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A Comparison of Deterministic and Probabilistic Methods for Determining the Required Amount of Spinning Reserve

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***Abstract*—**In an electric power system, spinning reserve requirements can be determined by using deterministic and/or probabilistic measures. Although deterministic methods are usual in many systems, application of probabilistic methods becomes increasingly important in the new environment of the electric power utility industry. This is because of the increased uncertainty associated with competition. In this paper 1) a new probabilistic method is presented which considers the reliability of transmission system in a simplified manner and 2) deterministic and probabilistic methods are compared. The studied methods are applied to the Roy Billinton Test System (RBTS).

***Keywords*—**Reliability, Spinning Reserve, Risk, Transmission, Unit Commitment.

I. INTRODUCTION

ELECTRIC power systems are typically operated at least cost subject to technical and reliability constraints [1]. Reliability constraint can be satisfied by providing the required amount of spinning reserve. In an electric power system, spinning reserve requirements can be determined by using deterministic and/or probabilistic measures. Traditionally, reliability constraints in the unit commitment (UC) problem are based on the (N-1) criterion, which means that there must be sufficient reserve in the system such that no load will lose power if any one line or any one generator fails. It is believed that a more consistent and realistic criterion would be based on probabilistic methods. In this paper, a new probabilistic method for determining the required amount of spinning reserve in an electric power system is presented. The proposed method applies a new probabilistic approach to unit commitment and considers the transmission system reliability. The results are compared with traditional deterministic measures by application to the Roy Billinton Test System (RBTS).

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II. RELIABILITY AND RISK IN OPERATING PHASE

There are many variations to the definition of reliability, but a widely accepted form [2] is: *Reliability is the probability of a system performing its purpose adequately for the period of time intended under the operating conditions encountered.* Traditionally, the basic techniques for reliability evaluation have been categorized in terms of their application to the main functional zones of an electric power system. These are: generation system, composite generation and transmission (or bulk power) system, and distribution system. The concept of hierarchical levels (HL) has been developed in order to establish a consistent means of identifying and grouping these functional zones. The first level (HLI) refers to generation facilities, the second level (HLII) refers to the composite generation and transmission (bulk power) system, and the third level (HLIII) refers to complete system including distribution [3].

The time span for an electric power system is divided into two sectors: the planning phase and the operating phase. Sufficient generation must be scheduled according to the forecasted load in power system operation. Reserve generation must also be scheduled in order to account for possible outages of generation units and transmission components [3]. Traditionally, reserve requirements have been based on either a deterministic or probabilistic approach. Reliability constraints are based on technical standards/operator experience in the deterministic approach. A widely used deterministic criterion is the N-1 criterion, which means that there must be sufficient spinning reserve on the system such that no load will lose power if any one line or any one generator fails. The probabilistic approach is a more realistic one in which a risk index enables a comparison to be made between various operating scenarios. The acceptable risk level is a management decision based on economic requirements. Once a risk level has been defined, sufficient generation can be scheduled to satisfy this risk level. This process can be done using the concept of unit commitment risk [3-6].

A. Unit Commitment Risk

Each unit is represented by a two state model in reliability studies (unit up and down states) where, λ and μ are the failure and repair rates respectively. The time dependent availability and unavailability of a unit are given by Equations

1 and 2 respectively.

$$\Pr_{Up}(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t} \quad (1)$$

$$\Pr_{Down}(t) = \frac{\lambda}{\lambda+\mu} - \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t} \quad (2)$$

It is assumed here that the system lead time is relatively short and therefore the probability of repair occurring during the small lead time is negligible. Under this condition the time dependent probabilities of the unit states at a given delay time of T can be approximated as

$$\Pr_{Down}(T) = 1 - e^{-\lambda T} \quad (3)$$

If $\lambda T << 1$, which is generally true for short lead times,

$$\Pr_{Down}(T) = \lambda T \quad (4)$$

Equation 4 is known as the outage replacement rate (ORR) and represents the probability that a unit fails and is not replaced during the lead time T. The ORR is directly analogous to the forced outage rate (FOR) used in planning studies [3-6].

The generation model required for evaluating unit commitment risk is a capacity outage probability table which is constructed using the priority list and the outage replacement rates of units (Table 1). The value of unit commitment risk can be deduced directly from the generation model. The acceptable risk level is a management decision based on economic and social requirements. The ability to incorporate risk evaluation in the continuous operating framework of an electric power system is an integral aspect in the ISO responsibility.

B. Transmission System Reliability

The transmission system in many papers has been assumed to be fully reliable. Transmission outages are therefore completely neglected. Even though transmission lines typically have failure probabilities smaller than generating units, in most systems, transmission outages significantly contribute to the system risk. Therefore, the outages of the transmission lines should be considered, at least in some simplified manner, when computing the necessary power reserves to fulfill a pre-specified reliability level.

Since the repair time of transmission lines is much smaller than of generation units, their repair process cannot be neglected during operation lead time T, i.e.,

$$\Pr_{Down}(T) = \frac{\lambda}{\lambda+\mu}(1 - e^{-(\lambda+\mu)T}) \quad (5)$$

Assuming that the system success depends on the availability of at least N_{Line}-1 transmission lines, the probability of transmission system success can be determined as

$$\Pr(\text{Transmission system success}) = \prod_{i=1}^{N_{Line}} (1-\Pr_{Down,i}(T)) + \sum_{i=1}^{N_{Line}} \left(\Pr_{Down,i}(T) \times \prod_{\substack{j=1 \\ j\neq i}}^{N_{Line}} (1-\Pr_{Down,j}(T)) \right) \quad (6)$$

where N_{Line} is the number of transmission lines. Composite (generation and transmission) system risk can be therefore determined as

$$\begin{aligned} Risk_{HLII} &= Risk_{Trans.} + (1-Risk_{Trans.}) \times Risk_{HLI} \\ &= 1 - (1-Risk_{HLI}) \times \Pr(\text{Transmission system success}) \end{aligned} \quad (7)$$

TABLE I
A TYPICAL CAPACITY OUTAGE PROBABILITY TABLE FOR A GENERATION SYSTEM WITH THREE UNITS

State	Generation units			Available Capacity	Unavailable Capacity	Individual Probability	Cumulative Probability
	1	2	3				
1	ON	ON	ON	$P_{1\max}+P_{2\max}+P_{3\max}$	0	$\Pr_1 = \prod_{i=1}^{3}(1-ORR_i)$	1
2	ON	ON	OFF	$P_{1\max}+P_{2\max}$	$P_{3\max}$	$\Pr_2 = ORR_3 \times \prod_{i=1}^{2}(1-ORR_i)$	$\sum_{i=2}^{8}\Pr_i$
3	ON	OFF	ON	$P_{1\max}+P_{3\max}$	$P_{2\max}$	$\Pr_3 = (1-ORR_1)\times ORR_2 \times (1-ORR_3)$	$\sum_{i=3}^{8}\Pr_i$
4	OFF	ON	ON	$P_{2\max}+P_{3\max}$	$P_{1\max}$	$\Pr_4 = ORR_1 \times \prod_{i=2}^{3}(1-ORR_i)$	$\sum_{i=4}^{8}\Pr_i$
5	ON	OFF	OFF	$P_{1\max}$	$P_{2\max}+P_{3\max}$	$\Pr_5 = (1-ORR_1)\times \prod_{i=2}^{3} ORR_i$	$\sum_{i=5}^{8}\Pr_i$
6	OFF	ON	OFF	$P_{2\max}$	$P_{1\max}+P_{3\max}$	$\Pr_6 = ORR_1 \times (1-ORR_2)\times ORR_3$	$\sum_{i=6}^{8}\Pr_i$
7	OFF	OFF	ON	$P_{3\max}$	$P_{1\max}+P_{2\max}$	$\Pr_7 = (1-ORR_3)\times \prod_{i=1}^{2} ORR_i$	$\sum_{i=7}^{8}\Pr_i$
8	OFF	OFF	OFF	0	$P_{1\max}+P_{2\max}+P_{3\max}$	$\Pr_8 = \prod_{i=1}^{3} ORR_i$	$\Pr_8$

III. Case Studies

A. Case 1

A 6-bus system designated as the Roy Billinton Test System (RBTS) (Fig. 1) is an excellent educational test system evolved from the reliability research activities conducted by the power systems research group at the University of Saskatchewan [7]. The system consists of 9 transmission lines, 11 generation units and 5 load points (see Appendix).

The risk of transmission system can be determined using the line availabilities, common mode failure probabilities (see Appendix) and contingency enumeration technique as shown in Table 2.

Using the generators data (see Appendix A-3) and the transmission system risk (Table 2), capacity outage probability tables can be derived. The minimum acceptable risk level of the system is 0.005 (see Appendix). The results of the RBTS analysis can be summarized as shown in Table 3. It can be seen that the minimum required reserve is 45 *MW* for all states considered here.

TABLE II
Contingency Enumeration for the RBTS Transmission Network

State	Failure event	Line(s) out	Probability
1	Single contingency	9	0.003599
2	Common mode failure	1, 6	0.000257
3	Double contingencies	9, any line	0.000242
4	Double contingency	1, 2	0.000090
5	Double contingency	1, 7	0.000090
6	Double contingency	2, 6	0.000090
7	Double contingency	6, 7	0.000090
8	Double contingency	1, 6	0.000027
9	Double contingency	5, 8	0.000012
	Total:		0.004497

The maximum load that can be supplied with a risk of 0.005 is 195 *MW* (Table 3). All units should be committed and a reserve of 45 *MW* is required to supply this load. If for example, the system load is less than 165 *MW* and more than 125 *MW*, all units but the 10 MW and 20 MW thermal units should be committed.

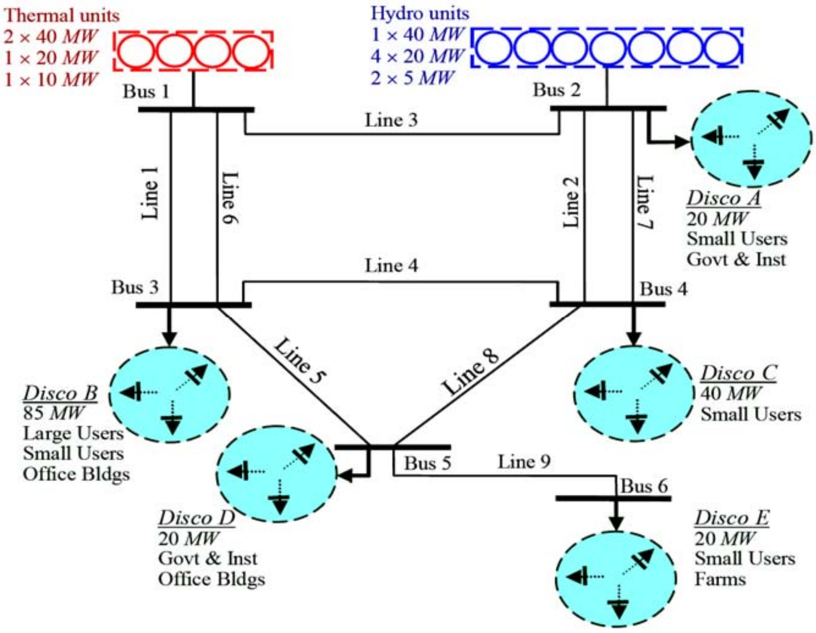

Fig. 1 The RBTS [7]

TABLE III
Summary of Results for the RBTS

State	Generation units: 40MW-Hydro	20MW-Hydro	20MW-Hydro	20MW-Hydro	20MW-Hydro	5MW-Hydro	5MW-Hydro	40MW-Thermal	40MW-Thermal	20MW-Thermal	10MW-Thermal	Capacity in (MW)	Capacity out (MW)	Maximum demand can be supplied (*MW*) (risk<0.005)	Required reserve *(MW)*
1	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	240	0	195	45
2	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF	230	10	185	45
3	ON	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	210	30	165	45
4	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	170	70	125	45
5	ON	ON	ON	ON	ON	ON	ON	OFF	ON	OFF	OFF	170	70	125	45
6	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	OFF	130	110	85	45

B. Case 2

As noted previously, there are several deterministic measures for determining the required amount of spinning reserve in power systems. In fact, most systems still use traditional deterministic techniques. These techniques are based on:

- Operator experience;
- Engineering judgment; and sometimes ever
- A simple rule of thumb.

A number of important deterministic measures currently used in different electric power systems are summarized in Table 4. As is shown in this table, probabilistic method is used only in a part of PJM (Pennsylvania-New Jersey-Maryland) interconnected electric power system in the United States of America.

In this case study, these traditional methods are applied to the Roy Billinton Test System (RBTS) as a well-known test system and compare the results with the results of our proposed probabilistic method. As a prerequisite, the unit commitment (UC) and optimal power flow (OPF) problems [8] should be solved for 24-hour duration using the load pattern given in Figure 2. The results of operational scheduling (UC and OPF problems) for the RBTS are shown in Table 5.

Different methods of determining the required amount of spinning reserve can be compared by using the operational schedule shown in Table 5. The results are shown in Table 6 and are compared in Figure 2.

TABLE IV
SPINNING RESERVE REQUIREMENTS IN DIFFERENT POWER SYSTEMS

System	Criterion, (r_d^t)
Australia and New Zealand	$\max\left(u_i^t\ p_i^t\right)$
BC Hydro	$\max\left(u_i^t\ P_i^{max}\right)$
Belgium	UCTE rules, currently at least 460 MW
California	$50\%\times\max\left(5\%\times P_{hydro}+7\%\times P_{other\ generation}\ ;\ P_{largest\ contingency}\right)+P_{non\text{-}firm\ import}$
France	UCTE rules, currently at least 500 MW
Manitoba Hydro	$80\%\max\left(u_i^t\ P_i^{max}\right)+20\%\left(\sum_{i=1}^{N}P_i^{max}\right)$
PJM (Southern)	$\max\left(u_i^t\ P_i^{max}\right)$
PJM (Western)	$1.5\%p_d^{max}$
PJM (other)	1.1% of the peak + probabilistic calculation on typical day and hours
Spain	Between $3\left(p_d^{max}\right)^{\frac{1}{2}}$ and $6\left(p_d^{max}\right)^{\frac{1}{2}}$
The Netherlands	UCTE rules, currently at least 300 MW
UCTE	No specific recommendation. The recommended maximum is: $\left(10p_{d,zone}^{max}+150^2\right)^{\frac{1}{2}}-150$
Yukon Electrical	$\max\left(u_i^t\ P_i^{max}\right)+10\%p_d^{max}$

TABLE V
24-HOUR SCHEDULE FOR THE RBTS

Hr.	Units schedule (MW)										
1	38.80	20.00	20.00	20.00	20.00	5.00	5.00	OFF	OFF	OFF	OFF
2	30.80	20.00	20.00	20.00	20.00	5.00	5.00	OFF	OFF	OFF	OFF
3	24.83	20.00	20.00	20.00	20.00	5.00	5.00	OFF	OFF	OFF	OFF
4	22.84	20.00	20.00	20.00	20.00	5.00	5.00	OFF	OFF	OFF	OFF
5	22.84	20.00	20.00	20.00	20.00	5.00	5.00	OFF	OFF	OFF	OFF
6	24.83	20.00	20.00	20.00	20.00	5.00	5.00	OFF	OFF	OFF	OFF
7	31.34	20.00	20.00	20.00	20.00	5.00	5.00	10.00	10.00	OFF	OFF
8	40.00	20.00	20.00	20.00	20.00	5.00	5.00	14.71	14.71	OFF	5.00
9	40.00	20.00	20.00	20.00	20.00	5.00	5.00	23.05	23.05	OFF	5.28
10	40.00	20.00	20.00	20.00	20.00	5.00	5.00	23.82	23.82	OFF	5.66
11	40.00	20.00	20.00	20.00	20.00	5.00	5.00	23.82	23.82	OFF	5.66
12	40.00	20.00	20.00	20.00	20.00	5.00	5.00	23.05	23.05	OFF	5.28
13	40.00	20.00	20.00	20.00	20.00	5.00	5.00	23.05	23.05	OFF	5.28
14	40.00	20.00	20.00	20.00	20.00	5.00	5.00	23.05	23.05	OFF	5.28
15	40.00	20.00	20.00	20.00	20.00	5.00	5.00	21.31	21.31	OFF	5.00
16	40.00	20.00	20.00	20.00	20.00	5.00	5.00	22.25	22.25	OFF	5.00
17	40.00	20.00	20.00	20.00	20.00	5.00	5.00	24.09	24.09	5.00	5.80
18	40.00	20.00	20.00	20.00	20.00	5.00	5.00	24.85	24.85	5.00	6.17
19	40.00	20.00	20.00	20.00	20.00	5.00	5.00	24.85	24.85	5.00	6.17
20	40.00	20.00	20.00	20.00	20.00	5.00	5.00	23.82	23.82	OFF	5.66
21	40.00	20.00	20.00	20.00	20.00	5.00	5.00	19.42	19.42	OFF	5.00
22	40.00	20.00	20.00	20.00	20.00	5.00	5.00	11.89	11.89	OFF	5.00
23	29.35	20.00	20.00	20.00	20.00	5.00	5.00	10.00	10.00	OFF	OFF
24	30.80	20.00	20.00	20.00	20.00	5.00	5.00	OFF	OFF	OFF	OFF

TABLE VI
THE REQUIRED AMOUNT OF SPINNING RESERVE FOR THE RBTS BASED ON DIFFERENT DETERMINISTIC MEASURES

Hour	Load (MW)	Required Spinning Reserve (MW)								
		PJM (W)	UCTE	Cal	AUS and NZL	Spain Min.	Spain Max.	BC, PJM(S), NED, FRA and BEL	Yuk	Man
1	124	1.86	4.08	19.4	13.8	33.4	66.8	40	52.4	80
2	117	1.75	3.84	15.4	30.8	32.4	64.8	40	51.7	80
3	111	1.67	3.66	12.4	24.8	31.6	33.2	40	51.1	80
4	109	1.64	3.60	11.4	22.8	31.3	62.7	40	51	80
5	109	1.64	3.60	11.4	22.8	31.3	62.7	40	51	80
6	111	1.67	3.66	12.4	24.8	31.6	63.2	40	51.1	80
7	137	2.05	4.50	15.7	31.8	35.1	70.2	40	53.7	80
8	159	2.39	5.21	20	40	37.8	75.7	40	55.9	80
9	176	2.64	5.75	20	40	39.8	79.5	40	57.6	80
10	178	2.66	5.81	20	40	40	80	40	57.7	80
11	178	2.66	5.81	20	40	40	80	40	57.7	80
12	176	2.64	5.75	20	40	39.8	79.5	40	57.6	80
13	176	2.64	5.75	20	40	39.8	79.5	40	57.6	80
14	176	2.64	5.75	20	40	39.8	79.5	40	57.6	80
15	172	2.58	5.63	20	40	39.4	78.7	40	57.2	80
16	174	2.61	5.69	20	40	39.6	79.1	40	57.4	80
17	183	2.75	5.99	20	40	40.6	81.2	40	58.3	80
18	185	2.78	6.05	20	40	40.8	81.6	40	58.5	80
19	185	2.78	6.05	20	40	40.8	81.6	40	58.5	80
20	178	2.66	5.81	20	40	40	80	40	57.7	80
21	168	2.53	5.51	20	40	38.9	77.8	40	56.8	80
22	154	2.30	5.03	20	40	37.2	74.4	40	55.3	80
23	135	2.03	4.44	19.7	39.4	34.9	69.8	40	53.5	80
24	117	1.75	3.84	15.4	30.8	32.4	64.8	40	51.7	80

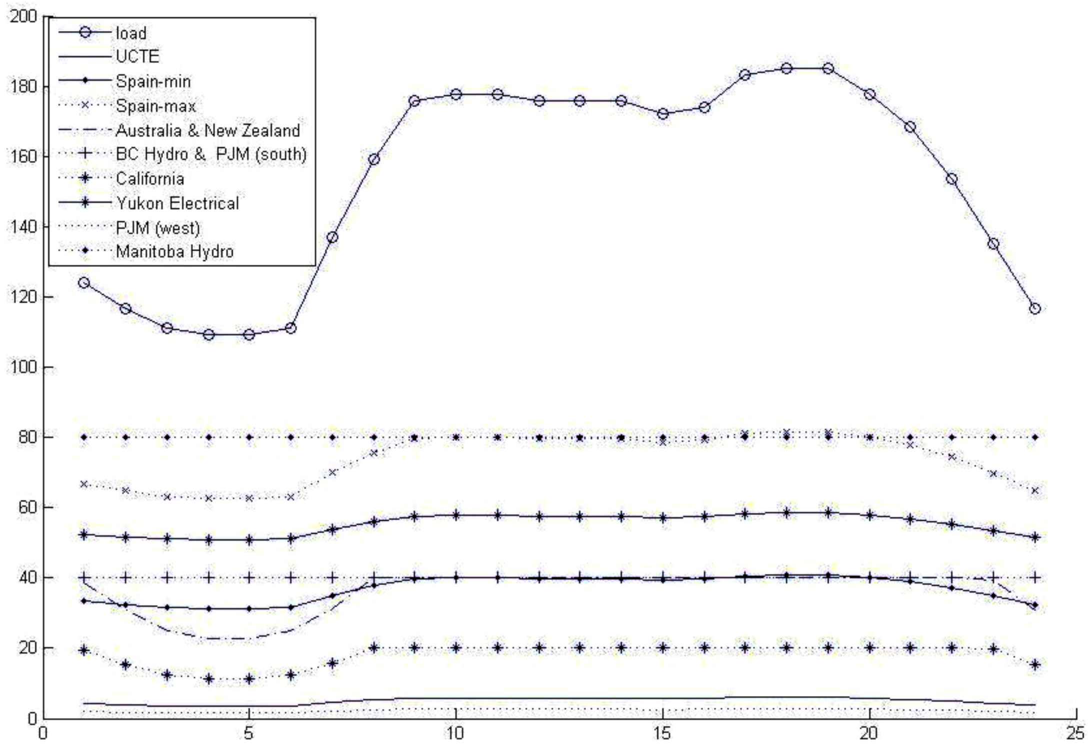

Fig. 2 24-hour duration using the load pattern

IV. DISCUSSION AND CONCLUSION

In this paper, a probabilistic method for determining the required amount of spinning reserve has been presented in which: 1) the value of unit commitment risk has been deduced from the generation model, 2) the required generation model has been constructed using the outage replacement rate (ORR) of units and 3) a method for considering transmission network reliability in the scheduling process which simplifies the HLII assessment problem has been developed. The suggested method has been applied to the RBTS to show its applicability. It has been seen that the minimum required reserve was 45 *MW* for all hours of the load pattern considered here. It has been stated that there are several deterministic methods for determining the required amount of spinning reserve usually used in different power systems. These methods have been applied to the RBTS. A comparison between the proposed probabilistic method and the traditional deterministic methods shows considerable differences between their results. It can be seen that some methods over-estimate the amount of required spinning reserve while some others under-estimate it. The measures used in BC Hydro and southern PJM have determined the required amount of spinning reserve as 40 MW (in all 24 hours) which is the nearest to the amount resulted from the proposed probabilistic method.

APPENDIX

TABLE A-I
GENERATORS DATA FOR THE RBTS

Unit *(MW)*	Type	MTTF *(hr)*	MTTR *(hr)*	ORR (T=1hr)
5	Hydro	4380	45	0.000228
10	Thermal	2190	45	0.000457
20	Hydro	3650	55	0.000274
20	Thermal	1752	45	0.000571
40	Hydro	2920	60	0.000342
40	Thermal	1460	45	0.000685

TABLE A-II
TRANSMISSION LINES DATA FOR THE RBTS

Line	From Bus	To Bus	λ *(f/yr)*	μ *(r/yr)*	Pr(Down)
1	1	3	5.25	876	0.005387
2	2	4	17.50	876	0.017687
3	1	2	14.00	876	0.014211
4	3	4	3.50	876	0.003599
5	3	5	3.50	876	0.003599
6	1	3	5.25	876	0.005387
7	2	4	17.50	876	0.017687
8	4	5	3.50	876	0.003599
9	5	6	3.50	876	0.003599

100 MVA base
230 kV base

TABLE A-III
COMMON MODE FAILURES IN THE RBTS TRANSMISSION NETWORK

Line	From Bus	To Bus	λ *(f/yr)*	μ *(r/yr)*	Probability
1 6	1	3	0.150	547.5	0.000257
2 7	2	4	0.500	547.5	0.000857

TABLE A-IV
DISCOS DATA FOR THE RBTS

Disco	Bus	Demand *(MW)*	Maximum acceptable risk level
A	2	20	0.005
B	3	85	0.003
C	4	40	0.008
D	5	20	0.002
E	6	20	0.010
Total:		185	0.005

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