IEEE Transactions on Power Systems, Vol.6, No. 2, May 1991

A RELIABILITY TEST SYSTEM FOR EDUCATIONAL PURPOSES - BASIC DISTRIBUTION SYSTEM DATA AND RESULTS

R.N.Allan* R.Billinton** I.Sjarief* L.Goel** K.S.So*

* Electrical Energy and Power Systems Group, UMIST, Manchester, England
** Power Systems Research Group, University of Saskatchewan, Saskatoon, Canada

Abstract

This paper describes an electrical distribution system for use in teaching power system reliability evaluation. It includes all the main elements found in practical systems. However, it is sufficiently small that students can analyse it using hand calculations and hence fully understand reliability models and evaluation techniques. The paper contains all the data needed to perform basic reliability analyses. It also contains the basic results for a range of case studies and alternative design/operating configurations.

Keywoods: reliability test system, distribution systems, educational studies, customer indices.

INTRODUCTION

The IEEE Application of Probability Methods (APM) Subcommittee published a Reliability Test System (RTS) in 1979 [1]. This has proved to be a valuable and consistent reference source for comparing alternative techniques and computer programs. It has been used extensively in recent years [2,3] in reliability assessment of generation systems and in composite systems by utilities, consultants and universities. Its major advantage is that it provides a consistent set of data, since extended in Refs [4,5], enabling a wide range of techniques and applications to be much more easily compared than previously possible. It is sufficiently large that practical factors can be realistically modelled and assessed but also sufficiently small that the effect of sensitivity studies can be easily identified. The major weakness of the RTS is that it requires the use of computer programs to perform the vast majority of the reliability analyses. This makes it less appropriate for educational purposes because it is essential for students to fully understand reliability models and evaluation techniques by performing hand calculations before either using or writing computer programs that purport to perform the same task. This manual manipulation is a vital part of the complete teaching programme. Since the RTS is too complex for this task, there is a need for a simpler system that can be used during the teaching of power system reliability evaluation and assessment.

This problem was partially overcome by the development of a 6 busbar test system defined as the RBTS, the basic data and results for which are published in Refs [6,7]. These previous papers centre only on the data and results for the generation and transmission system: they do not include any information relating to distribution sytems.

90 SM 280-8 PWRS A paper recommended and approved by the IEEE Power Engineering Education Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1990 Summer Meeting, Minneapolis, Minnesota, July 15-19, 1990. Manuscript submitted January 22, 1990; made available for printing April 24, 1990.

The unavailability of electrical supplies at customers' terminals is usually dominated by failures in the distribution networks. It is therefore important that students know the processes of failure and restoration in this part of the system and understand the models and evaluation techniques for assessing the impact of these processes on load point reliability indices.

The purpose of this paper is to extend the RBTS to include distribution systems that contain the main elements found in practical systems but which are sufficiently small that they can be easily analysed using hand calculations. The paper contains all the basic data needed to perform continuity analyses together with limited load flow data so that some design studies containing load flow solutions are also possible. The paper also contains basic results of continuity studies for a range of sensitivity studies and alternative design/operating configurations.

DESCRIPTION OF THE DISTRIBUTION NETWORKS

The RBTS has 5 load busbars (BUS2-BUS6). Two of these busbars (BUS2 and BUS4) were selected and distribution networks designed for each. BUS2 has generation associated with it and BUS4 does not. This permits the effects and differences caused by the generation and transmission system on the overall load point indices to be seen. The peak loads defined in the RBTS for different customer types are shown in Table 1.

TABLE 1 Peak Loads in the RBTS

customer type	peak loads, MW bus 2	bus 4
residential	7.25	19.00
small user	3.50	16.30
government/institutions	5.55	-----
commercial	3.70	4.70
TOTAL	20.00	40.00

TABLE 2 Feeder Types and Lengths

feeder type	length km	feeder section numbers
a) BUS 2		
1	0.60	2 6 10 14 17 21 25 28 30 34
2	0.75	1 4 7 9 12 16 19 22 24 27 29 32 35
3	0.80	3 5 8 11 13 15 18 20 23 26 31 33 36
b) BUS 4		
1	0.60	2 6 10 14 17 21 25 28 30 34 38 41 43 46 49 51 55 58 61 64 67
2	0.75	1 4 7 9 12 16 19 22 24 27 29 32 35 37 40 42 45 48 50 53 56 60 63 65
3	0.80	3 5 8 11 13 15 18 20 23 26 31 33 36 39 44 47 52 54 57 59 62 66

0885-8950/91/0500-0813$01.00©1991 IEEE

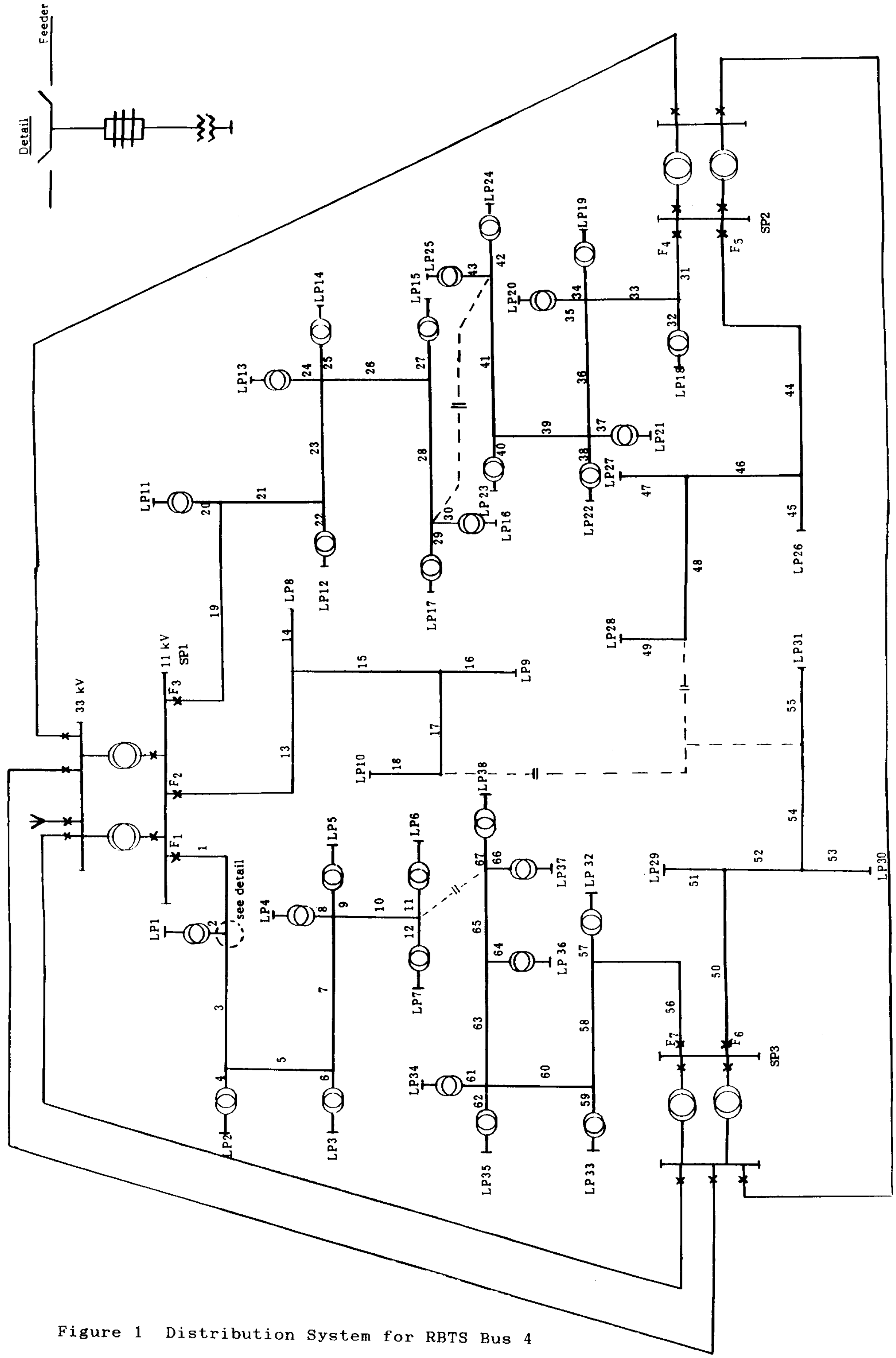

Figure 1 Distribution System for RBTS Bus 4

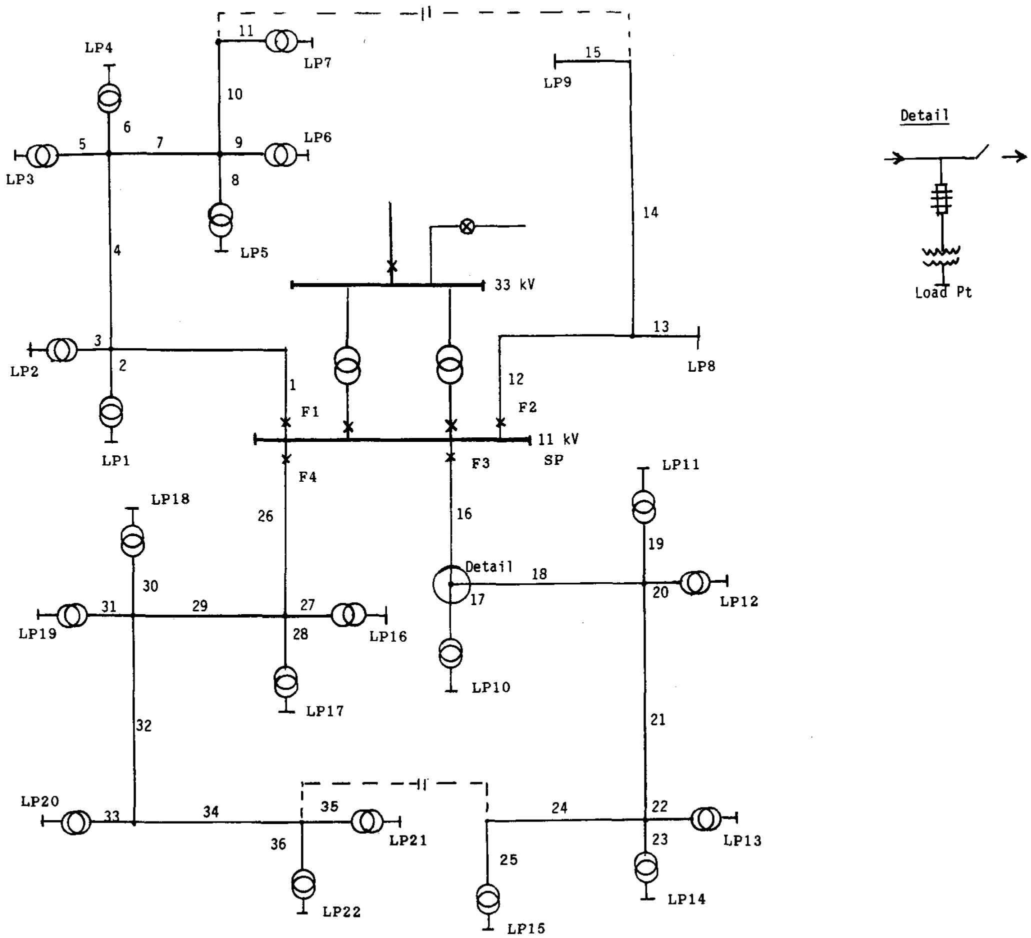

Figure 2 Distribution System for RBTS Bus 2

The design of these distribution networks followed general utility principles and practices regarding topology, ratings and loading levels. The single line diagrams are shown in Figures 1 and 2 for BUS4 and BUS2 respectively. The following comments relate to these designs.

a) residential, commercial and government/institution loads are metered on the low voltage side and the transformer is utility property and included in the analysis. The small user loads are metered on the high voltage side and the transformer is customer property and not included.
b) the feeders are operated as radial feeders but connected as a mesh through normally open sectionalising points. Following a fault on a feeder, the ring main units permit the sectionalising point to be moved and customers to be supplied from alternative supply points.
c) the loading level of BUS4 (40MW) is sufficient to justify higher reliability provided by a 33kV ring linking three supply points (SP1,SP2 and SP3). The loading level of BUS2 (20MW) only justifies a single supply point.
d) all breakers in the system are identified.
e) all the 11kV feeders and laterals are considered either as overhead lines or as cables.
f) each 11kV feeder and lateral is one of three types, the lengths being 0.6, 0.75 or 0.8 km. These types are shown in Table 2.

CUSTOMER AND LOADING DATA

The RBTS defines the customer type and total peak load at each of its busbars (Table 1) but the number of customers of each type and individual load levels are not given. These are now defined and shown in Table 3 for each load point, several of which are considered the same. The defined average load assumes that this will be the average value seen by the load point due to diversity between customers and normal load variations through the day and through the year. This customer data can be appropriately combined to give the feeder loading data shown in Table 4. This shows the load and number of customers on each feeder and on the main RBTS busbar together with the values for each 33/11kV supply point (SP) in the case of BUS4.

SYSTEM DATA

The reliability data assumed for the 33kV and 11kV system components is shown in Table 5. This includes sufficient data to perform the basic analyses included in this paper together with more complex analyses such

TABLE 3 Customer Data

number of load points	load points	customer type	load level per load point, MW average	peak	number of customers
a) BUS 2					
5	1-3, 10, 11	residential	0.535	0.8668	210
4	12, 17-19	residential	0.450	0.7291	200
1	8	small user	1.00	1.6279	1
1	9	small user	1.15	1.8721	1
6	4, 5, 13, 14, 20, 21	govt/inst	0.566	0.9167	1
5	6, 7, 15, 16, 22	commercial	0.454	0.7500	10
TOTALS			12.291	20.00	1908
b) BUS 4					
15	1-4, 11-13, 18-21, 32-35	residential	0.545	0.8869	220
7	5, 14, 15, 22, 23, 36, 37	residential	0.500	0.8137	200
7	8, 10, 26-30	small user	1.00	1.63	1
2	9, 31	small user	1.50	2.445	1
7	6, 7, 16, 17, 24, 25, 38	commercial	0.415	0.6714	10
TOTALS			24.58	40.00	4779

TABLE 4 Loading Data

feeder number	load points	feeder load, MW average	peak	number of customers
a) BUS 2				
F1	1-7	3.645	5.934	652
F2	8-9	2.15	3.500	2
F3	10-15	3.106	5.057	632
F4	16-22	3.390	5.509	622
BUS 2 TOTALS		12.291	20.00	1908
b) BUS 4				
F1	1-7	3.51	5.704	1100
F2	8-10	3.5	5.705	3
F3	11-17	3.465	5.631	1080
SP1 Totals		10.475	17.040	2183
F4	18-25	4.01	6.518	1300
F5	26-28	3.0	4.890	3
SP2 Totals		7.01	11.408	1303
F6	29-31	3.5	5.705	3
F7	32-38	3.595	5.847	1290
SP3 Totals		7.095	11.552	1293
BUS 4 TOTALS		24.58	40.00	4779

as effect of weather on the 33kV overhead line system, temporary failures, maintenance effects, etc. The fuses and disconnects are assumed to be 100% reliable. Table 5 also includes other required or useful data including 33kV circuit lengths and transformer ratings. The latter permit loading levels and supply restrictions to be taken into account if desired. It is assumed that the circuits themselves do not introduce any restrictions.

SYSTEM STUDIES

A range of reliability indices were calculated for a number of studies. The methods for evaluating these indices are described in detail in Refs [8,9] and applied to practical systems in Ref [3]. The indices include:

Load point indices. These are failure rate (λ), outage time (r), annual unavailability (U), load disconnected (L) and energy not supplied (E). These can be calculated at each specified load point.

System indices. These are SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS and AENS. They are fully specified and defined in Refs [3,8], and can be evaluated from the load point indices for a group of load points or the whole system.

The studies performed include:

11kV feeders. These studies consider the 11kV feeders only and ignore any failures in the 33kV system, the 33/11kV substation and the 11kV breakers. They assume the 11kV source breaker operates successfully when required, disconnects are opened whenever possible to isolate a fault, and the supply restored to as many load points as possible using appropriate disconnects and the alternative supply if available.

33kV system. These studies evaluate the reliability indices at the 11kV supply point busbars. They ignore any failures on the incoming 33kV supply circuits. They include the effect of passive and active failures [8] on all components from the 33kV busbars down to the 11kV supply point busbars together with active failures on the outgoing 11kV feeder breakers.

RELIABILITY RESULTS

Several case studies are performed on the 11kV feeders. These centre on the inclusion or not of disconnects in the main feeders, fuses in each lateral and an alternative back-fed supply. The effect of replacing a failed low voltage transformer with a spare instead of repairing it is also evaluated. Finally in all cases the effect of constructing the 11kV system with overhead lines and alternatively with underground cables is also assessed.

The base case assumes the system as designed in Figs 1 and 2, i.e. with disconnects, with fuses, with alternative supply and repairing transformers. The individual load points indices (λ,r,U) are shown in Tables 6 and 7 for BUS4 and BUS2 respectively. The most significant features are that:

- the failure rates for the "line" system are higher due to the higher failure rate of overhead lines
- the average downtimes for the "cable" system are longer due to the outage (switching) times being longer.
- the indices for the short feeders of BUS4 (2,5,6) are less than those for the long feeders (1,3,4,7). The reduced values of failure rate are due to a smaller number of failures and the reduced values of down time occur because the load point transformer is neglected ince these feeders supply small users.

TABLE 5 Reliability and System Data

component	λ_P	λ_A	λ_T	λ''	r	r_P	r''	r_C	s
transformers									
138/33	0.0100	0.0100	0.050	0.5		15	168	0.083	1.0
33/11	0.0150	0.0150	0.050	1.0		15	120	0.083	1.0
11/0.415	0.0150	0.0150			200	10			1.0 ("line" system)
									3.0 ("cable" system)
breakers									
138	0.0058	0.0035	0.050	0.2	8		108	0.083	1.0
33	0.0020	0.0015	0.020	0.5	4		96	0.083	1.0
11	0.0060	0.0040	0.060	1.0	4		72	0.083	1.0
busbars									
33	0.0010	0.0010	0.010	0.5	2		8	0.083	1.0
11	0.0010	0.0010	0.010	1.0	2		8	0.083	1.0
lines (single weather state)									
33	0.0460	0.0460	0.060	0.5	8		8	0.083	2.0
11	0.0650	0.0650			5				1.0
lines (two weather states)									
33 (normal)	0.0139	0.0139	0.018	0.5	8		8	0.083	2.0
(adverse)	5.860	5.860	7.60						
cables									
11	0.0400	0.0400			30				3.0

weather data: average duration of normal weather = 724hr
average duration of adverse weather = 4hr
line failures occuring in adverse weather = 70% of total

33kV line lengths: SP1-SP2 and SP2-SP3 = 10km
SP1-SP3 = 15km

transformer ratings: SP1(Bus4), SP(Bus2) = 16MVA each
SP2 and SP3 (Bus4) = 10MVA each

where: λ_P = permanent (total) failure rate (f/yr) [for lines/cables (f/yr.km)]
λ_A = active failure rate (f/yr) [for lines/cables (f/yr.km)]
λ_T = temporary failure rate (f/yr) [for lines/cables (f/yr.km)]
λ'' = maintenance outage rate (out/yr)
r = repair time (hr)
r_P = replacement time by a spare (hr)
r'' = maintenance outage time (hr)
r_C = reclosure time (hr)
s = switching time (hr)

and: single weather state - rates are annual averages
two weather states - rates are per year of appropriate weather condition

Sets of feeder and system indices (SAIFI, etc) for the base case plus 5 other studies are shown in Tables 8 and 9 for BUS4 and BUS2 respectively. The details of the case studies are included in the tables. As expected Case B produces the worst set of indices because this system is the most basic and least capital intensive. All the other studies provide facilities for improving load point reliability. The benefit to customers of providing these additional facilities by increased capital investment can be quantified in terms of reduced outage costs. This reliability cost/reliability worth assessment requires additional data and evaluation techniques which will be the scope of future publications.

Only one case study for each of the 33 kV systems is performed. The load point reliability indices as measured at each of the 11kV supply point busbars are shown in Table 10. The detailed analyses include the following failure events only:

- all first order permanent outages
- all second order overlapping permanent outages
- all first order active failure events

These results indicate firstly the significant contribution made by low order events compared with higher order ones and secondly, the importance of including the switching effects of active failures, etc. The importance of stressing these effects in an educational programme is clearly demonstrated.

Clearly there are many other outage contributions including third order events, effect of maintenance, temporary outages and weather, second order events involving active failures, etc. These can [8] and should be included in the sequential teaching and learning process.

CONCLUSIONS

This paper has presented an extension to the RBTS by providing all the basic data for teaching reliability assessment of distribution systems. All the networks, 33kV and 11kV, can be analysed using hand calculations, permitting full understanding and use of the basic models and evaluation techniques. Students can then either use existing computer programs or develop their own in order to analyse more practical systems and to perform an increasing number of sensitivity studies. A selected number of results are included in this paper in order to give confidence to

TABLE 6 Base Case Load Point Reliability Indices For Bus 4

load pt	cables			lines		
	λ f/yr	r h	U h/yr	λ f/yr	r h	U h/yr
feeder F1						
1	0.187	22.27	4.16	0.295	11.65	3.44
2	0.193	22.51	4.34	0.305	11.43	3.49
3	0.187	22.27	4.16	0.295	11.65	3.44
4	0.195	22.59	4.40	0.308	11.37	3.50
5	0.193	22.51	4.34	0.305	11.43	3.49
6	0.195	22.59	4.40	0.308	11.37	3.50
7	0.193	22.51	4.34	0.305	11.43	3.49
feeder F2						
8	0.112	8.79	0.98	0.182	1.86	0.34
9	0.118	9.86	1.16	0.192	2.02	0.39
10	0.120	10.20	1.22	0.195	2.07	0.40
feeder F3						
11	0.189	23.21	4.39	0.298	11.72	3.49
12	0.187	23.13	4.33	0.295	11.78	3.48
13	0.187	23.13	4.33	0.295	11.78	3.48
14	0.181	22.91	4.15	0.285	12.02	3.43
15	0.187	23.13	4.33	0.295	11.78	3.48
16	0.181	22.91	4.15	0.285	12.02	3.43
17	0.187	23.13	4.33	0.295	11.78	3.48
feeder F4						
18	0.197	22.11	4.36	0.311	11.23	3.49
19	0.191	21.86	4.18	0.301	11.44	3.44
20	0.197	22.11	4.36	0.311	11.23	3.49
21	0.197	22.11	4.36	0.311	11.23	3.49
22	0.191	21.86	4.18	0.301	11.44	3.44
23	0.197	22.11	4.36	0.311	11.23	3.49
24	0.197	22.11	4.36	0.311	11.23	3.49
25	0.191	21.86	4.18	0.301	11.44	3.44
feeder F5						
26	0.116	9.98	1.16	0.189	2.04	0.39
27	0.118	10.32	1.22	0.192	2.08	0.40
28	0.110	8.89	0.98	0.179	1.87	0.34
feeder F6						
29	0.118	8.49	1.00	0.192	1.81	0.35
30	0.124	9.53	1.18	0.202	1.97	0.40
31	0.118	8.49	1.00	0.192	1.81	0.35
feeder F7						
32	0.191	23.00	4.39	0.302	11.57	3.50
33	0.191	23.00	4.39	0.302	11.57	3.50
34	0.183	22.69	4.15	0.289	11.87	3.43
35	0.191	23.00	4.39	0.302	11.57	3.50
36	0.183	22.69	4.15	0.289	11.87	3.43
37	0.191	23.00	4.39	0.302	11.57	3.50
38	0.183	22.69	4.15	0.289	11.87	3.43

students in their endeavours. These should first be repeated at the initial stage of the teaching programme. They can then be followed by a greater number and range of studies.

REFERENCES

1. IEEE Committee Report, "IEEE Reliability Test System", IEEE Trans, PAS-98, 1979, pp 2047-2054.
2. Allan R.N., Billinton R., Shahidehpour S.M. and Singh C., "Bibliography on the Application of Probability Methods in Power System Reliability Evaluation 1982-1987", IEEE Trans on Power Systems, PWRS-3, 1988, pp 1555-1564.
3. Billinton R. and Allan R.N., "Reliability Assessment of Large Electric Power Systems", Kluwer (Boston), 1988.
4. Billinton R., Vohra P.K. and Kumar S., "Effect of Station Originated Outages in a Composite System Adequacy Evaluation of the IEEE Reliability Test System", IEEE Trans, PAS-104, 1985, pp 2649-2656.
5. Allan R.N., Billinton R. and Abdel-Gawad N.M.K., "The IEEE Reliability Test System - Extensions to and Evaluation of the Generating System", IEEE Trans on Power Systems, PWRS-1, 1986, pp 1-7.
6. 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, 1989, pp 1238-1244.
7. Billinton R., Kumar S., Chowdhury N., Chu K., Goel L., Khan E., Kos P., Nourbakhsh G. and Oteng-Adjei J., "A Reliability Test System for Educational Purposes - Basic Results", IEEE Summer Power Meeting, 1989, paper 89 SM 645-3 PWRS.
8. Billinton R. and Allan R.N., "Reliability Evaluation of Power Systems", Plenum Publishing (New York), 1984.
9. Billinton R. and Allan R.N., "Reliability Evaluation of Engineering Systems", Plenum Publishing (New York), 1983.

TABLE 7 Base Case Load Point Reliability Indices For Bus 2

load pt	cables			lines		
	λ f/yr	r h	U h/yr	λ f/yr	r h	U h/yr
feeder F1						
1	0.153	31.84	4.87	0.240	14.90	3.58
2	0.161	31.75	5.11	0.253	14.40	3.64
3	0.161	31.75	5.11	0.253	14.40	3.64
4	0.153	31.84	4.87	0.240	14.90	3.58
5	0.161	31.75	5.11	0.253	14.40	3.64
6	0.159	31.77	5.05	0.250	14.51	3.63
7	0.161	30.75	4.95	0.253	14.24	3.60
feeder F2						
8	0.086	22.47	1.93	0.140	3.89	0.54
9	0.086	20.58	1.77	0.140	3.60	0.50
feeder F3						
10	0.155	31.47	4.88	0.243	14.73	3.58
11	0.161	31.75	5.11	0.253	14.40	3.64
12	0.163	31.73	5.17	0.256	14.29	3.66
13	0.161	30.41	4.90	0.253	14.19	3.59
14	0.163	30.41	4.96	0.256	14.08	3.61
15	0.155	31.47	4.88	0.243	14.73	3.58
feeder F4						
16	0.161	31.75	5.11	0.253	14.40	3.64
17	0.155	31.82	4.93	0.243	14.78	3.59
18	0.155	31.47	4.88	0.243	14.73	3.58
19	0.163	31.40	5.12	0.256	14.24	3.65
20	0.163	31.40	5.12	0.256	14.24	3.65
21	0.161	30.41	4.90	0.253	14.19	3.59
22	0.163	30.41	4.96	0.256	14.08	3.61

BIOGRAPHIES

R.N.Allan is Reader in Electrical Power Systems at UMIST, Manchester, England. He has published over 100 papers and co-authored 3 books on the subject of reliability. He is a Fellow of the IEEE and a Chartered Engineer in the UK.

R.Billinton is Associate Dean in the College of Engineering at University of Saskatchewan. He has published over 300 papers and authored and co-authored 6 books on reliability. He is a Fellow of the IEEE and a Registered Professional Engineer in the Province of Saskatchewan.

I.Sjarief was born in Indonesia. He obtained a BTech degree in Electrical Engineering from Institut Teknologi Badung in Indonesia. He was the Senior Electrical Consultant and Director of an engineering consultant company. He is now working for his MSc at

TABLE 8 System Indices for Bus 4

	lines							cables						
	SAIFI	SAIDI	CAIDI	ASAI	ASUI	ENS	AENS	SAIFI	SAIDI	CAIDI	ASAI	ASUI	ENS	AENS
a) base case (A): disconnects - fuses - alternative supply - repair of transformers														
F1	0.302	3.47	11.50	0.999604	0.000396	12196	11.09	0.191	4.29	22.43	0.999511	0.000489	15109	13.74
F2	0.190	0.38	1.98	0.999957	0.000043	1323	441.0	0.117	1.12	9.63	0.999872	0.000128	3954	1318
F3	0.294	3.47	11.81	0.999604	0.000396	12007	11.12	0.186	4.30	23.11	0.999509	0.000491	14858	13.76
F4	0.308	3.48	11.30	0.999603	0.000397	13930	10.72	0.195	4.30	22.03	0.999510	0.000490	17205	13.23
F5	0.187	0.37	2.00	0.999957	0.000043	1120	373.3	0.115	1.12	9.75	0.999872	0.000128	3354	1118
F6	0.195	0.37	1.87	0.999958	0.000042	1268	422.7	0.120	1.06	8.85	0.999879	0.000121	3687	1229
F7	0.298	3.47	11.67	0.999604	0.000396	12469	9.67	0.188	4.31	22.90	0.999508	0.000492	15439	11.97
syst	0.300	3.47	11.56	0.999604	0.000396	54293	11.36	0.190	4.29	22.58	0.999510	0.000490	73605	15.40
b) case B: no disconnects - no fuses - no alternative supply - repair of transformers														
F1	0.675	23.85	35.33	0.997277	0.002723	83713	76.10	0.455	31.50	69.23	0.996404	0.003596	110565	100.5
F2	0.283	1.42	5.00	0.999838	0.000162	4952	1650	0.174	5.22	30.00	0.999404	0.000596	18270	6090
F3	0.662	23.79	35.93	0.997285	0.002715	82415	76.31	0.447	31.26	69.93	0.996432	0.003568	108316	100.2
F4	0.729	27.05	37.10	0.996913	0.003087	108450	83.42	0.494	35.22	71.30	0.995979	0.004021	141232	108.6
F5	0.280	1.40	5.00	0.999840	0.000160	4200	1400	0.172	5.16	30.00	0.999411	0.000589	15480	5160
F6	0.280	1.40	5.00	0.999840	0.000160	4900	1633	0.172	5.16	30.00	0.999411	0.000589	18060	6020
F7	0.665	23.80	35.79	0.997283	0.002717	85561	66.33	0.449	31.32	69.76	0.996425	0.003575	112595	87.28
syst	0.682	24.64	36.13	0.997187	0.002813	374085	78.28	0.462	32.36	70.10	0.996306	0.003694	524519	109.8
c) case C: no disconnects - fuses - no alternative supply - repair of transformers														
F1	0.302	4.43	14.70	0.999494	0.000506	15579	14.16	0.191	8.28	43.37	0.999054	0.000946	29146	26.50
F2	0.190	0.95	5.00	0.999892	0.000108	3325	1108	0.117	3.50	30.00	0.999600	0.000400	12270	4090
F3	0.294	4.39	14.96	0.999498	0.000502	15208	14.08	0.186	8.14	43.69	0.999071	0.000929	28142	26.06
F4	0.308	4.46	14.51	0.999490	0.000510	17892	13.76	0.195	8.40	43.08	0.999041	0.000959	33662	25.89
F5	0.187	0.93	5.00	0.999893	0.000107	2800	933.3	0.115	3.44	30.00	0.999607	0.000393	10320	3440
F6	0.195	0.98	5.00	0.999889	0.000111	3410	1136	0.120	3.60	30.00	0.999589	0.000411	12570	4190
F7	0.298	4.41	14.83	0.999496	0.000504	15849	12.29	0.188	8.20	43.54	0.999064	0.000936	29416	22.80
syst	0.300	4.42	14.74	0.999496	0.000504	74013	15.49	0.190	8.25	43.38	0.999058	0.000942	155515	32.54
d) case D: disconnects - no fuses - alternative supply - repair of transformers														
F1	0.675	5.12	7.58	0.999416	0.000584	19478	17.71	0.455	6.59	14.49	0.999247	0.000753	24990	22.72
F2	0.283	0.47	1.66	0.999946	0.000054	1649	549.5	0.174	1.30	7.45	0.999852	0.000148	4554	1518
F3	0.662	5.13	7.74	0.999415	0.000585	19212	17.79	0.447	6.59	14.73	0.999248	0.000752	24477	22.66
F4	0.729	6.04	8.28	0.999311	0.000689	24992	19.23	0.494	7.69	15.56	0.999123	0.000877	31723	24.40
F5	0.280	0.47	1.67	0.999947	0.000053	1400	466.7	0.172	1.29	7.50	0.999853	0.000147	3870	1290
F6	0.280	0.45	1.61	0.999949	0.000051	1566	522.0	0.172	1.22	7.08	0.999861	0.000139	4236	1412
F7	0.665	5.43	8.17	0.999380	0.000620	20141	15.61	0.449	6.95	15.47	0.999207	0.000793	25688	19.91
syst	0.682	5.44	7.98	0.999379	0.000621	88403	18.50	0.462	6.97	15.11	0.999204	0.000796	119539	25.01
e) case E: disconnects - fuses - alternative supply - replacement of transformers														
F1	0.301	0.62	2.05	0.999929	0.000071	2192	1.99	0.191	1.44	7.51	0.999836	0.000164	5105	4.64
F2	0.190	0.38	1.98	0.999957	0.000043	1323	441.0	0.117	1.12	9.63	0.999872	0.000128	3954	1318
F3	0.294	0.62	2.11	0.999929	0.000071	2132	1.97	0.186	1.45	7.80	0.999834	0.000166	4982	4.61
F4	0.308	0.63	2.03	0.999929	0.000071	2501	1.92	0.195	1.45	7.42	0.999835	0.000165	5776	4.44
F5	0.187	0.37	2.00	0.999957	0.000043	1120	373.3	0.115	1.12	9.75	0.999872	0.000128	3354	1118
F6	0.195	0.37	1.88	0.999958	0.000042	1268	422.7	0.120	1.06	8.85	0.999879	0.000121	3687	1229
F7	0.298	0.62	2.09	0.999929	0.000071	2224	1.72	0.188	1.46	7.76	0.999833	0.000167	5193	4.03
syst	0.300	0.62	2.07	0.999929	0.000071	12740	2.67	0.190	1.45	7.62	0.999835	0.000165	32052	6.71
f) case F: disconnects - no fuses - no alternative supply - repair of transformers														
F1	0.675	11.48	17.01	0.998690	0.001310	49974	45.43	0.455	15.67	34.44	0.998211	0.001789	66842	60.77
F2	0.283	1.04	3.67	0.999882	0.000118	3639	1213	0.174	3.65	21.00	0.999583	0.000417	12816	4272
F3	0.662	11.39	17.20	0.998700	0.001300	49174	45.53	0.447	15.45	34.57	0.998236	0.001764	65933	61.05
F4	0.729	13.43	18.42	0.998467	0.001533	64532	49.64	0.494	17.91	36.25	0.997956	0.002044	85390	65.68
F5	0.280	1.04	3.73	0.999881	0.000119	3132	1044	0.172	3.68	21.42	0.999579	0.000421	11052	3684
F6	0.280	1.02	3.65	0.999883	0.000117	3760	1254	0.172	3.59	20.90	0.999590	0.000410	13362	4454
F7	0.665	13.26	19.94	0.998487	0.001513	51843	40.19	0.449	17.85	39.75	0.997963	0.002037	69506	53.88
syst	0.682	12.45	18.25	0.998579	0.001421	225985	47.29	0.462	16.80	36.38	0.998083	0.001917	325446	68.10

Units: SAIFI - interruptions/customer.yr, SAIDI - hr/customer.yr
CAIDI - hr/customer interruption, ENS - kWhr/yr,
AENS - kWhr/customer.yr

TABLE 9 System Indices for Bus 2

	lines							cables						
	SAIFI	SAIDI	CAIDI	ASAI	ASUI	ENS	AENS	SAIFI	SAIDI	CAIDI	ASAI	ASUI	ENS	AENS
a) base case (A): disconnects - fuses - alternative supply - repair of transformers														
F1	0.248	3.62	14.59	0.999587	0.000413	13172	20.20	0.158	5.03	31.77	0.999426	0.000574	18268	28.02
F2	0.140	0.52	3.74	0.999940	0.000060	1122	561.0	0.086	1.85	21.52	0.999789	0.000211	3968	1984
F3	0.250	3.62	14.50	0.999586	0.000414	11203	17.73	0.160	5.05	31.65	0.999424	0.000576	15463	24.47
F4	0.247	3.61	14.59	0.999588	0.000412	12248	19.69	0.158	4.98	31.54	0.999432	0.000568	16956	27.26
syst	0.248	3.61	14.55	0.999588	0.000412	37746	19.78	0.159	5.02	31.65	0.999427	0.000573	54655	28.65
b) case B: no disconnects - no fuses - no alternative supply - repair of transformers														
F1	0.626	23.61	37.71	0.997305	0.002695	86040	131.9	0.425	30.60	72.00	0.996507	0.003493	111537	171.1
F2	0.192	0.96	5.00	0.999890	0.000110	2064	1032	0.118	3.54	30.00	0.999596	0.000404	7611	3805
F3	0.559	20.35	36.40	0.997678	0.002322	63192	99.99	0.378	26.64	70.48	0.996959	0.003041	82744	130.9
F4	0.626	23.61	37.71	0.997305	0.002695	80021	128.65	0.425	30.60	72.00	0.996507	0.003493	103734	166.8
syst	0.602	22.50	37.48	0.997432	0.002568	231263	121.2	0.409	29.26	71.52	0.996660	0.003340	305626	160.2
c) case C: no disconnects - fuses - no alternative supply - repair of transformers														
F1	0.248	4.17	16.76	0.999524	0.000476	15194	23.30	0.158	7.30	46.10	0.999166	0.000834	26609	40.81
F2	0.140	0.70	5.00	0.999920	0.000080	1505	752.5	0.086	2.58	30.00	0.999705	0.000295	5547	2774
F3	0.250	4.18	16.68	0.999523	0.000477	12980	20.54	0.160	7.34	45.98	0.999163	0.000837	22805	36.08
F4	0.247	4.16	16.81	0.999525	0.000475	14181	22.80	0.158	7.29	46.16	0.999168	0.000832	24944	40.10
syst	0.248	4.16	16.77	0.999525	0.000475	43825	22.97	0.159	7.30	46.07	0.999166	0.000834	79905	41.88
d) case D: disconnects - no fuses - alternative supply - repair of transformers														
F1	0.626	7.11	11.35	0.999189	0.000811	24680	37.85	0.425	9.45	22.24	0.998921	0.001079	33109	50.78
F2	0.192	0.58	3.00	0.999934	0.000066	1235	617.7	0.118	1.95	16.50	0.999778	0.000222	4174	2087
F3	0.559	6.01	10.75	0.999314	0.000686	18816	29.77	0.378	8.18	21.63	0.999067	0.000933	25527	40.39
F4	0.626	7.15	11.42	0.999184	0.000816	22481	36.14	0.425	9.50	22.36	0.998915	0.001085	30189	48.54
syst	0.602	6.74	11.19	0.999231	0.000769	67197	35.22	0.409	9.04	22.09	0.998968	0.001032	92999	48.74
e) case E: disconnects - fuses - alternative supply - replacement of transformers														
F1	0.248	0.77	3.10	0.999912	0.000088	2790	4.28	0.158	2.18	13.77	0.999751	0.000249	7880	12.09
F2	0.140	0.52	3.74	0.999940	0.000060	1122	561.0	0.086	1.85	21.52	0.999789	0.000211	3968	1984
F3	0.250	0.78	3.09	0.999912	0.000088	2355	3.73	0.160	2.20	13.78	0.999749	0.000251	6610	10.46
F4	0.247	0.76	3.06	0.999914	0.000086	2587	4.16	0.158	2.13	13.48	0.999757	0.000243	7295	11.73
syst	0.248	0.77	3.08	0.999913	0.000087	8844	4.64	0.159	2.17	13.69	0.999752	0.000248	25753	13.50
f) case F: disconnects - no fuses - no alternative supply - repair of transformers														
F1	0.626	9.74	15.56	0.998888	0.001112	54103	82.98	0.425	12.78	30.06	0.998542	0.001458	70251	107.8
F2	0.192	0.78	4.05	0.999911	0.000089	1700	850.0	0.118	2.78	23.59	0.999682	0.000318	6099	3050
F3	0.559	8.47	15.15	0.999033	0.000967	40895	64.71	0.378	11.41	30.20	0.998697	0.001303	54008	85.46
F4	0.626	11.66	18.63	0.998669	0.001331	52528	84.45	0.425	15.20	35.75	0.998265	0.001735	68432	110.0
syst	0.602	9.93	16.49	0.998866	0.001134	149188	78.19	0.409	13.10	32.03	0.998504	0.001496	198790	104.2

TABLE 10 Reliability Indices at 11kV Supply Points

failure event	number	λ f/yr	r hr	U hr/yr
a) BUS 4				
supply point SP1				
1st order	2	2.000×10^{-3}	2.00	4.000×10^{-3}
2nd order	4	1.194×10^{-6}	5.93	7.078×10^{-6}
active	10	5.450×10^{-2}	1.00	5.450×10^{-2}
TOTAL		5.650×10^{-2}	1.04	5.851×10^{-2}
supply point SP2				
1st order	3	3.000×10^{-3}	2.00	6.000×10^{-3}
2nd order	16	3.933×10^{-4}	3.99	1.567×10^{-3}
active	15	9.150×10^{-2}	1.00	9.150×10^{-2}
TOTAL		9.490×10^{-2}	1.04	9.907×10^{-2}
supply point SP3				
1st order	3	3.000×10^{-3}	2.00	6.000×10^{-3}
2nd order	4	1.194×10^{-6}	5.93	7.078×10^{-6}
active	16	9.300×10^{-2}	1.00	9.300×10^{-2}
TOTAL		9.600×10^{-2}	1.03	9.901×10^{-2}
b) BUS 2				
supply point SP				
1st order	2	2.000×10^{-3}	2.00	4.000×10^{-3}
2nd order	4	1.194×10^{-6}	5.93	7.078×10^{-6}
active	8	5.400×10^{-2}	1.00	5.400×10^{-2}
TOTAL		5.600×10^{-2}	1.04	5.801×10^{-2}

UMIST studying reliability evaluation of distribution systems.

L.Goel was born in India. He obtained a BTech degree from the Regional Engineering College, Warangal, India. He subsequently worked as a project engineer with a premier consultancy organisation. He obtained his MSc from the University of Saskatchewan. He is now studying for a PhD. His research topic concerns power system reliability and cost/benefit analysis.

K.S.So was born in Hong Kong. He obtained an Associateship in Electrical Engineering from Hong Kong Polytechnic. He subsequently worked in the Generation Division of the Hong Kong Electric Co being involved with commissioning and operation. He obtained his MSc from UMIST. He is now studying for a PhD. His research concerns power system reliability evaluation.