A Test System For Teaching Overall Power System Reliability Assessment

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Abstract- This paper presents the concept of overall power system reliability evaluation using an educational test system. The paper extends an existing test system by developing the necessary distribution and subtransmission networks. The extended test system has all the main facilities, such as generation, switching stations, transmission, sub transmission and radial distribution networks found in a practical system. The test system, is however, sufficiently small that students can analyze it using hand calculations or by developing small computer programs to fully understand the reliability models and evaluation techniques. Overall power system reliability evaluation is concerned with providing acceptable customer service. This is an important concern in today's electric utility environment. This should therefore be an essential element in teaching power system reliability evaluation at either the graduate or undergraduate level. The extended test system presented in this paper and the concepts presented assist in satisfying this requirement.

I. INTRODUCTION

Reliability evaluation of a complete electric power system including generation, transmission, station and distribution facilities is an important ability in overall power system planning and operation [1]. Due to the enormity of the problem, reliability analysis is not usually conducted on a complete power systems and reliability evaluations of generating facilities, transmission systems, station configurations, and of distribution system segments are usually performed independently [1,2]. There are many benefits associated with the ability to perform overall system reliability evaluation. The overall indices provide reliability prediction from a customer point of view and can be used to rank the functional zone contributions. Incorporation of the concepts of customer service in teaching power system reliability evaluation involves a focus on the behavior of all the components involved in providing that service. An overall power system model has been sequentially developed for this purpose. Initial data and results were published in [3,4].This system evolved from the reliability research activities conducted by Power Systems Research Group at the University of Saskatchewan.

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The basic data for performing reliability evaluation of the generation system (hierarchical level one, HLI) and for the composite generation and transmission system (hierarchical level 2, HLII) are provided in [3,4]. Reference 5 provides distribution network data at buses 2 and 4. This paper extends the distribution system data and presents the basic indices, and necessary data to conduct overall system reliability (hierarchical level 3, HLIII).

HLIII reliability evaluation includes all the segments of an electric power system in an overall assessment of actual consumer load point reliability. The primary reliability indices at HLIII are the expected failure rate λ, the average duration of failure r, and the annual unavailability U, at the customer load points [1]. Individual customer indices can also be aggregated with the number of customers at each load point to obtain HLIII system reliability indices. These indices are the system average interruption frequency index (SAIFI), the system average interruption duration index (SAIDI), the customer average interruption duration index (CAIDI) and the average service availability index (ASAI). The customer load point indices, SAIFI, SAIDI, CAIDI and ASAI are performance parameters obtained from historical event reporting. Many electric power utilities throughout the world compile these statistics on individual feeders, segments of the system, and on the entire system. This paper illustrates how similar indices can be predicted and provides an overall test system which can be used in a graduate or undergraduate setting to illustrate the calculation of these indices.

II. DESCRIPTION OF THE TEST SYSTEM

The RBTS is a 6 bus test system with five load buses (bus2-bus6). The RBTS has eleven generators and nine transmission lines. The installed capacity is 240 MW and the peak load of the system is 185 MW. This system has five voltage levels, 230 kV, 138 kV, 33 kV, and 11 kV. The existing system has been extended by developing additional distribution and sub station facilities. The overall system is shown in Figure 1.

III. DEVELOPMENT OF DISTRIBUTION NETWORKS AT BUSES 3, 5 AND 6.

The distribution network at bus 3 of the RBTS represents a typical industrial and large user distribution system with a

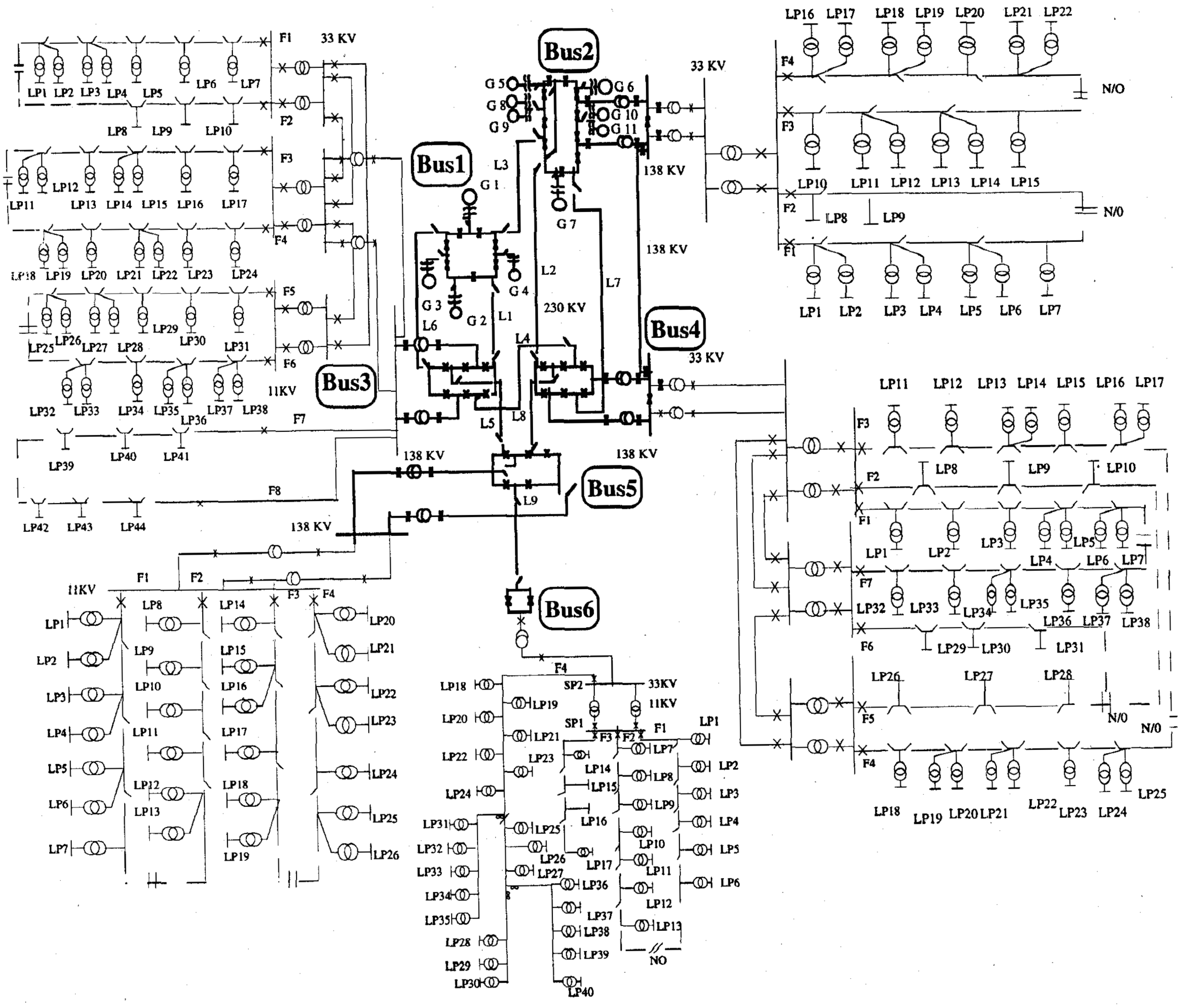

Figure 1. Complete Single Line Diagram of the RBTS

peak load of 85 MW. Bus 3 has industrial, large user, office buildings, residential and commercial customers.The distribution network at bus 5 represents a typical urban type network consisting of residential, government and institutional, office and buildings, and commercial customers. The peak load of the distribution system at bus 5 is 20 MW. The distribution network at bus 6 is a typical rural network with agricultural, small industrial, commercial and residential customers. The peak load of this network is 20 MW. The distribution networks are shown in Figure 1 and are labeled in detail in Figures 2, 3 and 4. The customer and loading data of the networks are given in Table 1 and the lengths of the feeder sections are presented in Table 2.

The design of these distribution networks follow general utility principles and practices regarding topology, ratings and loading levels [6]. The developed sub stations for these distribution networks are as shown in Figure 1. The failure rates and repair durations of the various distribution components such as transformers, breakers, busbars, and feeder sections follows the same data presented in [5].

A wide range of reliability indices can be calculated for the radial distribution networks at buses 3,5 and 6. These are both load point and system indices. Load point indices include failure rate (λ), outage time (r), annual unavailability (U) and energy not supplied (E).

Table 1. Customer Data

Number of Load Points	Load Points	Customer Type	Load Level per Load Point, MW Peak	Average	Number of Customers
Bus 3					
15	1, 4-7, 20,24, 32, 36	residential	0.8367	0.4684	250
5	11,12, 13,18, 25	residential	0.8500	0.4758	230
4	2, 15, 26, 30	residential	0.7750	0.4339	190
3	39, 40, 44	large users	6.9167	4.3886	1
3	41-43	large users	11.5833	7.3496	1
3	8, 9, 10	small industrial	1.0167	0.8472	1
9	3, 16, 17, 19, 28,29,31, 37, 38	commercial	0.5222	0.2886	15
2	14, 27	office buildings	0.9250	0.5680	1
Total			*85.00*	*52.63*	*5805*
Bus 5					
4	1-2, 20, 21	residential	0.7625	0.4269	210
4	4, 6, 15, 25	residential	0.7450	0.4171	240
5	26, 9-11, 13	residential	0.5740	0.3213	195
5	3, 5, 8,17, 23	government and inst.	1.1100	0.6247	1
5	7,14,18,22,24	commercial	0.7400	0.4089	15
3	12, 16, 19	office buildings	0.6167	0.3786	1
Total			*20.00*	*11.29*	*2858*
Bus 6					
3	1 3 9	residential	0.3171	0.1775	138
4	2 4 11 19	residential	0.3229	0.1808	126
2	5 6	residential	0.3864	0.2163	118
5	7 8 10 18 23	residential	0.2964	0.1659	147
3	12 13 22	residential	0.3698	0.2070	132
4	25 28 31 36	residential	0.2776	0.1554	79
4	27 29 33 39	residential	0.2831	0.1585	76
2	14 17	commercial	0.8500	0.4697	10
1	15	small	1.9670	1.6391	1
1	16	small	1.0830	0.9025	1
2	32 37	farm	0.5025	0.1929	1
3	20 30 34	farm	0.6517	0.2501	1
2	21 35	farm	0.6860	0.2633	1
2	24 40	farm	0.7965	0.3057	1
2	26 38	farm	0.7375	0.2831	1
Total			*20.0000*	*10.7155*	*2938*

Table 2. Feeder Types and Lengths

Feeder Type	Length (km)	Feeder Section Numbers
Bus 3		
1	0.6	1 2 3 7 11 12 15 21 22 29 30 31 36 40 42 43 48 49 50 56 58 61 64 67 70 72 76
2	0.8	4 8 9 13 16 19 20 25 26 32 35 37 41 46 47 51 53 57 60 62 65 68 71 75 77
3	0.9	5 6 10 14 17 18 23 24 27 28 33 34 38 39 44 45 52 54 55 59 63 66 69 73 74
Bus 5		
1	0.5	1 6 9 13 14 18 21 25 27 31 35 36 39 42
2	0.65	4 7 8 12 15 16 19 22 26 28 30 33 37 40
3	0.8	2 3 5 10 11 17 20 23 24 29 32 34 38 41 43
Bus 6		
1	0.6	2 3 8 9 12 13 17 19 20 24 25 28 31 34 41 47
2	0.75	1 5 6 7 10 14 15 22 23 26 27 30 33 43 61
3	0.8	4 11 16 18 21 29 32 35 55
4	0.9	38 44
5	1.6	37 39 42 49 54 62
6	2.5	36 40 52 57 60
7	2.8	35 46 50 56 59 64
8	3.2	45 51 53 58 63
9	3.5	48

Load point indices for selected load points at buses 3, 5 and 6 are presented in Tables 3, 4 and 5. System indices include SAIFI, SAIDI, CAIDI, ASAI and provide a relative measure for a group of load points or for the entire distribution system. The basic system indices for the distribution systems at buses 3, 5 and 6 are presented in Table 6. Reference 1 illustrates the reliability effects of a range of distribution design modifications using a simple single feeder. The distribution systems shown in Figures 2,3 and 4 provide a base for student evaluation of similar sensitivity analysis.

IV. RELIABILITY ASSESSMENT AT HLIII

Overall (HLIII) power system reliability is concerned with assessment at the actual customer level. Customer satisfaction is an important concern in today's electric power utility environment. This requirement should be incorporated in both graduate and undergraduate lecture courses dealing with power system reliability evaluation. HLIII assessment incorporates the three functional zones of generation, transmission and distribution in the analysis.

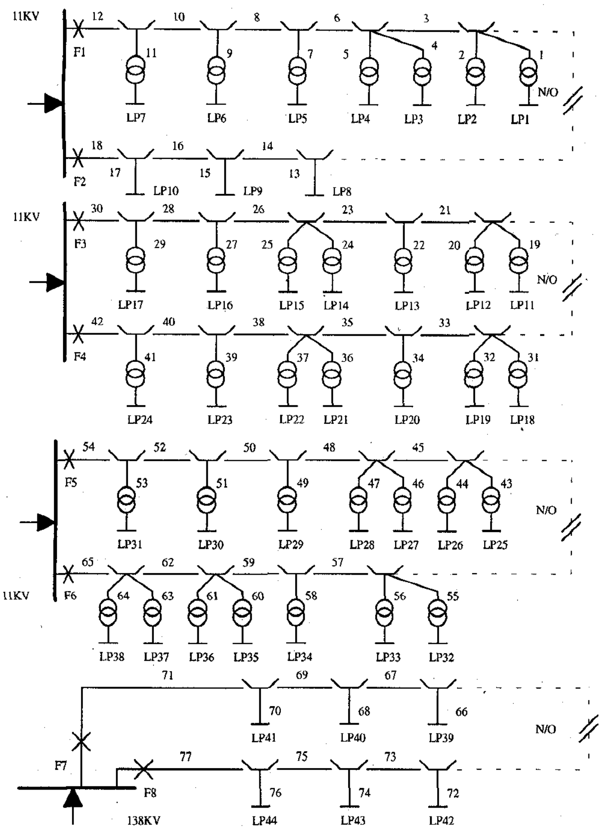

Figure 2 . Distribution System for RBTS Bus 3

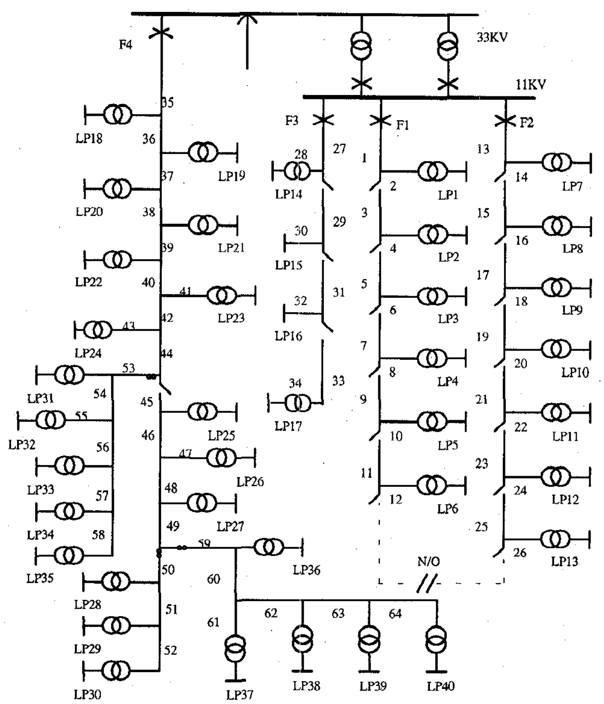

Figure 4 . Distribution System for RBTS Bus 6

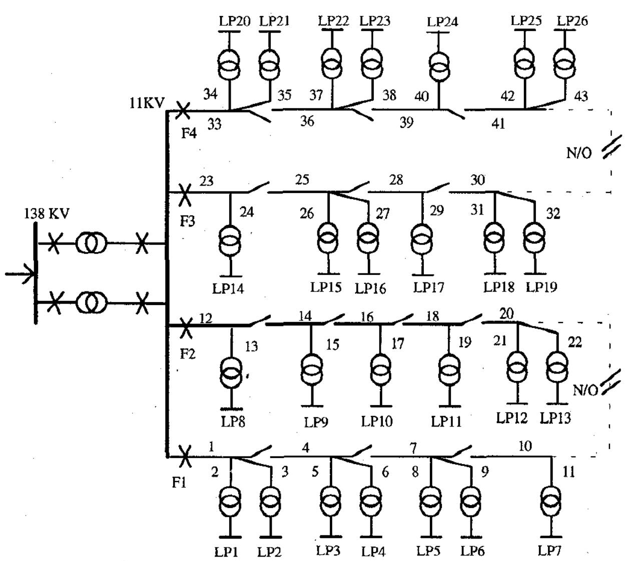

Figure 3 . Distribution System for RBTS Bus 5

Table 3. Base Case Reliability Indices for the Radial Distribution Network at Bus3.

Ld. Point	λ (f/yr)	r (hr)	u (hr/yr)	EENS (MWh/yr)
1	0.301	11.44	3.44	1.61223
3	0.314	11.17	3.51	1.01212
8	0.221	1.94	0.43	0.36345
11	0.314	11.17	3.51	1.66863
13	0.301	11.44	3.44	1.63770
21	0.301	11.44	3.44	1.61223
24	0.314	11.17	3.51	1.64268
27	0.321	10.96	3.51	1.99567
32	0.288	12.18	3.51	1.64268
38	0.269	12.70	3.41	0.98398
41	0.189	1.83	0.34	2.53194
44	0.202	1.77	0.36	1.56892

Table 4. Base Case Reliability Indices for the Radial Distribution Network at Bus5.

Ld Point	λ (f/yr)	r (hr)	u (hr/yr)	EENS (MWh/yr)
1	0.2360	15.08	3.56	1.51934
4	0.2165	16.17	3.50	1.46006
9	0.2588	13.69	3.54	1.13829
12	0.2490	14.35	3.57	1.35236
19	0.2360	15.25	3.60	1.36220
23	0.2263	15.69	3.55	2.21722
25	0.2068	17.07	3.53	1.47226
26	0.2263	16.03	3.63	1.16544

Table 5. Base Case Reliability Indices for the Radial Distribution Network at Bus6.

Ld. point	λ (f/yr)	r (hr)	u (hr/yr)	EENS (MWh/yr)
1	0.3303	11.10	3.67	0.65076
4	0.3303	11.10	3.67	0.66286
8	0.3725	10.10	3.76	0.62387
12	0.3595	10.28	3.70	0.76497
16	0.2405	4.19	1.01	0.90927
18	1.6725	5.02	8.40	3.26475
23	1.7115	5.02	8.60	1.42616
26	1.7115	6.71	11.48	3.25070
32	2.5890	5.02	12.98	1.67080
37	2.5598	6.14	15.72	2.22438
40	2.5110	6.16	15.48	3.45059

Table 6. Radial Distribution System Indices.

Index	*Bus 3*	*Bus 5*	*Bus 6*
SAIFI (fr/ syst. cust)	0.3027	0.2325	1.0067
SAIDI (hr/ syst. cust)	3.4726	3.5512	6.6688
CAIDI (hr/ cust)	11.4691	15.2751	6.6247
ASAI	0.999604	0.999595	0.999239
EENS (MWh/yr)	66.68024	40.11936	72.81531

The HLIII reliability assessment presented in this paper includes the independent outages of generating units, transmission lines, outages due to station originated failures, sub-transmission and radial distribution element failures. The method used is summarized in the three steps given below:

1. The probability, expected frequency and duration of each contingency at HLII that leads to load curtailment for each system bus are obtained. The contingencies considered include outages up to: four generation units, three transmission lines, two lines with one generator and two generators with one line. All outages due to station related failures and the isolation of load buses due to station failures are also considered. If the contingency results in load curtailment, a basic question is then how would the electric utility distribute this interrupted load among its customers. It is obvious that different power utilities will take different actions based on their experience, judgment and other criteria. The method used in this paper assumes that load is curtailed proportionately across all the customers. For each contingency j that leads to load curtailment of L_{kj} at Bus k, the ratio of L_{kj} to bus peak load is determined. The failure probability and failure frequency at each bus k are modified using this ratio. The failure probability and frequency due to an isolation case is not modified as the isolation affects all the customers.
2. At the sub transmission system level, the impact of all outages is obtained in terms of average failure rate and average annual outage time at each distribution system supply point.
3. At the radial distribution level, the effects due to outages of system components such as primary main/laterals/low voltage transformers, etc. are considered.

The HLIII indices for the RBTS were obtained using the above described approach and a seven step load model. The HLIII indices can be obtained for all the load points in a system. HLIII load point indices for selected load points at the buses 2,3,4,5 and 6 are shown in Tables 7 to 11.

Table 7. HLIII Load Point Indices at Bus2.

Bus no	λ (f/yr)	r (hr)	U (hr/yr)	% Distn.
1	0.3116	12.41	3.87	93.93
4	0.3116	12.41	3.87	93.93
13	0.3246	11.96	3.88	93.95
19	0.3278	12.01	3.94	94.03
22	0.3278	11.89	3.9	93.97

Table 8. HLIII Load Point Indices at Bus3.

Bus no	λ (f/yr)	r (hr)	U (hr/yr)	% Distn.
1	0.5013	8.98	4.5	78.63
4	0.5208	8.83	4.6	79.08
11	0.4683	9.66	4.52	78.72
19	0.4683	9.66	4.52	78.72
31	0.5168	8.84	4.57	78.95
39	0.3123	4.5	1.4	31.47
42	0.3058	4.32	1.32	27.09
44	0.3058	4.32	1.32	27.09

Table 9. HLIII Load Point Indices at Bus4.

Bus no	λ (f/yr)	r (hr)	U (hr/yr)	% Distn.
1	0.3721	10.15	3.78	92.47
4	0.3851	9.98	3.84	92.60
7	0.3819	10.02	3.83	92.57
19	0.4170	9.17	3.83	92.56
27	0.3078	2.54	0.78	63.69
35	0.4181	9.27	3.88	92.66
38	0.4051	9.41	3.81	92.54

Tables 7 to 11 also present the percentage contribution from distribution failures to the overall load point unavailability. The distribution facilities include the sub transmission and radial systems. It is also possible to obtain the percentage contribution of various segments of a system to the load point HLIII indices. Consider load point 19 at bus 3. The contributions from various segments to the overall unavailability is shown in Figure 5. HLIII system indices can be obtained for individual feeders, groups of feeders and for the entire system.

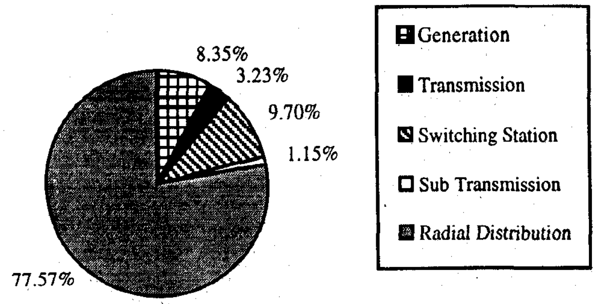

Figure 5. Unavailability at Load Point 19 of Bus 3.

Table 10. HLIII Load Point Indices at Bus5.

Bus no	λ (f/yr)	r (hr)	U (hr/yr)	% Distn.
1	0.3516	11.87	4.17	86.65
4	0.3321	12.39	4.12	86.46
12	0.3646	11.48	4.19	86.69
16	0.3321	12.28	4.08	86.33
24	0.3321	12.39	4.12	86.46
26	0.3418	12.41	4.24	86.87

Table 11. HLIII Load Point Indices at Bus6.

Bus no	λ (f/yr)	r (hr)	U (hr/yr)	% Distn.
1	1.6768	13.67	22.91	16.24
5	1.6865	13.59	22.92	16.28
8	1.7190	13.38	23.01	16.59
16	1.5870	12.76	20.25	5.25
20	3.0065	9.19	27.64	30.57
28	3.5590	9.35	33.29	42.35
32	3.9230	8.21	32.22	40.44
39	3.8450	9.03	34.72	44.72
40	3.8450	9.03	34.72	44.72

The system indices for buses 2 to 6 are presented in Table 12. This table also presents the HLIII system indices for the entire RBTS.

Table 13 shows the percentage contribution of distribution system failures to the overall system indices of SAIFI and SAIDI. It can be seen from this table that distribution failures contribute significantly to the overall reliability indices.

A wide range of studies can be conducted using the test system described in this paper. It is possible to identify how different facilities, such as generation, transmission, switching stations, sub transmission, and radial distribution systems influence the overall indices. A wide range of investigations can be carried out on suitable designs of different facilities. As an example, a switching station design can influence the reliability indices at more than one bus [6]. The overall implications of design changes such as this can be used to select a suitable station configuration. The ability to perform HLIII reliability evaluation provides the opportunity to investigate the effect of generation and transmission reinforcements on actual load point adequacy. The effect on the overall HLIII indices of various distribution system operational practices [6], such as providing alternate supply and protective devices [7,8] can also be studied.

Table 12. HLIII System Indices.

Index	*SAIFI*	*SAIDI*	*CAIDI*	*ASAI*
Bus 2	0.3206	3.9056	12.1842	0.999554
Bus 3	0.4826	4.5131	9.3521	0.999485
Bus 4	0.3985	3.8302	9.6125	0.999563
Bus 5	0.3481	4.1663	11.9695	0.999524
Bus 6	2.3481	25.9128	11.0355	0.997042
Overall System	***0.7224***	***7.6550***	***10.5969***	***0.999126***

Table 13. HLIII System Indices and the Contribution of Distribution Failures.

Index	*SAIFI*	*% Distn*	*SAIDI*	*%Distn*
Bus 2	0.3206	94.90	3.9056	93.98
Bus 3	0.4826	78.39	4.5131	78.68
Bus 4	0.3985	94.69	3.8302	92.58
Bus 5	0.3481	82.88	4.1663	88.63
Bus 6	2.3481	44.93	25.9128	25.94

V. CONCLUSIONS

This paper presents a basic electric power system network which can be used in teaching overall power system reliability assessment. The paper extends the basic system described in [3,4,5] and introduces the concept of overall assessment, which deals with actual customer levels of service. This is an important requirement in today's changing utility environment and one that should be stressed in teaching reliability concepts.

VI. REFERENCES

1. Billinton, R. and Allan, R. N., Reliability Evaluation of Power Systems, Pitman Books, New York and London, 1984.
2. Billinton, R. and Allan, R. N., Reliability Evaluation of Engineering Systems: Concepts and Techniques, Plenum Publishing, New York, 1983.
3. Billinton, R., Kumar, S., Chowdhury, N., Chu, K., Debnath, K., Goel, L., Khan, E., Kos, P., Nourbakhsh, G., and Oteng-Adjei, J., " A Reliability Test System for Educational Purposes - Basic Data", IEEE Trans. on Power Systems, PWRS-4, Vol. 4, No. 3, Aug. 1989, pp 1238-1244.
4. Billinton, R., Kumar, S., Chowdhury, N., Chu, K., Khan, E., Kos, P., Nourbakhsh, G., and Oteng-Adjei, J., " A Reliability Test System for Educational Purposes - Basic Results", IEEE Trans. on Power Systems, Vol. 5, No.1, Feb. 1990, pp. 319-325.
5. Allan, R. N., Billinton, R., Sjarief, I., Goel, L., and So, K. S., " A Reliability Test System for Educational Purposes - Basic Distribution System Data and Results", IEEE Trans. Power System, Vol. 6, No. 2, May 1991, pp. 813-820.
6. Gonen, T., Electric Power Distribution System Engineering, McGraw Hill Book Co., New York, 1986.
7. Lakervi, E., Holmes, E. J., Electric Distribution Network Design, Peter Peregrinus Ltd. London, 1989.
8. Westinghouse Electric Corporation "Electric Utility Reference Book - Distribution Systems", Vol.. 3, East Pittsburgh, 1965.

BIOGRAPHIES

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Discussion

L. Goel and X. Liang (School of Electrical & Electronic Engineering, Nanyang Tech. University, Nanyang Avenue, Singapore 639798):

We would like to congratulate the authors for presenting the distribution systems for three of RBTS's load buses, and also for presenting an overall hierarchical level three (HLIII) approach for the RBTS. While some work has been done in the area of HLIII reliability assessment [1], and also in the cost-benefit considerations [2,3], this paper is of immense educational value since it provides an overall power system that can be used in an engineering curriculum to teach reliability assessment at HLI, HLII and HLIII.

We would like to seek some clarifications from the authors with regard to some data for the distribution systems designed for the RBTS buses 3 and 6. We did some Monte Carlo Simulation studies of the designed networks reported in the paper, and found our results to be quite different (for some feeders) than those reported in the paper. The basic queries that we have are as follows:

- Feeder F4 of bus 6 (Figure 4 of the paper) is a 33kV feeder for which the failure rate (single weather condition) should be 0.046 failures/yr-kM as per the data provided in Reference 5 of the paper. We feel, however, that the authors have used a failure rate of 0.065 failures/yr-kM - the data given for 11kV feeder sections in Reference 5 of the paper.
- Reference 5 of the paper does not provide the data for the 33/0.415kV transformers in the feeder laterals. Since feeder F4 of bus 6 distribution system (Figure 4 of the paper) utilizes these transformers, and since this paper does not provide any additional component data, we are not sure what data was used by the authors. We are of the opinion, based on our own studies, that the authors used the same data as that provided for the 11/0.415kV transformers in Reference 5 of the paper.
- Feeders F7 and F8 of the RBTS bus 3 distribution system are 138kV feeders. Reference 5 of the paper also does not provide the relevant data for 138kV feeder sections. We would very much appreciate it if the authors would provide these data for single weather and two-weather state representations.

References

[1] R. Billinton, L. Goel, "Adequacy Assessment of an Overall Electric Power System", IEE Proceedings - C, Vol. 139, No. 1, Jan 1992, pp 57-63.

[2] L. Goel, R. Billinton, "A Procedure for Evaluating Interrupted Energy Assessment Rates in an Overall Electric Power System", IEEE Trans. on Power Systems, Vol. 6, No. 4, Nov 1991, pp 1396-1403.

[3] L. Goel, R. Billinton, "Utilization of Interrupted Energy Assessment Rates to Evaluate Reliability Worth in Electric Power Systems", IEEE Trans. on Power Systems, Vol. 8, No. 3, August 1993, pp 929-936.

Manuscript received February 15, 1996.

ROY BILLINTON AND SATISH JONNAVITHULA: We appreciate the discussers interest in our paper. The results presented in this paper were verified by both analytical and Monte-Carlo techniques and therefore we presume that the differences cited by the discussers are due to data uncertainty. We used a failure rate of 0.065 failures/yr-Km for the 33 kV rural feeder F4 of bus 6. The increase in failure rate from 0.046 to 0.065 was intended to represent the change in line design from the 33 kV urban transmission used in Reference 5 to the rural feeder in this paper. We used the same data for both 33/0.415 kV and 11/0.415 kV transformers. The failure rate of 0.065 failures/yr.-Km was also used for the 138 kV transmission. In regard to two weather state representations, we would like to suggest normal and adverse weather durations of 200 and 1.5 hours respectively, no repair during adverse weather and that 60 % of the line failures occur during adverse weather.

In conclusion, we would like to thank the discussers for their comments.

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