index for ranking dynamic contingencies. The rotor angle and speed are significant measures, thus the following two dot product are defined:

$$dot_2 = \sum_{i=1}^{NG} f_i \delta_i \quad (9)$$

$$dot_3 = \sum_{i=1}^{NG} \omega_i (\delta_i - \delta_i^{cl}) \quad (10)$$

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.

$$\begin{aligned} PI_3 &= \max dot_1(t) - \min dot_1(t) \\ PI_4 &= \max dot_2(t) - \min dot_2(t) \\ PI_5 &= \max dot_3(t) - \min dot_3(t) \\ for: t_{cl} &\le t \le t_{cl} + T \end{aligned} \quad (11)$$

During the simulation, sign change in dot_2 or dot_3 mean that the projection of accelerating power vector f on the rotor angle space vector changes its direction. A change in sign of dot_2 is an indication that the trajectory is crossing the Potential Energy Boundary Surface (PEBS) and a change in the sign of dot_3 is an indication that the system is swinging back.

Fig. 1 to 3 show curve of *dot1*, *dot2* and *dot3* in IEEE 9- bus test system respectively. For unstable cases (for example outage of line 2-7) variation in dot1, *dot2* and *dot3* is very large and for stable cases (for example outage of line 8-9) the respective values are small. As seen in these Figs, in instable cases there is no change in sign of *dot2* and *dot3*.

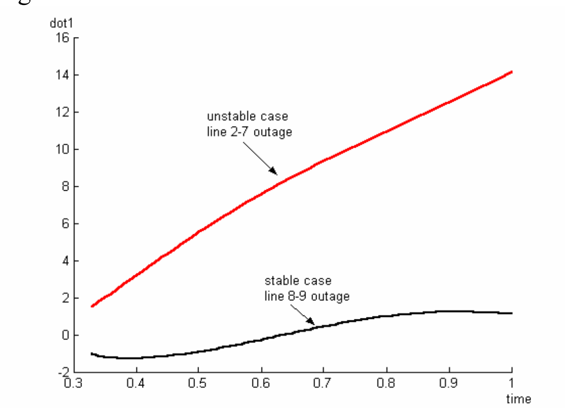

Fig.1 Dot1 for two case in 9bus IEEE test system

Transient energy function is probably the best-known direct method for fast transient stability assessment, which is obtained by considering the balance between kinetic and potential energy. The total kinetic energy (Vke) is given by:

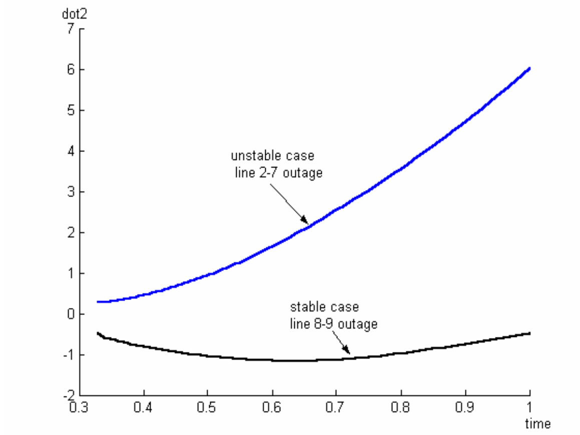

Fig. 2 Dot2 for two cases in 9bus IEEE test system

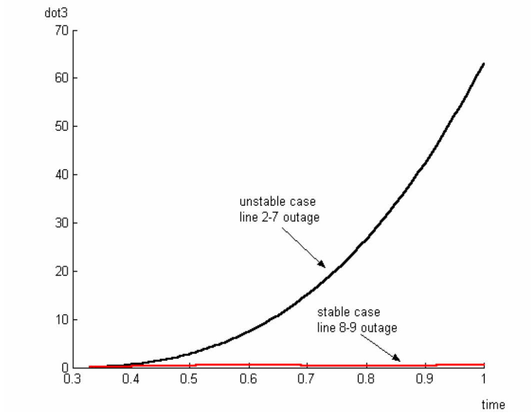

Fig. 3 Dot3 for two cases in 9bus IEEE test system

$$V_{ke} = \frac{1}{2} \sum_{i=1}^{NG} M_i \omega_i^2 \quad (12)$$

The total potential energy is defined as:

$$V_{pe} = \sum_{i=1}^{NG} \int_{\delta_i^s}^{\delta_i} (P_{mi} - P_{ei} - \frac{M_i}{M_t} P_{COI}) d\delta_i \quad (13)$$

$$V_{cl} = V_{pe} + V_{ke} \quad (14)$$

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

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. This involves additional computing time due to use the critical unstable point (UEP) determination.

The direct method of transient stability based on the transient energy function (TEF), can provide the users a stability index of power system. 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. Composite index is successful to properly rank the contingencies. As shown in next section, this index will provide a better ranking for severely unsecured cases in test systems.

The purpose of the composite index is to take advantage of the slightly different characteristics of the five indices to find the best index for contingency ranking.

In this paper composite index (CI) is presented and compared with (CI) in [4]. Composite index is driven by least mean square algorithm.

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 a, n -input, 1 -output linear system with n unknown parameters X :

$$AX = Y \tag{15}$$

where :

A : indices matrix

X : weight coefficient vector

Y : output vector (here vector of CI)

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

$$A\hat{X} = \hat{Y} \tag{16}$$

where:

$$A = \begin{bmatrix} PI_{11}\, PI_{12} \quad ...PI_{1n} \\ .... \\ PI_{m1}...............PI_{mn} \end{bmatrix}$$

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

And $Y = [\, Y_1 ....Y_m \,]^T$

A , is a matrix containing input values PI_1 to PI_5 and Y , is a vector containing the calculated output. 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 coefficients (X) we can determine a nearest value of it as $\widehat{X}$ so that:

$$min\, J = \left\| Y - \hat{Y} \right\|_2 \tag{17}$$

where:

J : goal function

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

$$J = \left\| Y - \hat{Y} \right\|_2 = (Y - \hat{Y})^T (Y - \hat{Y}) \tag{18}$$

Substituting eqn.(14) and (16) in eqn.(18) and rewriting it, the result is:

$$\begin{aligned} J &= (AX - A\hat{X})^T .(AX - A\hat{X}) \\ J &= (Y - A\hat{X})^T .(Y - A\hat{X}) \\ J &= (Y^T - \hat{X}^T .A^T).(Y - A\hat{X}) \\ J &= Y^T .Y - Y^T .A\hat{X} - \hat{X}^T A^T Y + \hat{X}^T A^T A\hat{X} \end{aligned} \tag{19}$$

For minimization objective function, the gradient of J must be zero. Thus:

$$\frac{\partial J}{\partial \hat{X}} = 0 \Rightarrow \hat{X} = (A^T A)^{-1} A^T Y \tag{20}$$

Substituting $\hat{X}$ in eqn. (16), $\hat{Y}$ 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-bustest system, Sistan 9 bus 230 kV and Khorasan 18-bus 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 and then performance indices PI_1 to PI_5 were calculated by IPLAN programs and then 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. For the three sample power systems, initially line outage contingency ranking is done base on ΔV for each outage and then PI_1 to PI_5 is calculated separately using IPLAN. In the developed algorithm, the determined ΔV vector is substituted in vector Y of eqn. (15). Now having indices matrix A and vector Y eqn. (20) calculates the required weighting factors, $\hat{X}$. Finally the computed $\hat{X}$ is substituted in eqn. (16) to obtain the composite index (CI).

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). Table 1 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) can determine the first two contingencies ranking appropriately. But, the proposed method, has correctly pointed out the contingency up to fourth order. To consider network configuration and fault clearance time changes and effect of these modifications on output, load in bus no.4 is increased by five percent and fault clearance time is decreased to 0.32 seconds. The consequences of these changes are shown in table-2. Note that the simulations were carried out without normalized indices, so the values of ΔV are high as compared to [4].

Table 1 Ranking result with 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 2 Ranking result with IEEE 9 bus power system with fault clearance time=0.32 and change in load of bus no.4

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	12.78	5.68	62.578	18.153	-35214	-35247.25
3-9*	2.63	2.76	5.488	2.192	18.94	6.4	-7992	-7865.41
1-4*	0.7	0.73	3.63	0.628	1.24	1.385	-507	-810.37
4*-5	0.62	0.77	1.71	0.472	1.032	0.92	564	609.06
4*-6	0.55	0.59	1.78	0.527	0.535	0.796	420	765.36
8*-9	0.53	0.69	2.374	0.633	0.553	0.955	367	882.57
7*-8	1.03	1.26	2.448	0.959	1.013	1.342	1543	1096.43
6*-9	0.78	0.86	0.772	0.771	1.164	0.857	1156	1190.92
5*-7	1.03	1.17	0.885	1.285	2.05	1.238	1308	1287.92

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-3 and 4 show the results of simulations for different indices. As mentioned earlier, *CI* using the developed LMS method has computed more accurate contingency ranking order. Fig. 4 and 5 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).

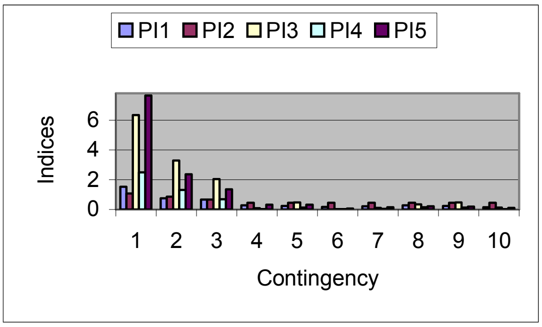

Fig. 4 Ranking contingencies with PI1 to PI5 indices in Sistan power system.

Table 3 Ranking result with 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 4 Ranking result in Sistan power system with fault clearance time=0.26 and change in load of bus no.1810

Line tripped	PI_1	PI_2	PI_3	PI_4	PI_5	*CI* with equal weights	*CI* with LMS	ΔV
1740*-1741	1.87	1.399	8.64	3.48	11.29	5.33	-20188	-20150.76
4231-4230*	0.75	0.867	3.59	1.42	2.2	1.765	-4841	-5039.41
1811-1810*	0.66	0.579	2.12	0.675	1.24	1.055	-1851	-2000.69
1810*-1830	0.316	0.458	0.254	0.08	0.397	0.30	253	39.0
4230*-3720	0.182	0.445	0.083	0.026	0.079	0.163	663	262.5
1740*-4230	0.267	0.477	0.886	0.244	0.295	0.433	21	275.08
1740*-3540	0.343	0.477	0.643	0.283	0.326	0.414	260	289.17
1810*-1740	0.262	0.458	0.253	0.117	0.24	0.266	250	307.77
1740*-3720	0.27	0.477	0.869	0.242	0.268	0.425	55	327.21
1810*-3540	0.217	0.458	0.267	0.073	0.174	0.236	489	366.16

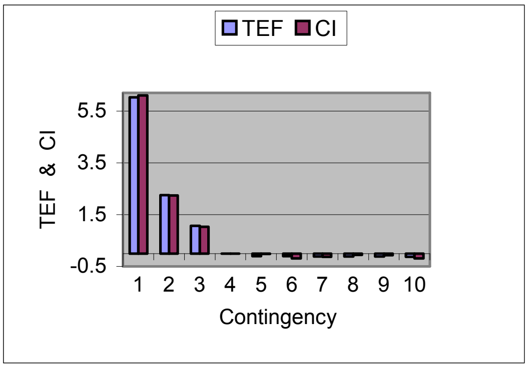

Fig. 5 Performance of *CI* and ΔV in Sistan power system

Table 5 shows ranking result in Sistan power system, that values are normalized.

The Khorasan 18-bus power system has four generators of GENCLS type. Table 6 and 7 demonstrates the simulation results for this system, which indicates the usefulness of the developed method. As seen in tables 6 and 7 *CI* using the developed LMS method has computed more accurate contingency ranking order.

Table 5 Normalized *CI* and ΔV in Sistan 230 kV power system with fault clearance time=0.36

Line tripped	*CI* with LMS	ΔV
1740*-1741	6.093	6.02
4231-4230*	2.241	2.246
1811-1810*	1.03	1.063
1810*-1830	-0.00754	-0.006
1740*-4230	-0.015	-0.098
4230*-3720	-0.1874	-0.103
1810*-1740	-0.123	-0.109
1740*-3540	-0.053	-0.1117
1740*-3720	-0.063	-0.116
1810*-3540	-0.188	-0.121

Table 6 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

Table 7 Ranking result with Khorasan 400 kV power system with fault clearance time=0.26

Line tripped	PI_1	PI_2	PI_3	PI_4	PI_5	*CI* with equal weights	*CI* with LMS	ΔV
3570*-3571	7.8	7.63	73.3	28.9	186.15	60.75	-509350	-506930.0
3550*-3551	5.88	5.66	54.97	20.2	112.8	39.9	-313210	-333891.0
4060*-4061	7.26	1.43	63.61	25.3	145.65	48.65	-312850	-308545.0
3540*-3541	5.84	5.85	45.02	17.42	94.51	33.728	-190350	-172197.0
3570*-4060	1.69	1.17	0.98	0.95	13.14	3.58	21690	-4638.0
3550*-4130	1.15	1.09	0.246	0.153	7.99	2.125	24700	5043.0
3550*-3560	1.09	0.99	0.25	0.069	7.3	1.939	120	5767.0
3550*-3570	1.09	1.097	0.214	0.08	7.47	1.99	-60	5836.0
3520*-4060	1.194	0.865	1.145	0.79	6.25	2.048	29120	6831.0
3570*-3580	1.05	1.03	0.462	0.124	6.85	1.903	-40	7084.0
3540*-3580	0.845	0.851	0.456	0.03	3.9	1.216	3570	9670.0
3510*-3540	0.6	0.61	0.455	0.029	1.55	0.648	7040	10179.0
3540*-3560	0.77	0.776	0.453	0.036	3.3	1.067	4360	10574.0
2520-3520*	0.76	0.77	1.018	0.207	3.14	1.179	3760	11408.0
3520*-4130	0.768	0.747	0.995	0.227	2.95	1.137	6490	11773.0
3540*-4130	0.53	0.537	0.48	0.033	0.92	0.5	7630	13012.0
3530*-3550	0.748	0.79	0.21	0.089	2.68	0.903	12940	13480.0
3570*-4380	0.713	0.719	0.464	0.13	1.75	0.755	14480	15001.0

4 Conclusion

This paper demonstrated that various performance indices couldn't reliably capture all the instable cases individually. Each index can't rank the severity of contingency for different system under different conditions, but the combination of indices can give a better results in ranking especially for worst cases. Results on three test systems showed that combination of indices CI with use of LMS will provide a better ranking for worst cases and with respect to equal weight factor method is closer to benchmark.

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Appendix

Table A1 generator dynamic data in 9 bus system

Parameter	bus1	bus2	bus3
T'_{do}	8.96	8.5	3.27
T''_{do}	0.05	0.037	0.032
T'_{qo}	0.31	1.24	0.31
T''_{qo}	0.05	0.074	0.079
H	23.64	6.4	5.047
D	1.24	0.67	0.48
X_d	0.146	1.75	2.201
X_q	0.0969	1.72	2.112
X'_d	0.0608	0.427	0.556
X'_q	0.0608	0.65	0.773
X''_q	0.025	0.275	0.327
X_l	0.01	0.22	0.246

Table A2 Exciter parameter in 9 bus system

Parameter	bus1,2,3
T_R	0.0
K_A	20.0
T_A	0.2
$V_{R\,max}$	7
$V_{R\,min}$	0.0
K_E	1
T_E	0.314
k_f	0.063
T_F	0.35
E_1	4.1
$S(E_1)$	2.5484
E_2	2
$S(E_2)$	0.5884

X_d : d-axis synchronous reactance
X'_d : d-axis transient reactance
X_q : q-axis synchronous reactance
X'_q : q-axis transient reactance
X''_q : q axis subtransient reactance
T_E : field circuit time costant
k_f : stablizer gain
K_A : amplifier gain
T_F : stablizer time constant
T'_{do} : d-axis open circuit transient time constant
T''_{do} : d-axis open circuit subtransient time constant