Determination of Critical Contingency Based on L-Index and Impact Assessment on Power System

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Abstract The outage of transmission line creates contingency in power system. Therefore, determination of critical contingency is essential for stability analysis purpose. In this article, the critical bus is identified using well-known L-index method, and thereafter, the critical contingency is found through maximum L-index value considering all contingency scenarios. Moreover, the deviation of the bus voltage profile is presented through a new index, i.e., voltage deviation index (VDI). Furthermore, the deviation of the post-contingency power loss is evaluated through proposed loss deviation index (LDI). The case studies are performed on IEEE 6 and 30 bus systems in MATLAB environment. The analysis of the test results will be helpful for contingency-constrained voltage stability study.

Keywords Power system · Contingency · L-index

1 Introduction

In the recent years, the transmission network experiences a lot of stress due to deregulation of entire power grid network. In the deregulated network, each entity, i.e., transmission, generation and distribution operates independently to promote the overall efficiency and flexible operation [1] of the system. However, if contingency occurs in power system due to outage of generator, transmission line or transformer, the system becomes more and more stressed. This stressed network is more vulnerable to collapse. Therefore, power system stability analysis is required to find the critical bus and critical line so that the power engineers and planners can take appropriate action to avoid the system breakdown.

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K. Namrata et al. (eds.), *Smart Energy and Advancement in Power Technologies*, Lecture Notes in Electrical Engineering 926,
https://doi.org/10.1007/978-981-19-4971-5_42

The researchers have reported several methods in literature [2–6] for stability analysis purpose. In [2], authors proposed Lmn index for line stability analysis. The value of Lmn index must be less than 1 for stable system. The fast voltage stability index (FVSI) is presented in [3] for determination of critical line. The FVSI value nearest to 1 represents the critical line. Sekhawat et al. [4] analyzed the voltage stability using FVSI and Lmn indices. The weak bus identification and maximum loadability determination are done using line stability indices. Authors proposed novel voltage stability index (NVSI) [5] which takes into account both active and reactive power. Unlike FVSI and Lmn, proximity of the value of the NVSI to unity indicates that the system is approaching toward instability. Three line stability indices, i.e., FVSI, Lmn, NVSI and one bus stability index, i.e., ratio index are used in [6] for stability analysis. Additionally, the shunt compensators are used for reactive power support. Furthermore, the L-index is proposed in [7] as a stability measuring tool and used in [8] for determination of critical contingency. The authors in [9] used the performance index as a tool for contingency ranking. The real power, reactive power and voltage are considered combinedly for ranking evaluation. The popular fast decoupled technique is used in [10] for contingency selection. The impact of contingency due to line outage is presented in [11] through PV curve. It is also observed that bus voltages decrease with the increased loading scenario. Further, the optimization of weighting factor is employed in [12] for improving the contingency ranking. The authors proposed voltage and reactive power-related index in [13] for screening and ranking of contingency. The authors in [14] identified the contingency due to line outage using the synchronized measurements at generator buses. A probabilistic performance index is used for ranking of the contingency in [15], and the technique is applied up to second-level contingency. In this study, the critical bus and critical line of the system are determined. Furthermore, the impact of contingency on power grid network is also evaluated in terms of voltage deviation and power loss deviation.

2 Methodology

The whole study is mainly divided into two parts.

- Voltage stability analysis
- Contingency analysis

In voltage stability part, the weak bus and line of the system are identified. The identification of the weakest bus and weakest line is utmost required in order to avoid unpredictable voltage collapse. Further, the weakest bus is to be determined for placing suitable compensating devices for improving the performance of the whole system.

In contingency analysis part, the comparison of the load bus voltage and system loss between base case and critical contingency case is outlined. The detailed description of the whole methodology is highlighted in the following section.

2.1 Analysis of Voltage Stability

The analysis of voltage stability is conducted to find the critical bus and critical line. It is of paramount importance to find the weak bus of the power network. The weak bus is to be monitored properly to avoid the voltage collapse. Furthermore, the compensating action for reactive power support is to be done at the weak bus in order to get optimum economic benefit. Although several methods are available to identify the weak bus, the popular L-index [7]-based method is adopted here. The L-index for k-th load bus is represented by Eq. (1)

$$L_k = \left| 1 - \sum_{i=1}^{n_g} F_{ki} \frac{V_i}{V_k} \right|, \quad k = 1, 2, \ldots, n_l \tag{1}$$

Here, n_g is the number of generator bus, and n_l is the number of load bus. The voltage at i-th and k-th bus is represented by V_i and V_k, respectively. Further, the matrix F_{ki} can be expressed by following Eq. (2)

$$F_{ki} = -[Y_{LL}]^{-1}[Y_{LG}] \tag{2}$$

Here, Y_{LL} is the sub-matrix of bus admittance matrix, and the elements are associated with only load buses. Similarly, Y_{LG} is the sub-matrix of bus admittance matrix, and the elements are associated with load buses and generator buses.

The L-index value lies between 0 and 1. The maximum L-index value corresponds to the critical value. The L-index value close to 0 represents that the system is secured and stable. For zero loading condition, system bus voltages are 1 p.u., and thus, the L-index for load buses will be close to zero which indicates the stable system.

2.2 Contingency Analysis

The second part of our study is finding out the critical contingency and its impact assessment. This task is performed by identifying the critical line. Now, the critical line is identified through repeated load flow study for all possible contingency scenarios. For each contingency scenario, the L-indices of the load buses are calculated and maximum L-index value represents the critical contingency. Therefore, the corresponding line due to which that particular contingency occurs is designated as critical line.

Now, it is interesting to note that each contingency results into the deviation of the system voltage profile and system losses. Deviation of voltage is to be measured to avoid voltage collapse and maintain proper voltage stability. On the other hand, the deviation of system loss is to be measured for loss minimization purpose or to ensure maximum usable power. Therefore, the quantification of the deviation of the system voltage and deviation of the system loss is very vital. In this context, a new index, i.e., voltage deviation index (VDI) is introduced here to quantify the post-contingency voltage deviation. The VDI is expressed by Eq. (3)

$$\mathrm{VDI} = \frac{\sum_{i=1}^{n_l} V_i - \sum_{i=1}^{n_l} V_i^k}{\sum_{i=1}^{n_l} V_i} \tag{3}$$

Here, V_i and V_i^k represent the base case voltage of i-th bus and voltage of i-th bus after k-th contingency.

Furthermore, another index, i.e., loss deviation index (LDI) is introduced to measure the loss deviation. The LDI is written by Eq. (4)

$$\mathrm{LDI} = \frac{\mathrm{Loss} - \mathrm{Loss}^k}{\mathrm{Loss}} \tag{4}$$

Here, in Eq. (4), Loss and Loss^k represent the base case system loss and system loss after k-th contingency. Now, the total system loss can be calculated as

$$\mathrm{Loss} = \sum_{i=1, i \neq j}^{L} L_{ij} \forall \,\mathrm{lines} \tag{5}$$

Here, L denotes total number of lines, and L_{ij} denotes power loss at line connecting between i-th bus and j-th bus. Further, the loss at any line can be computed by using following Eq. (6)

$$L_{ij} = P_{ij} + P_{ji} \tag{6}$$

Here, P_{ij} and P_{ji} denote the real power flows from i-th bus to j-th bus and j-th bus to i-th bus, respectively. The real power flows from i-th bus to j-th bus can be written by Eq. (7)

$$P_{ij} = \mathrm{Re}\left[V_i\left(I_{ij}^*\right)\right] \tag{7}$$

Here, I_{ij} denote the current flows from i-th bus to j-th bus.

By stepwise, the whole computational process is demonstrated below:

1. Read the system data.
2. Run the load flow program.
3. Calculate the L-index value for load buses using (1) and (2).
4. Determine the maximum L-index value, and the corresponding bus is designated as critical bus.
5. Simulate the contingency one by one, and for each contingency, the maximum L-index value is stored.
6. Sort the L-index value for different contingency scenarios.
7. Find out the maximum value of L-index among all contingency scenarios.

8. The maximum L-index value corresponds to the critical contingency, and designate the critical line.
9. Calculate the VDI and LDI for critical contingency.
10. Display results.

3 Numerical Results and Discussion

The presented scheme is designed in MATLAB, and the logical program is executed. The simulation is done with MATLAB 7.10.0 (R2013a) platform loaded in a computer having Intel core-i3 processor.

3.1 IEEE 6 Bus Study

The whole case study is conducted on IEEE 6 bus network (Fig. 1) which has eleven lines, three load buses and two generator buses (buses 2 and 3).

The L-index value for load buses 1, 2 and 3 (buses 4, 5, 6) is found to be 0.2162, 0.2958 and 0.2506, respectively. The computed L-index value for base case is presented in Fig. 2 which shows that the maximum L-index is found for load bus 2, i.e., bus 5. Hence, bus 5 is designated as critical bus. Now, the L-index value for different contingency scenarios is also calculated, and the maximum value for each contingency scenario is presented by Fig. 3. The maximum L-index value among all

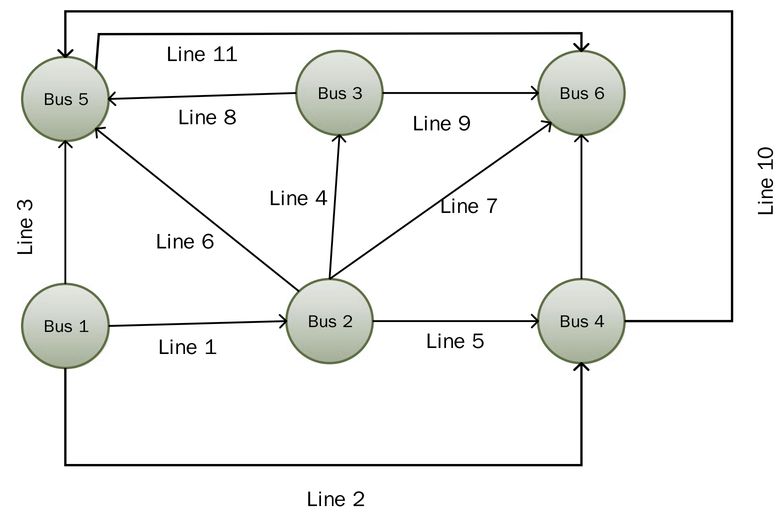

Fig. 1 Schematic of IEEE 6 bus system

contingencies is found 0.8114 which refers to the contingency 9, i.e., outage of line 9. Therefore, line 9 is designated as critical line.

Now, the VDI is calculated for all possible contingencies, and the VDI is represented in Fig. 4. It is seen from Fig. 4 that almost all the VDIs are positive. The positive VDI indicates the degradation of the voltage profile after contingency. Further, the

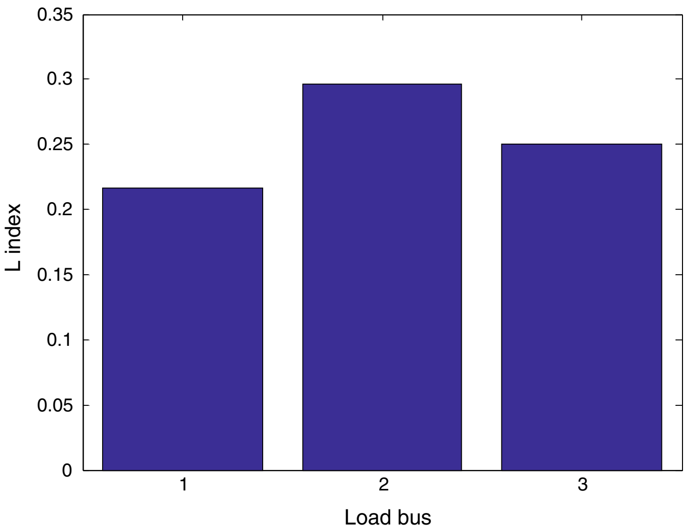

Fig. 2 L-index value for load buses of IEEE 6 bus network

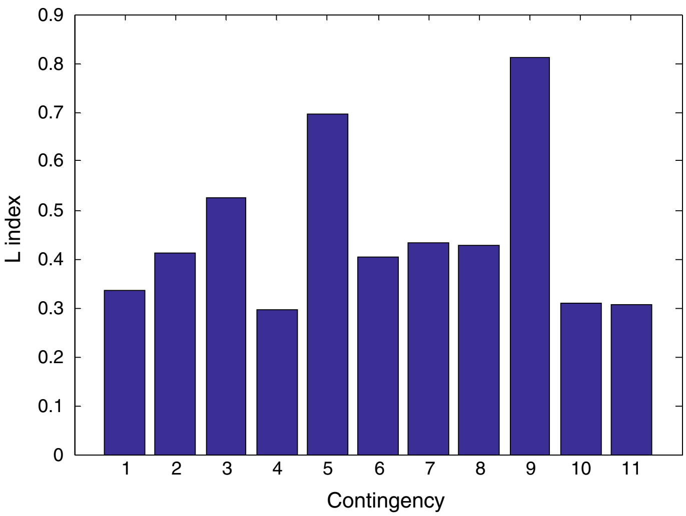

Fig. 3 Maximum L-index value for different contingencies of IEEE 6 bus network

LDIs for all contingencies are displayed in Fig. 5. It is observed that almost all the LDIs are negative. The negative LDI indicates the increase of loss after contingency. It is seen that for critical contingency, i.e., contingency 9, the VDI is positive and LDI is negative.

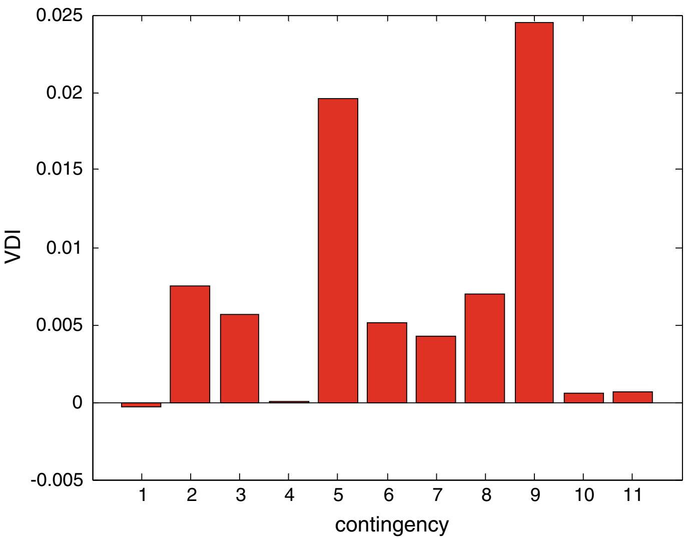

Fig. 4 VDI for different contingencies of IEEE 6 bus network

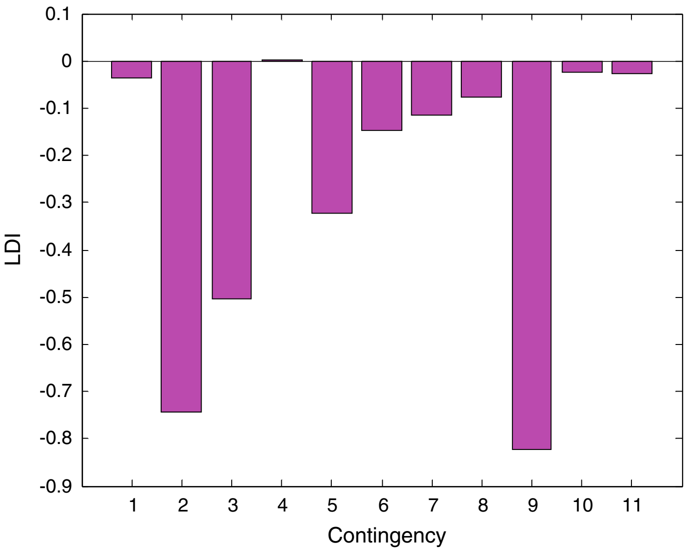

Fig. 5 LDI for different contingencies of IEEE 6 bus network

Table 1 Bus voltage comparison between base case and critical contingency case

Bus no.	Base case voltage (p.u)	Critical contingency voltage (p.u)
4	0.9864	0.9824
5	0.9797	0.951
6	1.0014	0.8834

In order to show the deviation of the voltage profile after contingency, the comparison of the bus voltages is represented in Table 1 which shows that the load bus voltages decrease during contingency. Here, only the comparison of bus voltages between critical contingency case and base case is shown.

3.2 IEEE 30 Bus Study

This system has 41 lines, 24 load buses and 5 generator buses (bus and line data given in Appendix). For this system, considering the base case, the maximum L-index value is found 0.0846 which corresponds to load bus 24 (Fig. 6), i.e., bus 30. Hence, bus 30 is designated as critical bus. Now, the L-index value for different contingency scenarios is also computed, and the maximum value for each contingency scenario is displayed in Fig. 7. It is observed from Fig. 7 that the maximum L-index value among all contingencies is 0.3068 which corresponds to the contingency 33. It is worth noting that load flow solution diverges during outage of line 13, 16 and 34. Therefore, these three contingencies are not considered in the simulation study. Hence, contingency 33 basically represents the outage of line 36, and this line 36 is designated as critical line.

After determination of critical bus and critical line, the VDI is calculated. The computed VDI for different contingencies is presented in Fig. 8. It is noticed that all the VDIs are positive which indicate that the voltage profile degrades after contingency. Similarly, the LDI for all contingencies is also calculated and presented in Fig. 9. Figure 9 implies that most of the LDI values are negative which indicate that the loss is increased after contingency. For critical contingency, it is observed that VDI is positive and LDI is negative. Hence, the corrective actions are needed to compensate the loss and voltage degradation due to contingency. The power system planners will take the action as per the requirement. Some possible actions may be load reduction, placement of SVC or FACTS devices, distributed generation (DG) penetration, etc.

The presented study can be extended in the following area:

- The multiple line contingency may be considered in the future work as here only $N - 1$ contingency is discussed
- The contingency due to tripping of generator, transformer or other than line element may be taken into account as future scope of this work

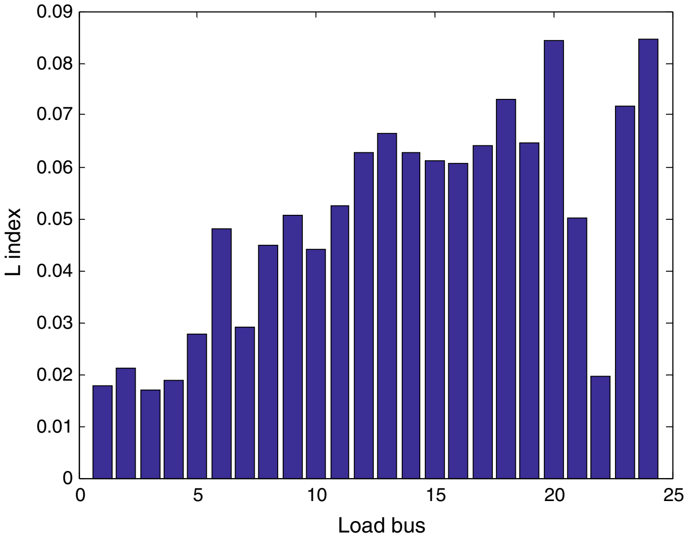

Fig. 6 L-index value for load buses of IEEE 30 bus network

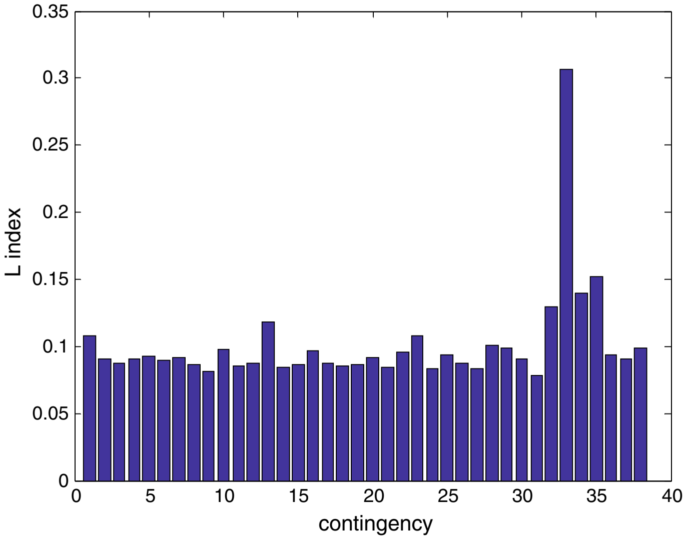

Fig. 7 Maximum L-index value for different contingencies of IEEE 30 bus network

- The appropriate action like placing of FACTS devices may be considered for improving the voltage stability and performance of the network. In this context, the determination proper location and the sizing of the devices will be another future scope of this study

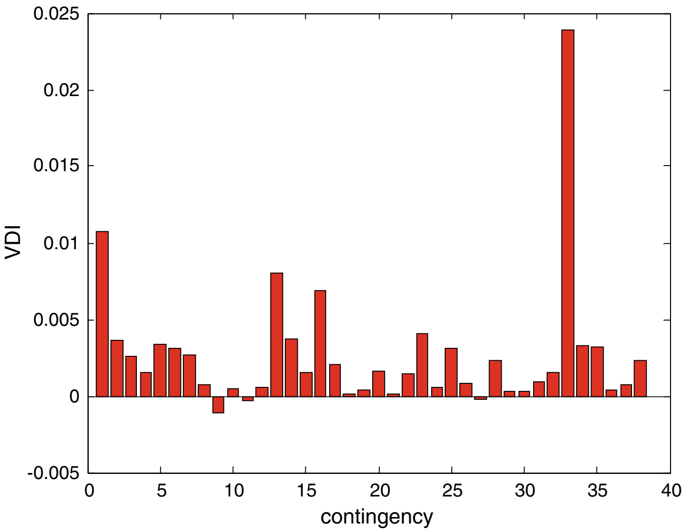

Fig. 8 VDI for different contingencies of IEEE 30 bus network

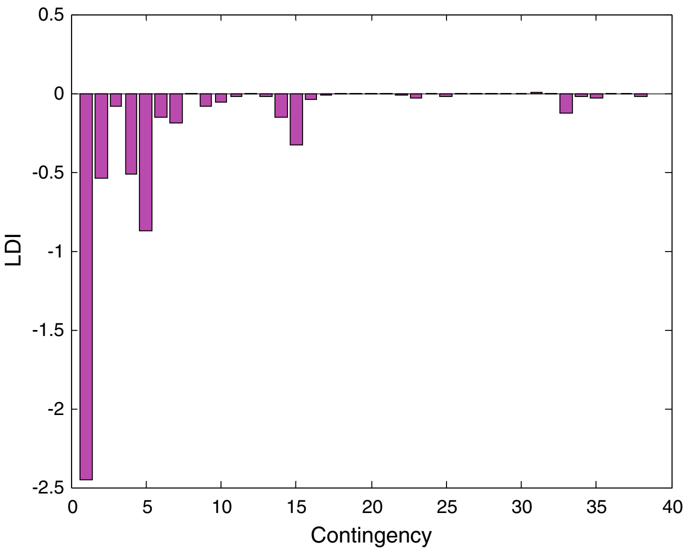

Fig. 9 LDI for different contingencies of IEEE 30 bus network

- The large network such as IEEE 57 bus, 118 bus may be considered as the test bed.

4 Conclusion

In this work, the voltage stability analysis as well as contingency analysis are conducted. The critical bus is identified through L-index value, and thereafter, the critical contingency is also determined. The impact of the contingency is evaluated through two novel indices, i.e., VDI and LDI. In majority of cases, the VDI found positive and LDI found negative. Therefore, it can be concluded that contingency generally degrades the voltage profile of the system and increases the power loss in the system. This study will be helpful to the power system planners for contingency analysis. The information regarding critical bus and critical line may be used for monitoring purpose or installation of suitable devices in order to improve the system stability or transfer capability. In the near future, the work may be extended considering the load variation scenario which is evident in real power network.

Appendix

See Tables 2 and 3.

Table 2 Bus data of IEEE 30 bus network (Type: 3—slack bus, 2—PV bus, 1—load bus)

Bus no.	Type	V	PL	QL	Pg	Qg	Qmax	Qmin	G	B
1	3	1.06	0	0	0	0	0	0	0	0
2	2	1.043	21.7	12.7	40	48.9	50	−40	0	0
3	1	1	2.4	1.2	0	0	0	0	0	0
4	1	1	7.6	1.6	0	0	0	0	0	0
5	2	1.01	94.2	19	0	36.6	40	−40	0	0
6	1	1	0	0	0	0	0	0	0	0
7	1	1	22.8	10.9	0	0	0	0	0	0
8	2	1.01	30	30	0	41.2	40	−10	0	0
9	1	1	0	0	0	0	0	0	0	0
10	1	1	5.8	2	0	0	0	0	0	0.19
11	2	1.082	0	0	0	16.3	24	−6	0	0
12	1	1	11.2	7.5	0	0	0	0	0	0
13	2	1.071	0	0	0	10.3	24	−6	0	0
14	1	1	6.2	1.6	0	0	0	0	0	0
15	1	1	8.2	2.5	0	0	0	0	0	0
16	1	1	3.5	1.8	0	0	0	0	0	0
17	1	1	9	5.8	0	0	0	0	0	0
18	1	1	3.2	0.9	0	0	0	0	0	0

(continued)

Table 2 (continued)

Bus no.	Type	V	PL	QL	Pg	Qg	Qmax	Qmin	G	B
19	1	1	9.5	3.4	0	0	0	0	0	0
20	1	1	2.2	0.7	0	0	0	0	0	0
21	1	1	17.5	11.2	0	0	0	0	0	0
22	1	1	0	0	0	0	0	0	0	0
23	1	1	3.2	1.6	0	0	0	0	0	0
24	1	1	8.7	6.7	0	0	0	0	0	0.043
25	1	1	0	0	0	0	0	0	0	0
26	1	1	3.5	2.3	0	0	0	0	0	0
27	1	1	0	0	0	0	0	0	0	0
28	1	1	0	0	0	0	0	0	0	0
29	1	1	2.4	0.9	0	0	0	0	0	0
30	1	1	10.6	1.9	0	0	0	0	0	0

Table 3 Line data of IEEE 30 bus network

Line no.	From bus	To bus	R	X	Ysh	Tap
1	1	2	0.0192	0.0575	0.0528	1
2	1	3	0.0452	0.1652	0.0408	1
3	2	4	0.057	0.1737	0.0368	1
4	3	4	0.0132	0.0379	0.0084	1
5	2	5	0.0472	0.1983	0.0418	1
6	2	6	0.0581	0.1763	0.0374	1
7	4	6	0.0119	0.0414	0.009	1
8	5	7	0.046	0.116	0.0204	1
9	6	7	0.0267	0.082	0.017	1
10	6	8	0.012	0.042	0.009	1
11	6	9	0	0.208	0	0.978
12	6	10	0	0.556	0	0.969
13	9	11	0	0.208	0	1
14	9	10	0	0.11	0	1
15	4	12	0	0.256	0	0.932
16	12	13	0	0.14	0	1
17	12	14	0.1231	0.2559	0	1
18	12	15	0.0662	0.1304	0	1

(continued)

Table 3 (continued)

Line no.	From bus	To bus	R	X	Ysh	Tap
19	12	16	0.0945	0.1987	0	1
20	14	15	0.221	0.1997	0	1
21	16	17	0.0524	0.1923	0	1
22	15	18	0.1073	0.2185	0	1
23	18	19	0.0639	0.1292	0	1
24	19	20	0.034	0.068	0	1
25	10	20	0.0936	0.209	0	1
26	10	17	0.0324	0.0845	0	1
27	10	21	0.0348	0.0749	0	1
28	10	22	0.0727	0.1499	0	1
29	21	22	0.0116	0.0236	0	1
30	15	23	0.1	0.202	0	1
31	22	24	0.115	0.179	0	1
32	23	24	0.132	0.27	0	1
33	24	25	0.1885	0.3292	0	1
34	25	26	0.2544	0.38	0	1
35	25	27	0.1093	0.2087	0	1
36	28	27	0	0.396	0	0.968
37	27	29	0.2198	0.4153	0	1
38	27	30	0.3202	0.6027	0	1
39	29	30	0.2399	0.4533	0	1
40	8	28	0.0636	0.2	0.0428	1
41	6	28	0.0169	0.0599	0.013	1

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