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Research Paper

Transmission Reliability Cost Allocation Based on Contingency Filtering by Economic Indices in Large Power Systems

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Abstract: In this paper, the new approach for the transmission reliability cost allocation (TRCA) problem is proposed. In the conventional TRCA problem, for calculating the contribution of each user (generators & loads or contracts) in the reliability margin of each transmission line, the outage analysis is performed for all system contingencies. It is obvious that this analysis is very time-consuming for large power systems. This paper suggests that this calculation should be done only for major contingencies. To do this, at first, the contingency filtering technique (CFT) is introduced based on the new economic indices that quantify the severity of each contingency to determine the critical contingencies. Then the results of contingency filtering are used in the TRCA problem. The simulation results are reported for the IEEE 118-bus test system. The obtained results show that by application of CFT in TRCA problem, the simulation time is greatly reduced, but the percentage of error remains within an acceptable limit.

Keywords: Transmission Cost Allocation, Reliability Cost, Large Power System, Contingency Ranking, Filtering, Critical Contingency, Economic Index.

1 Introduction

SINCE deregulation in the power industry, the transmission cost allocation (TCA) problem has become a major concern in transmission open access, and many research works can be found in the literature on this subject [1-3]. To maintain system security, independent system operator (ISO) must retain some part of the transmission capacity as reliability margin which is not used in normal conditions [4, 5]. Therefore, it is reasonable to consider the reliability issue in the problem of transmission cost allocation. To do so, the transmission cost is divided into two parts: transmission line usage charge and system reliability charge, in which the cost of each part is allocated to users according to the specified algorithm. A number of papers have been published on this matter as transmission reliability cost allocation (TRCA) [6-11]. In TRCA problem two main questions will arise, the first question is how much of the transmission cost is associated with the reliability and second question is how this part of cost is allocated to users. To answer the first question, there are different opinions. It is obvious that considering the same amount for all lines in any operating conditions is not reasonable. Authors in [6] believe that the ratio between the transmission usage and reliability benefit must not be equal for all lines and should be calculated based on a reliability index. Hur *et al.* from different view have calculated the reliability contribution to line cost based on using a proportionality assumption and the ratio between the transmission reliability margin (TRM) and the total transmission capacity (TTC) [7]. Heng *et al*. consider charges for network security based on long run incremental cost pricing with SCOPF formulation [8].

In response to the second question, the main part of computation is devoted to identify the reliability contributions of each transmission user to the TRM of each line and to do so, the outage analysis to be performed for the system contingencies [9-11]. This analysis is very time consuming problem if all

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contingencies are considered, especially for large power systems. To overcome this problem, the present paper suggests that the results of the proposed contingency filtering technique can be used in TRCA problem. Therefore, those contingencies have lower importance are ignored, and the outage analysis is carried out only for critical contingencies.

Contingency ranking or filtering is an important step in power system security and reliability analysis, by which the solution can be accelerated. Upon making use of a suitable performance index (PI), the high ranked contingencies are identified and separated from those having lower importance. This filtering procedure becomes more important when the system is large and numerous contingencies to be considered [12-14]. Experience has shown that the result of contingency ranking is highly dependent on the selection and definition of PI which is used for measuring the severity of each contingency. Choice of parameters in PI is dependent on the application of contingency ranking and filtering. For example, in voltage stability study, the voltage magnitude and voltage stability margin to be used in PI [15] whereas in transmission planning and management, the line power flow and transmission losses are generally exploited [16]. In security-constrained optimal power flow (SCOPF) problem, parameters of OPF such as objective functions or Lagrangian multipliers are the most suitable choice [17].

In the present paper, as our intention is to use the results of contingency ranking to accelerate the TRCA problem, owing to its economic nature, the economic indices are the best choice for the definition of PI, so that they could fully reflect both system and power market operations. In [18], a few economic indices such as objective function and Euclidean norm of the Lagrangian multipliers are defined. There are many LMP-based economic indices for measuring the effects of transmission network on the competition level. The congestion cost is the most important index for this purpose which has been applied for congestion management and transmission expansion problem. Transmission Rent (TR) and flatness of LMPs are also other indices can be used for this analysis.

In this paper, our aim is to allocate the transmission reliability cost based on the contingencies ranking results with respect to their impact on the level of competition in power markets. There are many LMP-based economic indices are used to measuring the effects of transmission network on the competition level.

The rest of the paper is organized as follows. In Section 2, the general idea for proposed TRCA algorithm is stated. In Section 3 economic indices are described in details. The contingency filtering procedure is explained in Section. 4. In Section 5, we demonstrate that how the result of the contingency filtering can be used in TRCA problem. The presented approach is applied to IEEE 118-bus test system as a numerical example, and the obtained results are shown in Section 6 along with the necessary comparison. The conclusions are given in Section 7.

2 Proposed TRCA Algorithm Based on Contingency Filtering

In this section, the general idea for proposed TRCA algorithm is stated. The flowchart of procedure is illustrated at Fig. 1. The transmission capacity to be divided in two parts. The first part is the base capacity which is used in normal state and the other part is concerned with reliability margin which is needed for contingency state to maintain the security of the system. Therefore, it is reasonable to assign a portion of the transmission costs to system reliability. In the present paper, the reliability costs (RC) is calculated based on proportionality assumption and by the ratio between Transmission Reliability Margin (TRM) and Total Transmission Capacity (TTC). The ISO should allocate this cost to the users according to their level of benefit acquiring from transmission reliability. This task is called the TRCA. Due to the network structure and various locations of users, the users (loads and generators) will receive different levels of reliability, so it will be reasonable that the payments are made in proportion to their reliability usage. To do this, we should calculate the contribution of each user in reliability margin of each transmission line and for obtaining this information, outage analysis is needed for all contingencies.

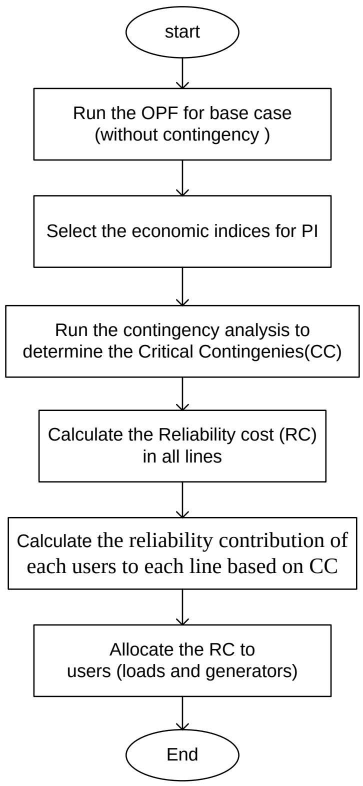

Fig. 1 General description of Proposed TRCA algorithm based on contingency filtering.

It is obvious that such analysis for a large scale power system is very time consuming, so ISO cannot do TRCA hourly. In the present paper, as our intention is to use the results of contingency ranking to accelerate the TRCA problem. In our method, the outage analysis is performed only for high importance (critical) contingencies. Now we calculate the reliability contribution of transmission agent to the TRM of a particular line under only critical contingencies.

Upon making use of a suitable performance index (PI), the high ranked contingencies are identified and separated from those having lower importance. Experience has shown that the result of contingency ranking is highly dependent on the selection and definition of PI which is used for measuring the severity of each contingency. Owing our problem has the economic nature, the economic indices are the best choice for the definition of PI, so that they could fully reflect both system and power market operations.

3 Economic Indices

To achieve the objectives of contingency ranking in deregulated environments, it is necessary to define some criteria to measure the effects of transmission network on the competition level of an electric market, so we have to define the PIs in which the economic parameters are exploited. Since in power markets, the most important economic parameter is LMP, the PIs are defined based on the LMP. Therefore, at first we explain the importance of the LMP and the procedure of its calculation in a power market and then the economic indices are introduced for contingency ranking and filtering problem.

The LMP at a bus is defined as the minimum marginal cost of supplying the next increment of load at that bus without violation of transmission limits. It means that the LMPs are dependent on generators bid, market clearing rules and transmission constraints. The LMPs are obtained within an OPF framework.

In this paper, DCOPF is used to model the market and the generation bid is considered as an objective function to be minimized. Equality constraints include the active power balance equation at each bus and inequality constraints are contain limits on line power flow and generation level. So DCOPF is formulated as follows:

$$Min \quad \sum_{i\in Ng} \rho_{g_i}\left(P_{g_i}\right)$$

Subject to:

$$\sum_{j=1}^{N_b} B_{ij}\left(\delta_i-\delta_j\right)=P_{g_i}-P_{d_i} \qquad i=1,2\ ,\ldots,N_b$$

$$P_l=\sum_{j=1}^{N_b}\left(H_{lj}\times\delta_j\right)\le P_l^{max} \qquad l=1,2,\ldots,N_l$$

$$P_{g_i}\le P_{g_i}^{max} \qquad i=1,2,\ldots N_g \tag{1}$$

where, ρ_{gi} is the bid function of generation unit i, P_{g_i} and P_{d_i} are the generation and the consumption at node i respectively. N_b, N_g, and N_l are the number of nodes, generators and lines respectively and δ_i is the voltage angle of node i. B is the network susceptance matrix and H is the Matrix relating voltage angles to lines flow. The parameter $P_{g_i}^{max}$ is the generation limit of generator i and also P_l^{max} is the flow limit in line l.

The Lagrangian function of the above optimization problem can be written as follows:

$$\begin{aligned}L=&\sum_{i\in N_g}\rho_{g_i}\left(P_{g_i}\right)+\sum_{i=1}^{N_b}\left(\lambda_i\times\sum_{j=1}^{N_b}B_{ij}\left(\delta_i-\delta_j\right)\right)\\&+\sum_{l=1}^{N_l}\left(\gamma_l\times\sum_{j=1}^{N_b}\left(\left(H_{lj}\times\delta_j\right)-P_{l_i}^{max}\right)\right)\\&+\sum_{i=1}^{N_g}\left(\sigma_i\times\sum_{j=1}^{N_b}\left(P_{g_i}-P_{g_i}^{max}\right)\right)\end{aligned} \tag{2}$$

where λ_i is the Lagrange multiplier associated with the power balance constraint at node i, γ_l and δ_i are the Lagrange multipliers related to limits for transmission line l and generation unit i respectively. LMP at bus i is λ_i^{opt} that satisfies Kuhn-Tucker condition of the Lagrangian function at the optimal point, so

$$LMP_i=\lambda_i^{opt} \qquad i=1,2,\ldots,\ N_b \tag{3}$$

The LMPs provide important economic signals that fully reflect both system and market operations at a specified time and can play an important role in energy transmission and power system management.

In this paper, our aim is to utilize the economic indices to specify the importance of the contingencies regarding their effects on the level of market competition. Accordingly, a contingency filtering is performed and the most effective contingencies are determined. The economic indices are described in the following subsections.

3.1 Transmission Rent

In nodal pricing markets (for instance, the PJM market in the United States), all participants purchase and sell electric energy based on the LMP of their buses. In these markets the transmission rent (TR) is defined as the difference between what the loads pay and what the generators are paid and can be calculated from (4) and is denoted by $PI1$ in this paper. We will use this parameter for measuring the severity of each contingency. Those Contingencies give rise to a higher TR, are more important from market point of view, hence they will take a higher rank in the contingency ranking procedure.

$$PI_1=TR=\sum_{i=1}^{N_b}\left(\mathrm{P_{d_i}}-\mathrm{P_{g_i}}\right)\times LMP_i \tag{4}$$

3.2 Congestion Cost

Other economic index based on LMP is the congestion cost (CC). The CC is mainly based on the actual power flow through the congested transmission line and is equal to the product of the difference in LMPs between the source buses and sink buses times the line power flow as formulated in (5) and is denoted by *PI*2. In view of this index, those contingencies bring about a higher difference in LMPs among buses are more important and consequently leading to a higher *CC*. It is clear that if either DCOPF is used for market model or in ACOPF the losses are not taken into account, the *CC* will be equal to *TR*.

$$PI_2 = CC = \sum_{l=1}^{N_l} \left(LMP_{l1} - LMP_{l2} \right) \times P_l \tag{5}$$

where LMP_{l1} and LMP_{l2} are LMP at source and sink buses of line l respectively and P_l is the active power flow in line l.

3.3 Flatness of LMP

In a perfect competitive market, from transmission point of view, all producers and consumers sell and buy electric energy at the same price; i.e. prices at all buses are the same, hence, the price profile will be flat. In this market there is no restriction for consumers to purchasing from any producer. However, this condition does not happen due to the transmission losses and power transfer limits, so the difference between the LMPs is pronounced. The degree of difference represents the effects of transmission network on the level of market competition. As the price profile becomes flatter, the differences among the LMPs are reduced, so the competition level increases from transmission point of view. In this paper, we propose to measure the flatness of LMPs by the standard deviation of LMPs (SDLMP). In this way, those contingencies leading to a greater increase in SDLMP are more important, so gaining a higher rank in the contingency ranking procedure. Fig. 2 shows that in the contingency state SDLMP increases in compare with non-contingency state as a base case. This figure is related to IEEE 118-bus test system and the corresponding information is found in Section 6.

Therefore, the increment in standard deviation of LMP (*ISDLMP*) can be treated as a contingency ranking index (PI_3), which is defined by (6):

$$PI_3 = ISDLMP_k = Std\left(\overline{LMP}_k\right) - Std\left(\overline{LMP}_0\right) \tag{6}$$

Where, $\overline{LMP}_k$ is a vector of LMPs in k-th contingency and $\overline{LMP}_0$ is a vector of LMPs in the non-contingency condition. In this index although quantities of lines power are not used, but it well considers all network constraints.

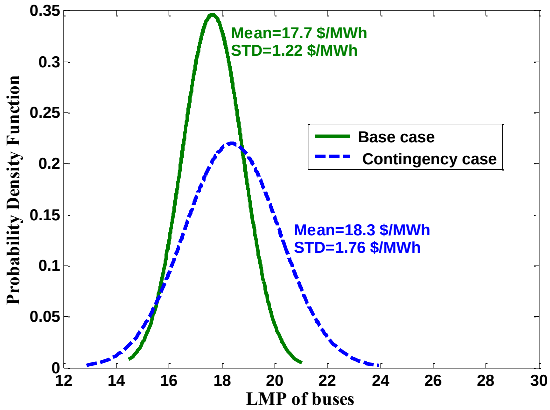

Fig. 2 Normal pdf curve of LMPs for non-contingency as a base case and contingency state

To compare the results of our proposed economic indices employed for contingency ranking (*TR*, *CC* and *ISDLMP*), two economic indices from [7] are selected. These are the Euclidean norm of LMPs formulate in (7) by *PI*4 and the objective function of OPF define as the PI_5 in (8):

$$PI_4 = LMP_{i2} = \sqrt[2]{\sum_{i=1}^{N_b} LMP_i^2} \tag{7}$$

$$PI_5 = \left(\frac{F_k}{F_0} - 1 \right) \times 100 \tag{8}$$

where, F_k and F_0 are the objective function of OPF in k-th contingency and non-contingency state, respectively. So PI_5 shows the percent of variation in objective function due to k-th contingency.

4 Contingency Filtering Procedure

In this section, the procedure of the proposed contingency ranking and filtering scheme is explained. Fig. 3 illustrates the flowchart of the procedure. At first, the OPF program is run for base case (non-contingency state) and the economic performance indices (PIs) are calculated using (4)–(8) for this state. Next we select a single contingency and after being modeled in OPF, the OPF program is executed and PIs are calculated for contingency state. Then a comparison is made between PIs resulting from these two states. If the rate of change in PI is greater than a pre-specified value, say α, the variable CCN (critical contingency number) becomes an additional one and the program proceeds until all contingencies are covered. When this process is terminated, the severity indices corresponding to all contingencies are determined and CCN is also identified. Now the contingencies can be ranked based on their severity and the filtering is accomplished with regard to the value of CCN. In other words, the value given by CCN represents the number of top ranked contingencies, (with $SI > \alpha$) i.e. the most important and

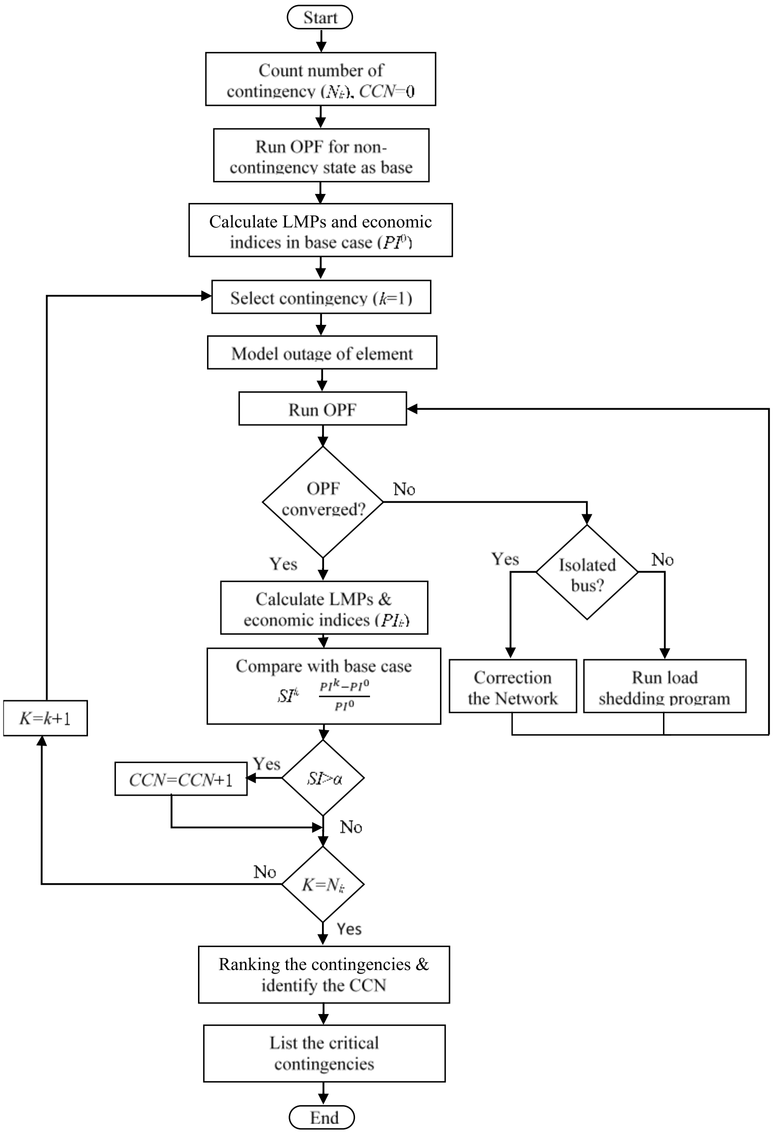

Fig. 3 Flowchart of contingency filtering procedure.

dominant ones in view of their effects on market.

In our proposed algorithm, in order to determine the number of most effective contingencies, the severity index (SI) is used. This index is defined by (9), in which the PI_i^k and PI_i^0 are the performance indices i related to the k-th contingency and non-contingency states respectively. According to this equation, the SI of each performance index is calculated for all contingencies. N_k is the number of contingencies.

$$SI_i^k(\%) = \frac{PI_i^k - PI_i^0}{PI_i^0} \times 100\,, \quad k = 1,2,\ldots,N_k\,, \; i = 1,\ldots,5 \qquad (9)$$

Now, if the magnitude of SI for each contingency is greater than the pre-specified value α, this contingency is considered as a critical contingency. The parameter α is included in the input data and its assigned value is dependent on the network dimension, operator experience and the nature of problem in which the contingency filtering is performed. Fig. 4 shows the SI of contingencies for α is equal to 5%. It is clear that for a higher value of α, the lower CCN is obtained by program.

5 Transmission Reliability Cost Allocation

Allocating a part of transmission capacity as a security and reliability margin is a necessary task in a power system operation and planning, so the system to be able to maintain its stability in the case of contingency. Therefore, it is reasonable to assign a portion of the transmission costs to system reliability. There are different approaches for calculating the transmission reliability costs as are reviewed in Section 1. In the present paper, the reliability costs (RC) is calculated based on proportionality assumption and by the ratio

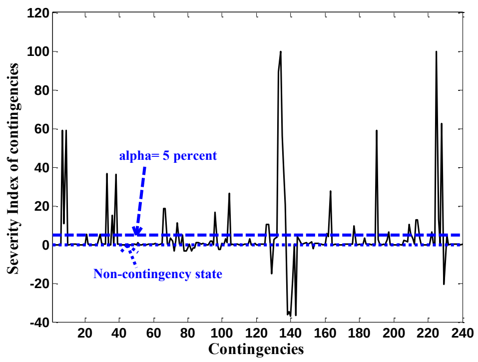

Fig. 4 Severity index of contingencies at α = 5%.

between TRM and TTC using (10).

$$RC_i = \frac{TRM_i}{TTC_i} \times TC_i \tag{10}$$

where TRM_i is the reliability margin of line i, TTC_i is the total transfer capacity of line i and TC_i is the total cost of line i.

Due to the network structure and various locations of users, they will receive different levels of reliability, so it will be reasonable if payments are made in proportion to their reliability usage. To do this, we should calculate the contribution of user U_j to the *TRM* of a particular line i under only critical contingencies from (11). Transmission users can be bilateral contracts or individual generators and loads.

$$R_i^{U_j} = \frac{\sum_{k=1}^{CCN} RC_{i,k}^{U_j}}{\sum_{i=1}^{m}\sum_{k=1}^{N_k} RC_{i,k}^{U_j}} \tag{11}$$

Where, $R_i^{U_j}$ is the reliability contribution of transmission line i by user U_j, $RC_{i,k}^{U_j}$ is the utilization of transmission line i by agent Uj under critical contingency k, *CCN* is the critical contingency number and m is the total number of users.

Finally, we can calculate the transmission reliability cost of line i allocated to user U_j by (12) and then the reliability cost of each user is computed by (13).

$$RC_i^{U_j} = R_i^{U_j} \times RC_i \tag{12}$$

$$RC_{U_j} = \sum_{i=1}^{N_l} RC_i^{U_j} \tag{13}$$

In our proposed method, when dealing with TRCA problem, as only the high ranked contingencies are considered, some errors are introduced in the calculation of reliability costs so, in order to assess this method, the amount of error to be calculated. To do this, at first, we calculate the reliability costs for agents when all contingencies are considered and they are represented by a vector X. The same calculation is done using the proposed method in which only the high ranked contingencies are considered, so the obtained reliability costs are represented by a vector X^*. Then ΔX is defined as a vector error with (14). The root mean square (RMS) of error is calculated using (15). This index of error is not able to provide an exact assessment, because once the RMS of error is satisfactory while the resulting error for a few users may be high. Hence, further indices, i.e. the standard deviation and the maximum of the vector error are used in the process of assessment. They can be evaluated from (16) and (17).

$$\Delta X = X - X^* \tag{14}$$

$$RMS - Error = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta X)^2} \tag{15}$$

$$STD - Error = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\Delta X - \overline{\Delta X}\right)^2} \tag{16}$$

$$MAX - Error = Max(\Delta X) \tag{17}$$

6 Simulation Results

In this section, we present numerical results obtained from implementation of proposed approaches on the modified IEEE 118-bus test system, summary information of this network is presented in Table 1. The full network data for this system is found in [12, 13]. This network has two voltage levels, 345kV with 12 buses and 11 lines and 138kV with 106 buses and 166 lines, as connected together via 9 transformers. This system has 54 generation units. The bids of generating companies are obtained from [13].

6.1 Contingency Ranking Results

The proposed method is implemented using MATLAB software. Simulation results consist of contingency ranking and filtering and application of filtering in TRCA problem. Once OPF is performed for all 240 contingencies, the value of *CCN* and also the values of SIs are determined. Based on these SIs, the contingencies can be ranked. The contingency ranking results for 30 top ranked out of a set of 240 contingencies, are shown in Table 2. It should be noted

Table 1 Brief information for IEEE 118-bus test system.

Index	Number	Capacity [MVA]		
		Total	Min	Max
All Lines	186	34200	100	500
345kV Branches	11	4700	100	500
138kV Branches	166	4500	500	500
Transformer	9	25000	100	500
Generators	54	8270	20	650
345kV Generators	5	1350	30	500
138kV Generators	49	6920	20	650
All Loads	91	4519	2	440
345kV Loads	2	212	28	184
138kV Loads	89	4307	2	440

Table 2 Contingency ranking results.

Rank	SI_1& SI_2 (*TR* & *CC*)		SI_3 (*ISDLMP*)		SI_4 (Norm2 LMP)		SI_5 (Obj. Fun)	
	Name	SI_1 [%]	Name	SI_3 [%]	Name	SI_4 [%]	Name	SI_5 [%]
1	G39	99.9	G4	174	G4	8.6	G39	4.24
2	L134	89.3	L9	161	L9	7.8	L134	3.55
3	L133	62.7	L7	53.1	L7	4.0	L133	3.40
4	G42	59.0	G42	46.9	G39	3.78	G28	3.4
5	L9	59.0	L134	44.3	L134	3.13	G27	3.36
6	L7	59.0	L133	42.6	L133	2.57	G11	1.93
7	G4	56.5	G39	30.3	G28	2.56	G20	1.93
8	L135	37.7	L33	26.1	G27	2.21	G21	1.74
9	L136	36.7	L135	18.5	G11	1.62	G4	1.74
10	L33	36.3	L136	17.6	G5	1.60	L9	1.74
11	L38	27.5	L137	14.4	G20	1.60	L7	1.14
12	L163	26.4	L104	11.2	G21	1.58	G24	1.13
13	L104	20.6	L38	10.9	G29	1.57	G25	1.01
14	L137	18.5	G27	10.9	G10	1.33	G45	0.99
15	L66	18.5	G28	9.0	G45	1.33	G43	0.93
16	L67	16.5	G40	8.9	G36	1.16	G29	0.93
17	L96	15.1	L129	8.1	G25	1.15	G10	0.93
18	L36	13.0	G11	6.3	G44	1.05	G5	0.92
19	G40	12.8	L8	5.6	G24	0.83	G36	0.85
20	G28	12.7	G29	5.5	G42	0.62	L135	0.85
21	G27	11.1	L163	5.4	L132	0.53	G40	0.78
22	L74	11.0	G5	5.3	L135	0.50	L136	0.77
23	L8	10.5	G10	5.3	L8	0.43	G44	0.72
24	G23	10.2	G20	5.3	L131	0.35	L129	0.38
25	L126	10.2	G21	4.9	L96	0.28	L33	0.35
26	L127	9.7	G36	4.4	G40	0.27	L137	0.25
27	L177	6.6	G45	3.7	L130	0.25	L38	0.22
28	G36	6.3	G24	3.7	L136	0.24	L104	0.21
29	G11	5.9	G25	3.2	G43	0.18	L132	0.18
30	L161	5.5	L96	2.7	G37	0.17	L8	0.17

that in the ranking process SI_1, SI_2, and SI_3 are our proposed indices defined by (7)–(9) while SI_4 and SI_5 are Euclidean norm of LMPs and the objective function of OPF from [7] defined by (10) and (11). The latter indices are used for the aim of comparison. Because of using the DCOPF, SI_1 (severity index based on *TR*) and SI_2 (severity index based on *CC*) provide same results.

It can be seen from Table 2, overlap of those contingency ranking results obtained based on different indices are slightly different and about 80% is observed. For example, generator 4 at bus 10 takes rank 1 using SI_3 and SI_4 indices while takes rank 7 by using SI_1 and rank 9 with SI_5. Based on these results we cannot say which index is preferred over others, however, the best index is one that introduces a smaller error in any intended applications. In the application of TRCA problem, as will be shown in the subsequent section, SI_1 and SI_2 appear to be more preferred since yielding a smaller error.

The value of *CCN* is dependent on α and also the performance index used. Fig. 5 shows the severity of contingencies based on *TR* index. Using this index and selecting α equal to 1%, *CCN* becomes 59, while as shown in Fig. 6, for the same value of α and with Euclidean norm of LMPs index, *CCN* reduces to 18. Table 3 shows the value of *CCN* with different values of α using all indices. These results indicate that the *TR* index provides more discrimination regarding the intensities between contingencies, while in the case of SI_3 and SI_4, the intensity of high ranked and low ranked contingencies is slightly different. Therefore, it seems that the *TR* index is more suitable for contingency assessment.

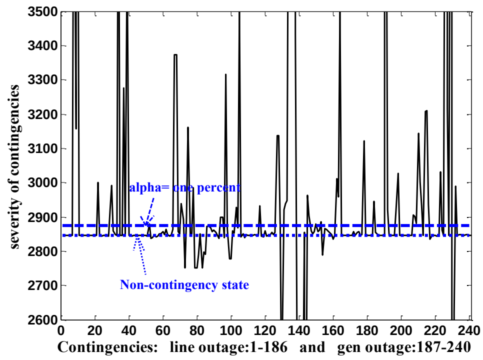

Fig. 5 Severity of contingencies based on *TR* index.

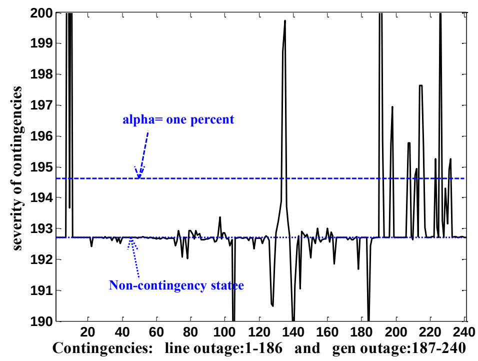

Fig. 6 Severity of contingencies based on Euclidean norm of LMPs index.

Table 3 Critical contingency number (CCN) for indices in different value of α.

α	*CCN*			
	SI_1& SI_2 (TR & CC)	SI_3 (ISDLMP)	SI_4 (Norm2 LMP)	SI_5 (Obj. Fun)
0.04	35	26	3	1
0.02	50	33	8	5
0.01	59	38	18	13
0.008	62	39	19	20
0.006	69	40	20	23
0.004	78	44	23	23
0.002	94	52	28	28
0.001	102	63	37	31
0.0005	117	73	45	34

It can be seen from Figs. 5 and 6, which the values of index for some contingencies are below the base case. It means that occurrence of such contingencies are not economically important, however, they may be technically important when in contingency analysis, technical indices such as voltage stability are also included. In the present study as DCOPF is used, the voltage constraints concepts are not considered. Considering the voltage stability in contingency ranking requires ACOPF which is beyond the scope of this paper.

6.2 Transmission Reliability Cost Allocation

This subsection considers how the contingency ranking and filtering results can be employed to solve the problem of transmission reliability cost allocation

Table 4 The simulation time and error indices for different number of contingencies.

CCN	Simulation Time	RMS-Error [%]				STD-Error [%]				Max-Error [%]			
		SI_1 & SI_2	SI_3	SI_4	SI_5	SI_1 & SI_2	SI_3	SI_4	SI_5	SI_1 & SI_2	SI_3	SI_4	SI_5
20	12.8	21.5	28	28.8	22.4	21.7	28	29	22.6	42.4	42.1	41.8	42.8
40	41.7	14.78	18.1	14.93	18.48	14.9	18.2	15	18.58	19	20.6	19.2	21.1
60	81.9	9.2	12.1	12.3	12.3	9.3	12.1	12.4	12.3	12.2	15.1	14	16.1
80	140.2	5.91	8.22	8.09	9.32	5.94	8.26	8.14	9.37	7.9	10.2	9.8	11.5
100	208.2	4.59	6.27	5.25	7.03	4.61	6.3	5.27	7.07	5.32	6.91	6.52	8.16
120	289.9	3.32	4.55	4.09	5.27	3.34	4.57	4.12	5.29	3.79	4.92	5.76	6.19
140	388.2	2.13	3.01	2.98	3.80	2.14	3.03	2.99	3.82	2.70	3.29	4.12	4.40
160	496.15	1.64	2.20	1.85	2.58	1.64	2.21	1.86	2.60	1.92	2.15	2.88	2.74
180	618.6	1.01	1.75	1.54	1.64	1.02	1.76	1.55	1.65	1.92	1.80	1.79	1.86
200	754.4	0.62	1.30	1.10	1.05	0.63	1.31	1.11	1.05	1.15	1.14	1.96	1.05
220	908.5	0.55	0.73	0.85	0.80	0.55	0.73	0.86	0.80	1.44	0.93	1.68	0.96
240	1078.9	0	0	0	0	0	0	0	0	0	0	0	0

(TRCA) based on proposed economic indices. Furthermore, it is used to identify which of these indices is more appropriate i.e. yielding a smaller error. For calculating the usage contribution of each user to each line, the Bialek power flow tracing method has been used. In accordance with procedure described in section4, at first TRCA is done for all 240 contingencies and to consider it as a base for purpose of comparison. Next, the TRCA is run for all critical contingencies, say 20 (*CCN*=20), based on 4 SIs. The difference between the results obtained from these two cases shows the amount of error which is introduced by our proposed filtering approach. Then the error indices are calculated for each of SIs using (17)–(20). Table 4 shows the results of proposed approach for different values of *CCN* considering three error indices (RMS, STD and Max) for all SIs. Also in the second column, the simulation time for each value of *CCN* is reported.

It can be seen from table 4, that the proposed index SI_1 in compare with other indices causes a smaller error, so this can be the most appropriate index for contingency filtering used in TRCA problem. Results also show that when the *CCN* is small the difference between RMS-error and Max-error is somewhat high but by increasing the *CCN*, this difference becomes smaller and acceptable. Therefore, for choosing an appropriate value of α to determine the *CCN* the difference between RMS and MAX error should be regarded. It is evident from results of Table 4; the simulation time is greatly decreased when the number of contingencies are limited. For example, if we consider half of the total contingencies (120), the amount of error is only 3.32% but the simulation time will decrease about 74%. This concept is further elaborated in Fig 7. This figure shows that by decreasing the *CCN*, the simulation time will exponentially decrease but the percentage of error remains within an acceptable limit.

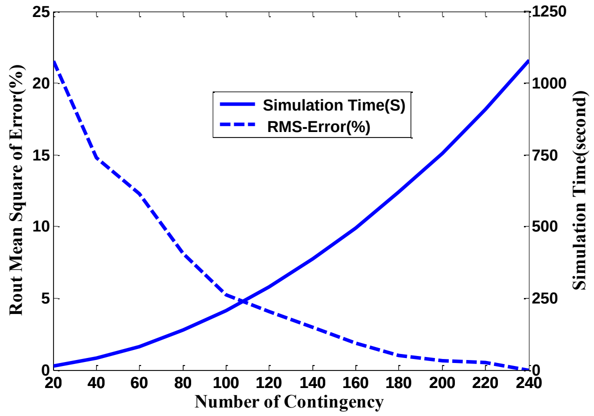

Fig. 7 Compare error and simulation time for different number of contingency.

7 Conclusion

In this paper, the results of contingency filtering are applied in TRCA problem so that the analysis is carried out only for critical contingencies. As the TRCA is an economic problem, in this paper three economic indices that these indices can well present the effects of transmission network on the competition level of a power market. Also, by defining the parameter α the number of critical contingencies can be controlled.

The obtained results show that when the number of critical contingencies is decreased, the simulation time is exponentially decreased, but the percentage of error remains within an acceptable limit.

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