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Transmission System Reliability Cost Analysis in Deregulated Power System

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Abstract: In power system operation and maintenance reactive power has a major role. But, in reliability evaluation, reactive power has been rarely dealt with. Malfunctions of reactive power sources are seldom considered. The complete causes of network damages for a contingency are also rarely considered. The Real power load shedding is used to recover power system damages without taking into account the role of reactive power. In this paper, Reactive power deficiency and the related voltage violations due to the malfunctions of reactive power sources are analyzed. To represent the result of reactive power deficiency on system reliability, some novel reliability indices are proposed in this paper. Another objective of this paper is to analyze the total system real power cost, which includes generation, reserve and interruption costs. An algorithm is proposed to estimate the total system cost. The sample 4 – bus system is used to illustrate the proposed technique theoretically and simulation has been carried out in MATLAB programming environment. The IEEE 30-bus system is also been analyzed to illustrate the proposed technique. The results are presented and analyzed.

Keywords: **Reactive Power Deficiency, Reliability Indices, System Interruption Cost, System Reliability Cost.**

I. INTRODUCTION

The main objective of deregulated power system is to offer reliable service and supply to its customers for the reduced cost [2].

For retaining transmission system voltage stability, reactive power is a basic constraint. Sufficient reactive power reserve is anticipated to retain system reliability through post contingency process. As an auxiliary service, reactive power supply and voltage control has a fundamental position in electricity market. The result of reactive power on transmission system reliability and safety has been well examined [3].

Due to inadequate reactive power reserve, large area blackouts may frequently occur. During a contingency, the real power part of line loading does not change considerably, but the reactive power flow can change severely. The reason is, reduced reactive power generation due to a component malfunction. Hence, to meet the necessity following a contingency, adequate reactive power reserve should be needed. It shows that reactive power is the main aspect to resolve system voltage troubles in power system operation and should be measured in reliability assessment [1].

A technique to evaluate reliability indices is proposed in this paper. Both real and reactive power deficiency due to failures of real and reactive power sources is considered in this paper. To characterize the result of reactive power deficiency on system reliability, novel reliability indices are proposed in this paper.

The cost based load shedding methodology used in system operation for contingency management is considered in this paper. The aim of this methodology is to calculate the total system cost including generation costs, reserve costs and customer interruption costs. Reliability supplies are considered in an implied manner by including the customer interruption cost. It does not mean customers can randomly select their reliability level, which is limited by its interruption cost [2].

As a previous work, the work has been done only regarding real and reactive powers curtailment for system stability and reliability, but cost analysis regarding this work has not been carried out so far. As an advanced work, in this paper the work regarding system reliability cost analysis is also carried out.

II. RELIABILITY EVALUATION WITH CONTINGENCY

Reliability assessment techniques have been well developed. In these methods, the preset maximum and minimum values are applied as the reactive power limits of generators. Network violations in a contingency state are usually alleviated through real power load shedding with less consideration for the role of reactive power. The expected value of the curtailed kWh due to the lack of reactive power generation and the expected value of voltage abnormality were calculated [4-9].

A. Reliability Indices

The effect of real power deficiency on real and reactive power expected load curtailments are denoted as EPC_P and EQC_P. Similarly, the effect of reactive power deficiency on real and reactive power expected load curtailments are denoted as EPC_Q and EQC_Q.

The effect of real and reactive power deficiencies on Expected Energy Not Supplied can be defined as $EENS_P$ and $EENS_Q$. Similarly, the effect of real and reactive power deficiencies on Expected Var Not Supplied

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are defined as $EVNS_P$ and $EVNS_Q$, respectively. The effect of voltage violations on expected Var is represented as $EVarS$. The necessary expressions for these reliability indices are as follows [1]

$$EPC_P = \sum_{i=1}^{NC} LC_{Pi} \times F_i \qquad (1)$$

$$EPC_Q = \sum_{i=1}^{NC} LC_{Qi} \times F_i \qquad (2)$$

$$EQC_P = \sum_{i=1}^{NC} QC_{Pi} \times F_i \qquad (3)$$

$$EQC_Q = \sum_{i=1}^{NC} QC_{Qi} \times F_i \qquad (4)$$

$$EENS_P = \sum_{i=1}^{NC} LC_{Pi} \times p_i \times 8760 \qquad (5)$$

$$EENS_Q = \sum_{i=1}^{NC} LC_{Qi} \times p_i \times 8760 \qquad (6)$$

$$EVNS_P = \sum_{i=1}^{NC} QC_{Pi} \times p_i \times 8760 \qquad (7)$$

$$EVNS_Q = \sum_{i=1}^{NC} QC_{Qi} \times p_i \times 8760 \qquad (8)$$

$$EVarS = \sum_{i=1}^{NC} VarS_{Qi} \times p_i \times 8760 \qquad (9)$$

Where, NC = Number of contingencies

LC_{Pi} and QC_{Pi} = The load curtailments of real and reactive powers because of real power deficiency for the i^{th} state.

LC_{Qi} and QC_{Qi} = The load curtailments of real and reactive powers because of reactive power deficiency for the i^{th} state.

$VarS_{Qi}$ = Var deficiency for i^{th} state.

B. Flow Chart

The total procedure of the reliability evaluation using the proposed technique is represented by the flow chart shown in Fig. 1.

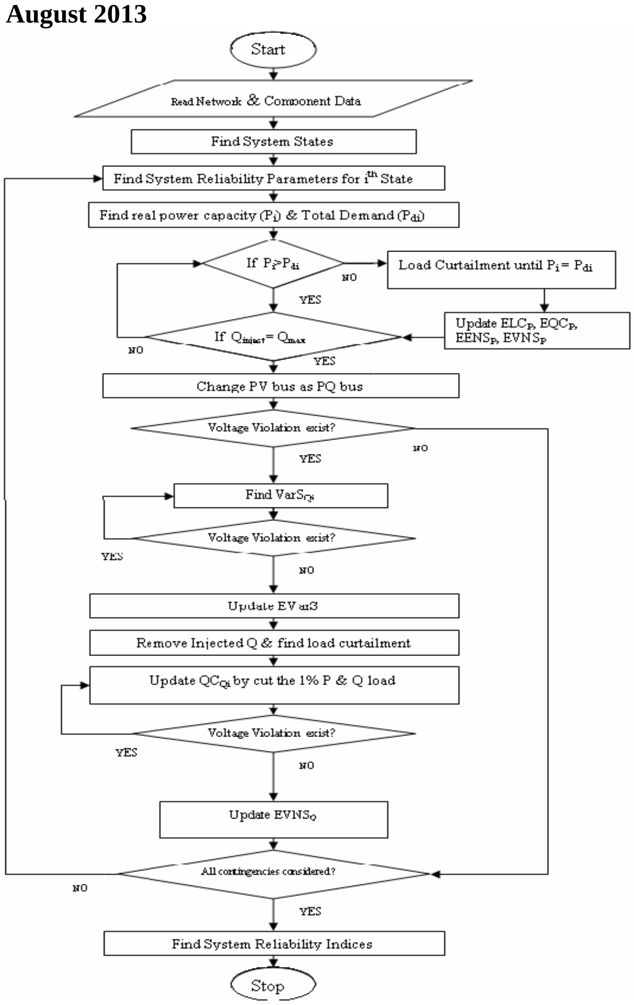

Fig. 1 Flow Chart for procedure of Reliability Evaluation

III. CASE STUDY – I SAMPLE 4 BUS SYSTEM

The sample 4 bus system shown in Fig. 2 is used to illustrate the proposed technique considered in this paper.

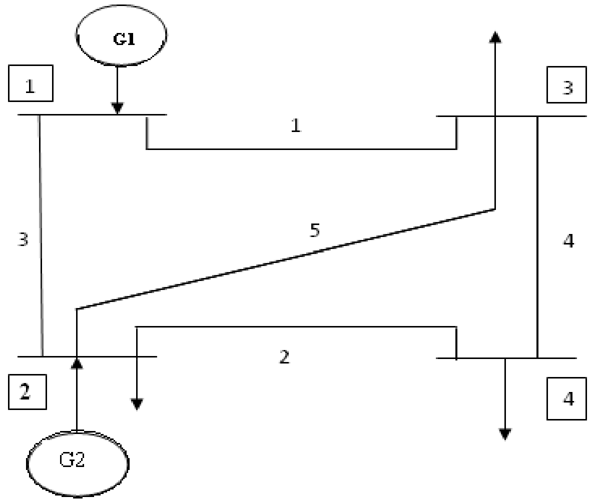

Fig. 2 Sample 4 Bus System

The reliability parameters for generators and transmission lines are given in Tables I and II respectively. The effects of the different aspects of reactive power on system and load point reliability are studied and presented.

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Table I: Reliability Parameters of Lines

line No.	Failure Rate (λ) failures/yr	Repair Rate (μ) repairs/yr
1	1.5	876
2	5	876
3	4	876
4	1	876
5	1.25	876

Table II: Reliability Parameters of Generators

Gen. No.	Failure Rate (λ) failures/yr	Repair Rate (μ) repairs/yr
1	1	876
2	2	876

A. Results for 4 bus system

The results for the system and load point reliability indices with real and reactive load curtailment for real and reactive powers are tabulated in the Tables III and IV. The value of the voltage set point is considered as 1.05p.u.

Table III: Reliability Indices with Real Load Curtailment For Both Real and Reactive Powers

Bus No.	EENS (MWh/yr) With bus isolation	EENS (MWh/yr) Without isolated	ELC (MW/yr) With bus isolation	ELC (MW/yr) Without bus isolation	EQC (MVar/yr) With bus isolation	EQC (MVar/yr) Without bus isolation
2	12.674	12.052	1.29	1.225	0	0
3	**25.347**	**24.103**	2.579	2.449	0.645	0.612
4	12.674	12.052	1.29	1.225	0.322	0.306
Total	50.694	48.207	5.159	4.898	0.967	0.918

Table IV: Reliability Indices with Reactive Load Curtailment For Both Real and Reactive Powers

Bus No.	EVarS (MVarh/yr) With isolated	EVarS (MVarh/yr) Without isolated
2	0	0.001
3	**15.142**	**14.395**
4	7.235	6.875
Total	22.377	21.271

The values of EENS at bus 3 are more when compared to values at other buses because of highest value of load at bus 3 which is shown in Appendix (Table XV). The total value of EENS with bus isolation i.e., 50.694 MWh/yr is more when compared to value of EENS without bus isolation i.e., 48.207MWh/yr.

The system expected load curtailment without bus isolation is smaller when compared to with bus isolation. The reason is that the real power is curtailed proportionally at all the buses to maintain the system stability. Similarly the reactive power curtailment also more with bus isolation when compared to without bus isolation. The reason is the reactive power is curtailed at all the buses proportionally according to their capacities to maintain the system voltage.

IV. CASE STUDY – II IEEE 30 BUS SYSTEM

The IEEE 30-bus system shown in Fig. 3 is analyzed to illustrate the proposed technique. The system has 6 generators and 24 loads. The effects of the different aspects of reactive power on system and load point reliability are studied and presented in this section [1].

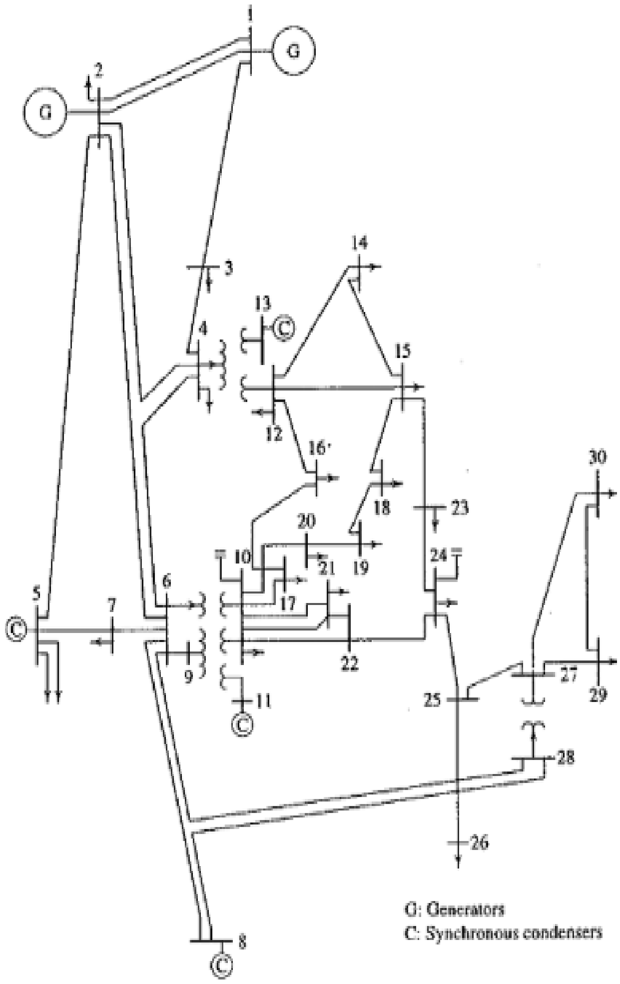

Fig. 3 Single line diagram of IEEE 30 bus system

The reliability parameters for generators and transmission lines are given in Tables V and VI respectively.

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Table V: Reliability Parameters of Lines

line No.	failure rate	repair rate
1	1	
2	1	876
3	1	876
4	1	876
5	1	876
6	1	876
7	1	876
8	1	876
9	1	876
10	1	876
11	1	876
12	1	876
13	1	876
14	1	876
15	1	876
16	1	876
17	1.5	876
18	1.5	876
19	1.5	876
20	1.5	876
21	1.5	876
22	1.5	876
23	1.5	876
24	1.5	876
25	1.5	876
26	5	876
27	5	876
28	5	876
29	5	876
30	5	876
31	1.5	876
32	1.5	876
33	1.5	876
34	5	876
35	5	876
36	1.5	876
37	5	876
38	5	876
39	5	876
40	1.5	876
41	1	876
		876

Table VI: Reliability Parameters of Generators

Gen. No.	Failure Rate	Repair Rate
1	6	194.67
2	4.5	219
5	6	194.67
8	6	194.67
11	6	194.67
13	6	194.67

A. Results of IEEE 30 Bus System

The results for the system and load point reliability indices with real and reactive load curtailment for real and reactive powers are tabulated in the Tables VII and VIII. The value of the voltage set point is considered as 1.05p.u.

Table VII: Reliability Indices with Real Load Curtailment for both Real and Reactive Powers

Bus No.	*EENS* (MWh/yr) With isolated	*EENS* (MWh/yr) Without isolated	ELC (MW/yr) With isolated	ELC (MW/yr) Without isolated	EQC (MVar/yr) With isolated	EQC (MVar/yr) Without isolated
2	17.866	16.073	0.705	0.634	0.413	0.371
3	1.976	1.848	0.078	0.075	0.039	0.038
4	6.257	5.680	0.247	0.226	0.052	0.050
5	**77.557**	69.511	3.063	2.734	0.618	0.554
7	**18.772**	16.884	0.741	0.666	0.354	0.319
8	**24.700**	22.191	0.975	0.875	0.975	0.872
10	4.775	4.354	0.189	0.174	0.065	0.061
12	9.221	8.334	0.364	0.330	0.244	0.221
14	5.105	4.648	0.202	0.185	0.052	0.050
15	6.751	6.123	0.267	0.243	0.081	0.076
16	2.882	2.658	0.114	0.107	0.059	0.055
17	7.410	6.712	0.293	0.266	0.189	0.171
18	2.635	2.437	0.104	0.098	0.029	0.029
19	7.822	7.081	0.309	0.281	0.111	0.102
20	1.811	1.700	0.072	0.069	0.023	0.024
21	14.408	12.977	0.569	0.513	0.364	0.328
23	2.635	2.437	0.104	0.098	0.052	0.050
24	7.163	6.491	0.283	0.258	0.218	0.197
26	2.882	2.658	0.114	0.107	0.075	0.070
29	1.976	1.848	0.078	0.075	0.029	0.029
30	8.727	7.892	0.345	0.313	0.062	0.058
Total	233.331	211.244	9.214	8.380	4.103	3.756

Table VIII: Reliability Indices with Reactive Load Curtailment for both Real and Reactive Powers

Bus No.	*EVarS* (MVarh/yr) With isolated	*EVarS* (MVarh/yr) Without isolated
2	10.456	9.407
3	0.988	0.930
4	1.317	1.225
5	15.643	14.050
7	8.974	8.080
8	24.700	22.158
10	1.647	1.520
12	6.175	5.574
14	1.317	1.225
15	2.058	1.889
16	1.482	1.373
17	4.775	4.321
18	0.741	0.709
19	2.799	2.552
20	0.576	0.562
21	9.221	8.301
23	1.317	1.225
24	5.516	4.984
26	1.894	1.741
29	0.741	0.709
30	1.564	1.446
Total	103.904	94.398

The values of EENS at bus 5 followed by 7 and 8 are more when compared to values at other buses because of highest values of loads at bus 5,7 and 8 which is shown in Appendix (Table XVII). The total value of EENS with bus

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isolation i.e., 233.331MWh/yr is more when compared to value of EENS without bus isolation i.e., 211.2447MWh/yr.

The system expected load curtailment without bus isolation is smaller when compared to with bus isolation. The reason is that the real power is curtailed proportionally at all the buses to maintain the system stability. Similarly, the reactive power curtailment is also more with bus isolation when compared to without bus isolation. The reason is that the reactive power is curtailed at all the buses proportionally according to their capacities to maintain the system voltage.

V. SYSTEM RELIABILITY COST ANALYSIS

Customer satisfaction is the main concern of reliability evaluation. Customer reliability cost indices can be evaluated from the load curtailment for each contingency state obtained from the load shedding technique.

A. System Reliability Cost Indices

The total customer interruption cost for state j ($TCOST_j$) and the total customer load curtailment for state j (LC_j) can be calculated as: [2]

$$TCOST^{j} = \sum_{i=1}^{N}\sum_{s=1}^{NS_i} CC_{is}^{j}(CP_{is}^{j}) \quad (10)$$

$$LC^{j} = \sum_{i=1}^{N}\left(\sum_{s=1}^{NS_i} CP_{is}^{j}\right) \quad (11)$$

where,

CC_{is}^{j} = Customer interruption cost (Rs./h)

CP_{is}^{j} = Real power load curtailment (MW)

N = Number of buses

NS_i = Number of customer sectors

The expected customer interruption cost ($ECOST_i$) for customer at bus 'i' can be calculated using the following equation

$$ECOST_i = \sum_{j=1}^{NC}\left(8760 \times p^{j} \times \sum_{s=1}^{NS_i}\left(CC_{is}^{j}\left(CP_{is}^{j}\right)\right)\right) \quad (12)$$

where,

p^j = State probability

NC = Number of contingencies

B. Results for System Reliability Cost Indices (4 Bus System)

The parameter values for customer interruption cost of different divisions are given in the Table IX.

Table IX: Parameter Values For Customer Interruption

Failure Time (min)	Interruption Cost (Rs./KWh)	
	Large Users	Industrial
1	4.015	25.3
20	6.105	73.26

The results of TCOST, LC and ECOST for large users are obtained as follows and are given in the Table X.

Table X: System Reliability Cost Indices for Large Users

Load Bus No.	TCOST Rs.(in Lakhs)/Year	LC(MW)	ECOST (Rs./Year)
2	1.56	653.305	256.032
3	**3.12**	**1306.611**	**512.064**
4	1.56	653.305	256.032
Total	6.24	2613.222	1024.128

The results of TCOST, LC and ECOST for Industrial users are obtained as follows and are given in the Table XI.

Table XI: System Reliability Cost Indices for Industrial Users

Load Bus No.	TCOST Rs.(in Lakhs)/Year	LC(MW)	ECOST (Rs./Year)
2	4.6	653.305	78.15
3	**9.2**	**1306.611**	**156.30**
4	4.6	653.305	78.15
Total	18.4	2613.222	312.60

The TCOST, LC and ECOST values at bus 3 are more when compared to values at other buses. The reason is, the load at bus 3 is more when compared other buses. From these results, it is observed that the bus 3 is the best location for any load curtailments. For this curtailment process at bus 3, the total customer interruption cost is also more.

C. Results for System Reliability Cost Indices (30 Bus System)

The parameter values for customer interruption cost of different divisions are given in the Table XII.

Table XII: Parameter Values for Customer Interruption

Failure Time (min)	Interruption Cost (Rs./KWh)	
	Large Users	Industrial
1	4.015	25.3
20	6.105	73.26
60	8.965	164.45
240	16.005	489.445
480	33.22	998.58

The results of TCOST, LC and ECOST for large users are obtained as follows and are given in the Table XIII.

Table XIII: System Reliability Cost Indices for Large Users

Load Bus No.	TCOST Rs.(in Lakhs)/Year	LC(MW)	ECOST (Rs./Year)
2	782.3	870.506	1.4
3	73.8	91.701	0.13
4	98.6	122.269	0.18
5	**1170.5**	**1451.939**	**2.1**
7	**871.5**	**932.954**	**1.51**
8	**1848.1**	**2292.535**	**3.33**
10	123.2	152.836	0.22
12	462	573.134	0.83
14	98.6	122.269	0.18
15	154	191.045	0.27
16	110.9	137.552	0.20
17	357.3	443.223	0.64

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18	55.4	68.776	0.10
19	209.51	259.821	0.38
20	43.1	53.492	0.08
21	689.9	855.880	1.25
23	98..6	122.269	0.18
24	448.2	511.999	0.75
26	141.7	175.761	0.25
29	55.4	68.776	0.10
30	119.9	145.194	0.21
Total	7913.91	9643.930	14.29

The results of TCOST, LC and ECOST for Industrial users are obtained as follows and are given in the Table XIV.

Table XIV: System Reliability Cost Indices for Industrial Users

Load Bus No.	TCOST (Rs./Year)	LC(MW)	ECOST (Rs./Year)
2	20055.19	870.506	1.4
3	1894.98	91.701	0.13
4	2526.64	122.269	0.18
5	**30003.83**	**1451.939**	**2.1**
7	**21212.72**	**932.954**	**1.51**
8	**47374.46**	**2292.535**	**3.33**
10	3158.29	152.836	0.22
12	11843.61	573.134	0.83
14	2526.64	122.269	0.18
15	3947.87	191.045	0.27
16	2842.47	137.552	0.20
17	9159.06	443.223	0.64
18	1421.23	68.776	0.10
19	5369.10	259.821	0.38
20	1105.40	53.492	0.08
21	17685.46	855.880	1.25
23	2526.64	122.269	0.18
24	10580.29	511.999	0.75
26	3632.04	175.761	0.25
29	1421.23	68.776	0.10
30	2997.90	145.194	0.21
Total	203285.10	9643.930	14.29

The TCOST, LC and ECOST values at bus 5,7 and 8 are more when compared to values at other buses. The reason is, the loads at bus 5,7 and 8 are more when compared other buses. From these results, it is observed that the bus 5,7 and 8 are the best locations for any load curtailments. For this curtailment process at bus 5,7 and 8 the total customer interruption cost is also more.

APPENDIX

The bus data including real and reactive power load and generation values for the given 4 – bus system is shown in the Table XV [4]

TABLE XV: BUS DATA (4 Bus System)

Bus No.	Load		Generation	
	MW	MVar	MW	MVar
1	0	0	80	0
2	40	0	80	0
3	**80**	**20**	0	0
4	40	10	0	0

The bus data including real and reactive power load and generation values for the given 30 – bus system is shown in the Table XVI

TABLE XVI: BUS DATA (30 Bus System)

Bus No	Load		Generation	
	MW	Mvar	MW	Mvar
1	0.0	0.0	0.0	0.0
2	21.70	12.7	40.0	0.0
3	2.4	1.2	0.0	0.0
4	7.6	1.6	0.0	0.0
5	**94.2**	19.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	**22.8**	10.9	0.0	0.0
8	**30.0**	30.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	5.8	2.0	0.0	0.0
11	0.0	0.0	0.0	0
12	11.2	7.5	0	0
13	0	0.0	0	0
14	6.2	1.6	0	0
15	8.2	2.5	0	0
16	3.5	1.8	0	0
17	9.0	5.8	0	0
18	3.2	0.9	0	0
19	9.5	3.4	0	0
20	2.2	0.7	0	0
21	17.5	11.2	0	0
22	0	0.0	0	0
23	3.2	1.6	0	0
24	8.7	6.7	0	0
25	0	0.0	0	0
26	3.5	2.3	0	0
27	0	0.0	0	0
28	0	0.0	0	0
29	2.4	0.9	0	0
30	10.6	1.9	0	0

VI. CONCLUSION

In this paper the system and load point reliability indices are calculated at both real and reactive power shortages and are separated according to their respective power curtailments. The sample 4 bus system and IEEE 30 bus system are used to analyze the system performance. From

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the above results it is observed that the reliability indices values are very high at some particular buses with respect to their load data given in the appendix. From the results, the exact location of the load curtailment has been found and it gives the required information for the system operators for their future planning of the new systems.

The system reliability cost analysis in terms of total customer interruption cost and expected customer interruption cost is also carried out. From the cost results, the location of the buses where the system requires maximum and minimum cost investment for the load curtailment and to maintain the system stability is identified. This location of the buses is very helpful for the system operators for the operation and planning of the system.

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BIOGRAPHIES

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