

Incorporating Substation Related Outages in Composite System Reliability Evaluation



Engineering

KEYWORDS : Bulk power system reliability, Reliability indices, Reliability test system, Station configuration.

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ABSTRACT

The reliability evaluation of a bulk power system normally includes the independent outages of generating units, transformers and transmission lines. Station originated outages, can, however, also have a significant effect on the composite system adequacy indices. Terminal station related failure events such as failures of breakers, transformers and bus sections are a major cause of multiple outages of major components (generators and/or transmission lines etc.). This paper illustrates the effects of terminal stations in composite system reliability evaluation by using the RBTS Reliability Test System (RBTS). The paper also presents a basic reliability test system. The basic system data necessary for adequacy evaluation at the generation and composite generation and transmission system levels are presented together with the fundamental data required to conduct reliability cost/reliability worth evaluation.

Introduction

“Reliability” defines as the ability of a power system to provide customers with an adequate supply. Modern society is highly dependent on the efficient operation of electric power systems and has developed in such a way that even a small interruption in electric power supply has a significant effect. Customers expect that electric power should be available 24 hours a day, 7 days a week without any interruption. The article Power Cuts Can Wreck Business April 12, 1999: Fortune Magazine is ample evidence that illustrates the dependence of the world’s advanced nations on electric power supply. In the early days of electricity supply, electric power was considered to be a luxury, but today it is a highly valued commodity. Although the number of electric power outages in developed nations has reduced considerably, developing nations are still coping with the problem of frequent power failures. Economic growth is highly dependent on the existence of reliable electricity supply at an affordable cost. Major electricity outages can occur due to incorrect planning and operation, equipment failures, vandalism, environmental conditions and adverse weather effects. The creation and operation of a completely reliable electric power system is technically and economically not viable. The practical way to avoid major power outages is to make a power system more reliable. This is usually accomplished by increasing the system redundancy and the capital investment.

Increasing the capital investment will result in increased cost to the customer. Therefore there has to be a balance between the cost and reliability of an electric power system. Power system planners and designers sometimes find it difficult to achieve a balance between reliability and cost during the planning phase. Many electric power utilities use both deterministic and probabilistic techniques during the planning phase in order to assess power system reliability. Probabilistic techniques can be used to incorporate a wide range of system behavior and are preferred over deterministic techniques. Many probabilistic techniques are now available in the form of computer softwares for reliability analysis.

BRIEF DESCRIPTION OF THE RBTS

The Roy Billinton Test System-RBTS This educational test system has 6 buses, including 4 load buses (PQ) and 2 generation buses (PV). The system has 9 lines and 11 conventional generating units. The voltage level of the transmission system is 230 kV and the voltage limits for the system buses are assumed to be 1.05

p.u. and 0.97 p.u. and the system annual peak load is 185 MW and the total installed generating capacity is 240 MW. Figure 1 shows the single-line diagram of the RBTS.

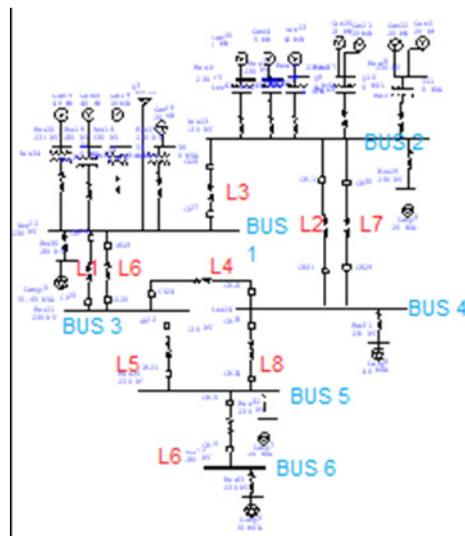


Figure 1: The single line diagram of the RBTS

The generating unit ratings and reliability data for the RBTS are shown in Table 1.

**TABLE-1
GENERATOR DATA FOR THE RBTS**

Unit no.	Bus no.	Rating (MW)	Failure rate (OCC/Yr)	Repair time (hrs)	Failure prob.
1	1	40.0	6.0	45.0	0.03
2	1	40.0	6.0	45.0	0.03
3	1	10.0	4.0	45.0	0.02
4	1	20.0	5.0	45.0	0.025
5	2	5.0	2.0	45.0	0.01
6	2	5.0	2.0	45.0	0.01
7	2	40.0	3.0	60.0	0.02
8	2	20.0	2.4	55.0	0.015
9	2	20.0	2.4	55.0	0.015
10	2	20.0	2.4	55.0	0.015

11	2	20.0	2.4	55.0	0.015
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Composite system (HL-II) adequacy evaluation using Analytical Technique

Analytical techniques represent the system by analytical models and evaluate the system risk indices from these models using mathematical solutions. The analytical approach can in many cases provide accurate probabilistic indices in a relatively short calculation time. Analytical techniques have been extensively developed for HL-I and HL II studies Analytical techniques, however, usually require assumptions to simplify the solutions. This is particularly the case when complex systems and operating procedures have to be modeled. The resulting analysis can therefore lose some of its significance. Analytical techniques are applied in this thesis.

**TABLE-2
BUS DATA FOR THE RBTS**

Bus No.	Load p.u		Pg	Q _{max}	Q _{min}	V ₀	V _{max}	V _{min}
	Active	Reactive						
1	0.00	0.0	1.0	0.5	-0.40	1.05	1	0.97
2	0.20	0.0	1.2	0.75	-0.40	1.05	1	0.97
3	0.85	0.0	0.0	0.0	0.00	0.0282	1	0.97
4	0.40	0.0	0.0	0.0	0.00	0.0071	1	0.97
5	0.20	0.0	0.0	0.0	0.00	0.0071	1	0.97
6	0.20	0.0	0.0	0.0	0.00	0.0071	1	0.97

**TABLE-3
TRANSMISSION LINE DATA FOR THE RBTS**

Line	Bus		Length Km	R	X	B / 2	Tap	Current rating p.u	Failure rate occ/yr	Re-pair time hrs	Failure Prob.
	From	To									
1,6	1	3	75	0.0342	0.18	0.0106	1.0	0.85	1.50	10.0	0.00171
2,7	2	4	250	0.1140	0.60	0.0352	1.0	0.71	5.00	10.0	0.00568
3	1	2	200	0.0912	0.48	0.0282	1.0	0.71	4.00	10.0	0.00455
4	3	4	50	0.0228	0.12	0.0071	1.0	0.71	1.00	10.0	0.00114
5	3	5	50	0.0228	0.12	0.0071	1.0	0.71	1.00	10.0	0.00114
8	4	5	50	0.0228	0.12	0.0071	1.0	0.71	1.00	10.0	0.00114
9	5	6	50	0.0228	0.12	0.0071	1.0	0.71	1.00	10.0	0.00114

Adequacy Indices for the HL-II Studies

There are many possible indices that can be used to measure the adequacy of a power system and different countries and utilities use different indices. Most adequacy indices are expected values of random variables. The basic indices in generating system adequacy are the LOLP, LOLE and LOEE as noted in the previous section. These indices can be calculated using the analytical methods.

The adequacy index concepts used in HL-I can be extended to composite system assessments. Additional indices are, however, required to reflect the composite system characteristics. Both load point and system indices are necessary to provide a complete assessment of composite system adequacy. The indices can be categorized as annualized and annual values. Annualized adequacy indices are determined using a single load level in a one year period and the system peak load is normally used. Annual adequacy indices, however, are calculated based on the actual time-varying load throughout the year. These indices include the expected customer unsupplied energy and can be used to determine the expected damage costs for the system.

The basic adequacy indices used in composite system studies are presented with reference to the ETAP program.

Introduction to ETAP software

The European Training Assessment Programme (ETAP) software is an analytical method based

Composite generation and transmission system reliability evaluation tool designed to perform reliability and reliability worth assessment of bulk electricity systems. (ETAP) is a subcommittee of the Education Committee of the European Society of Radiology (ESR). It was established in 2001 as a joint initiative between the EAR (European Association of Radiology) and the UEMS Radiology Section and is currently funded equally by the ESR and the UEMS (European Union of Medical Specialists). This commercial program can be used to provide a wide range of reliability indices.

Reliability indices in HL-II

PLC: Probability of Load Curtailments

$$PLC = \sum P_i \quad (1)$$

$i \in S$

Expected number of load curtailment (ENLC)

$$ENLC = \sum F_i \text{ occ. /yr} \quad (2)$$

$i \in S$

F_i : Is the system state frequency

$$F_i = \sum P_i \lambda_k \text{ occ. /yr} \quad (3)$$

$N \in K$

Where λ_k is the departure rate of component k and N is the set of all components of the system.

Expected duration of load curtailment (EDLC)

$$EDLC = PLC \times 8760 \text{ hrs/yr} \quad (4)$$

Average duration of load curtailment (ADLC)

$$ADLC = EDLC / EFLC \text{ hrs/disturbance} \quad (5)$$

Expected load curtailment (ELC)

$$ELC = \sum C_i P_i \text{ MW /yr} \quad (6)$$

$i \in S$

Where C_i is the load curtailment of system states i .

Expected demand not supplied (EDNS)

$$EDNS = \sum C_i P_i \text{ MW} \quad (7)$$

$i \in S$

Expected energy not supplied (EENS)

$$EENS = \sum D_i F_i C_i = \sum 8760 C_i P_i \text{ MWh/yr} \quad (8)$$

$i \in S$

Where D_i is the duration of system state i .

Expected damage cost (EDC)

$$EDC = \sum C_i F_i D_i W \text{ k\$/yr} \quad (9)$$

$i \in S$

Where C_i is the load curtailment of system state i ; F_i and D_i are the frequency and the duration of system state i ; W is the unit damage cost in \$/kWh.

TABLE - 4
THE LOAD BUS INDICES FOR THE RBTS

Load at	ENLC 1/yr	Probabil- ity min/yr	(ELC) MW/yr	(EENS) MWh/yr
Bus 2	0.000	0.000	0.000	
Bus 3	0.066	3.955	1.331	19.470
Bus 4	0.000	21.301	0.008	0.042
Bus 5	0.000	0.685	0.061	0.391
Bus 6	0.0014	600.68	16.161	135.744

TABLE - 5
THE SYSTEM INDICES FOR THE RBTS

System Indices		Units
SAIFI :System Average Interruption Frequency Index	66.0597	f / customer.yr
SAIDI :System Average Interruption Duration Index	782.9777	hr / customer.yr
CAIDI :Customer Average Interruption Duration Index	11.853	hr/customer interruption
ASAI Average service Availability Index	0.9106	pu
ASUI :Average Service Unavailability Index	0.08938	pu
EENS :Expected Energy Not Supplied	152.3497	MW hr / yr
ECOST :Expected Interruption Cost	673.386	k\$ / yr
AENS :Average Energy Not Supplied	48.3092	MW hr / customer.yr
IEAR :Interruption Energy Assessment Rate	9.969	\$ / kW hr

Composite System Evaluation with Station Related Outages

The influence of station failures on the power system performance can be appreciated from an event that was described on the BBC News, Monday October 14th, 2002, Power cut: Most of the Oxfordshire in the dark as the Cowley substation went down on Sunday evening. This event shows that the effect of faults that occur in a station can spread to other parts of a power system and can cause severe damages. Minimizing the effects of station related outages on the composite system reliability is an important planning activity. Stations consist of components such as circuit breakers, bus bars, disconnect ...etc and have a range of possible configurations. A small composite test system is used to examine the impact of four different station configurations which are ring bus, double-bus double-breaker, one and one-half breaker and one and one-third breaker configurations.

Model for station related multiple component outages

Station related outages can force two or more station connected devices out of service. The state space model of such an event is shown in Figure 2. The transition rates λ_1 and λ_2 are the failure rates and the transition rates μ_1 and μ_2 are the repair rates of components 1 and 2 respectively. The two system components are out of service in state 5 because of a station related outage. The rate λ_{12} from state 1 to state 5 and the rate μ_{12} from state 5 to state 1 are the common failure and repair rates respectively.

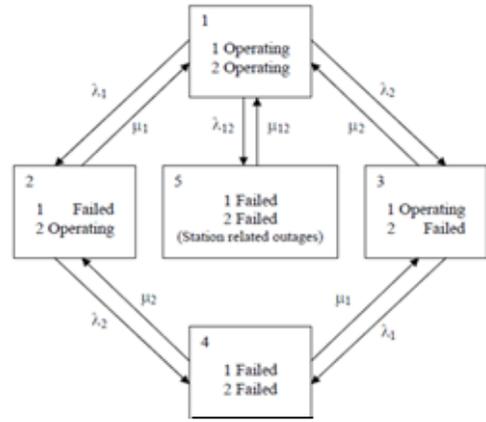


Figure 2: Model of two system components (including a common failure caused by station related outages)

The basic reliability data for major station components, circuit breakers, bus bars and transformers, are as follows:

Circuit breaker

- Active failure rate = 0.00963 failures per year
- Passive failure rate = 0.00107 failures per year
- Total failure rate = 0.0107 failures per year
- Average outage duration = 93.62 hours
- Switching time = 1 hour

Maintenance outage rate = 0.2 outages per year

Maintenance time = 108 hours

Bus bar

- Failure rate = 0.025 failures per year
- Outage duration = 10 hours

Station transformer

- Failure rate = 0.02 failures per year
- Outage duration = 768 hours
- Maintenance outage rate = 0.2 failures per year
- Maintenance time = 72 hours
- Switching time = 1 hour

The single line diagrams of the RBTS with different station configurations

Figures 3, 4, 5 and 6 represent the RBTS with ring bus, double bus double breakers, one and one half circuit breaker and one and one third circuit breaker schemes respectively

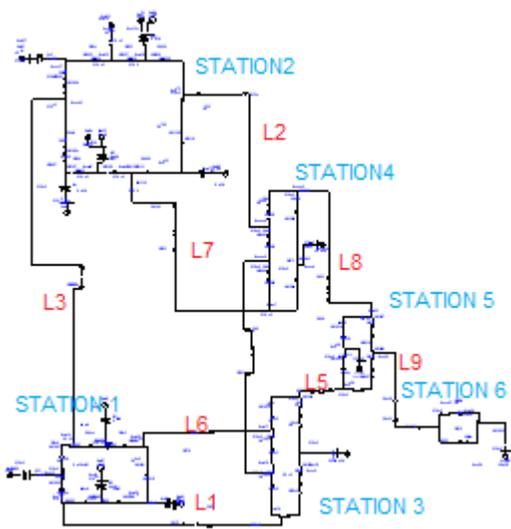


Figure 3: Single-line diagram of the RBTS with ring bus configurations

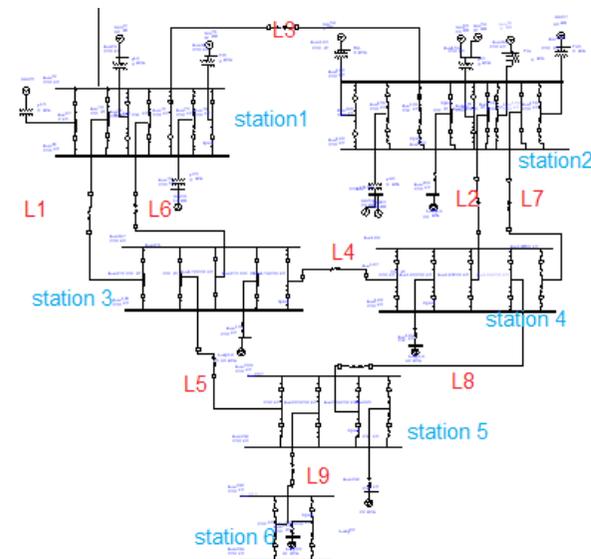


Figure 4: Single line diagram of the RBTS with double bus double breaker configurations

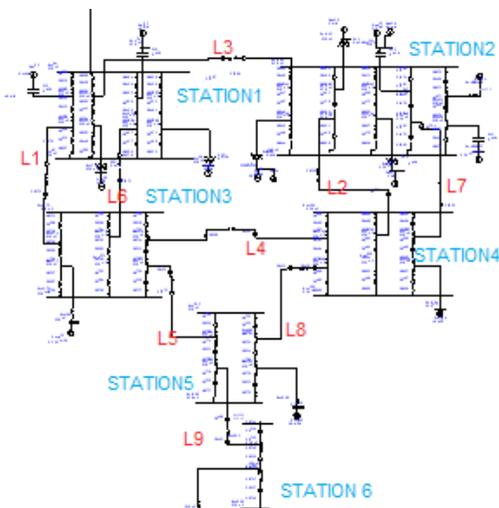


Figure 5: Single line diagram of the RBTS with one and one half breaker configurations

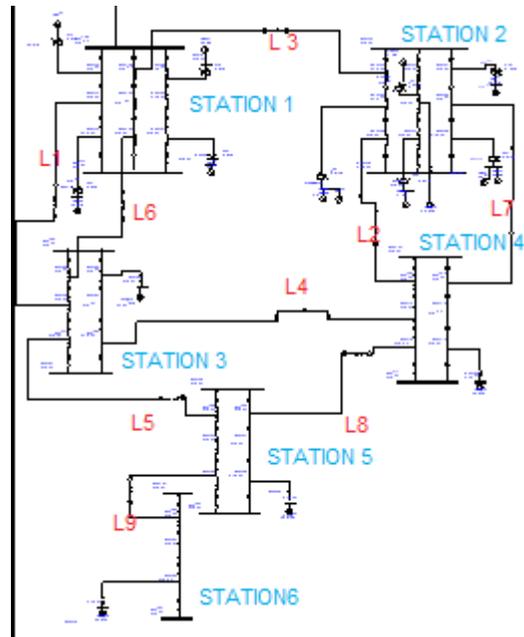


Figure 6: Single line diagram of the RBTS with one and one third circuit breaker configurations

RBTS reliability evaluation with station related outages RBTS with ring bus schemes

The reliability indices for the RBTS with ring bus station configurations are shown in Figure 3 are given in Tables 6 and 7. These indices can be compared with those shown in Tables 4 and 5. It can be seen that the load point and system indices show a significant increase due to the incorporation of station related outages.

**TABLE-6
LOAD BUS INDICES (RBTS WITH RING BUS SCHEMES)**

Load at	(ENLC) [1/yr]	Probabi-lity min/yr	(ELC) MW/yr	(EENS) MWh/yr
Bus 16	0.03121	28.19	0.323	3.1
Bus 17	0.16316	12.955	2.748	32.41
Bus 18	0.03243	51.301	0.821	7.3
Bus 19	0.03925	0.685	0.399	3.9
Bus 20	1.42687	600.68	17.52	151.23

**TABLE-7
SYSTEM INDICES (RBTS WITH RING BUS SCHEMES)**

System Indices		Units
SAIFI :System Average Interruption Frequency Index	74.09547	f / customer.yr
SAIDI :System Average Interruption Duration Index	814.777	hr / customer.yr
CAIDI :Customer Average Interruption Duration Index	10.5	hr/customer interruption
ASAI Average service Availability Index	0.9	pu
ASUI :Average Service Unavailability Index	0.09	pu
EENS :Expected Energy Not Supplied	191.5	MW hr / yr
ECOST :Expected Interruption Cost	900.31	k\$ / yr
AENS :Average Energy Not Supplied	59.674	MW hr / customer.yr
IEAR :Interruption Energy Assessment Rate	14.459	\$ / kW hr

RBTS with double bus double breaker schemes

The detailed single line diagram for the RBTS with double bus double breaker station configurations is shown in Figure 4. The load bus and system indices are shown in Tables 8 and 9 and these indices again show an increase compared to the base case indices given in Tables 4 and 5. This increase is however less than that for the RBTS with ring bus configurations is.

**TABLE-8
LOAD BUS INDICES (RBTS WITH DOUBLE BUS DOUBLE BREAKER SCHEMES)**

Load at	(ENLC) [1/yr]	Probabili-ty [min/yr]	(ELC) MW/yr	(EENS) MWh/yr
Bus 16	0.000	0.000	0.000	0.000
Bus 17	0.10778	2.001	1.238	18.825
Bus 18	0.00155	18.301	0.007	0.031
Bus 19	0.00645	0.685	0.061	0.218
Bus 20	1.24036	400.94	15.614	134.745

**TABLE-9
SYSTEM INDICES (RBTS WITH DOUBLE BUS DOUBLE BREAKER SCHEMES)**

System Indices		Units
SAIFI :System Average Interruption Frequency Index	72.1	f / customer.yr
SAIDI :System Average Interruption Duration Index	802.347	hr / customer.yr
CAIDI :Customer Average Interruption Duration Index	11.1	hr/customer interruption
ASAI Average service Availability Index	0.91	pu
ASUI :Average Service Unavailability Index	0.0913	pu
EENS :Expected Energy Not Supplied	155.3	MW hr / yr
ECOST :Expected Interruption Cost	688.9	k\$ / yr
AENS :Average Energy Not Supplied	58.12	MW hr / customer.yr
IEAR :Interruption Energy Assessment Rate	12.987	\$ / kW hr

RBTS with one and one half breaker schemes

The reliability indices for the RBTS with one and one half circuit breaker configurations are shown in Tables 10 and 11 are slightly higher than those obtained for the RBTS with double bus double breaker stations.

**TABLE-10
LOAD BUS INDICES (RBTS WITH ONE AND ONE HALF BREAKER SCHEMES)**

Load at	(ENLC) [1/yr]	Probabi-ty min/yr	(ELC) MW/yr	(EENS) MWh/yr
Bus 16	0.009	0.091	0.134	0.112
Bus 17	0.11198	3.955	1.547	18.825
Bus 18	0.00105	19.945	0.007	0.031
Bus 19	0.01498	0.765	0.189	0.651
Bus 20	1.22000	589.68	15.483	135.789

**TABLE-11
SYSTEM INDICES (RBTS WITH ONE AND ONE HALF BREAKER SCHEMES)**

System Indices		Units
SAIFI :System Average Interruption Frequency Index	72.1	f / customer.yr
SAIDI :System Average Interruption Duration Index	883.946	hr / customer.yr
CAIDI :Customer Average Interruption Duration Index	12.26	hr/customer interruption
ASAI Average service Availability Index	0.91	pu
ASUI :Average Service Unavailability Index	0.0913	pu
EENS :Expected Energy Not Supplied	167.628	MW hr / yr

ECOST :Expected Interruption Cost	684.74	k\$ / yr
AENS :Average Energy Not Supplied	58.12	MW hr / customer.yr
IEAR :Interruption Energy Assessment Rate	12.987	\$ / kW hr

RBTS with one and one third breaker schemes

The load bus and system indices are shown in Tables 12 and 13 for the RBTS with one and one third breaker configurations. The indices are again slightly higher than those for the base case indices.

**TABLE-12
LOAD BUS INDICES (RBTS WITH ONE AND ONE THIRD BREAKER SCHEMES)**

Load at	(ENLC) [1/yr]	Probabi-ly min/yr	(ELC) MW/yr	(EENS) MWh/yr
Bus 16	0.000	0.111	0.114	0.00
Bus 17	0.11189	3.456	1.970	18.818
Bus 18	0.00103	11.945	0.335	0.031
Bus 19	0.00439	0.456	0.0718	0.401
Bus 20	1.22000	200.68	15.494	135.508

**Table-13
SYSTEM INDICES (RBTS WITH ONE AND ONE THIRD BREAKER SCHEMES)**

System Indices		Units
SAIFI :System Average Interruption Frequency Index	72.1	f / customer.yr
SAIDI :System Average Interruption Duration Index	883.946	hr / customer.yr
CAIDI :Customer Average Interruption Duration Index	12.26	hr/customer interruption
ASAI Average service Availability Index	0.91	pu
ASUI :Average Service Unavailability Index	0.0913	pu
EENS :Expected Energy Not Supplied	179.865	MW hr / yr
ECOST :Expected Interruption Cost	681.44	k\$ / yr
AENS :Average Energy Not Supplied	58.12	MW hr / customer.yr
IEAR :Interruption Energy Assessment Rate	12.987	\$ / kW hr

Comparison of the system reliability indices for the RBTS

The comparison is based on the percentage increase in a system index over that obtained in the base case shown in Table 5. Figure 7 and table 14 presents a comparison of the increase in the system indices associated with the four station configurations considered.

It can be seen that the RBTS with ring bus configuration has the highest percentage increase compared to the RBTS with other station configurations.

**TABLE-14
THE COMPARISON OF THE SYSTEM RELIABILITY INDICES FOR THE RBTS AND THE FOUR STATION CONFIGURATION**

Station Configurations	SAIFI f / customer.yr	SAIDI hr / customer.yr	ASUI pu	EENS MW hr / yr	IEAR \$ / kW hr
_____	66.05	782.97	0.08	152.3	9.969
Ring bus schemes	74.09	814.77	0.09	191.5	14.45
Double bus double breaker schemes	72.1	802.34	0.09	155.3	12.9

One and one half breaker schemes	72.1	883.94	0.09	167.6	12.98
One and one third breaker schemes	72.1	883.94	0.09	179.8	12.9

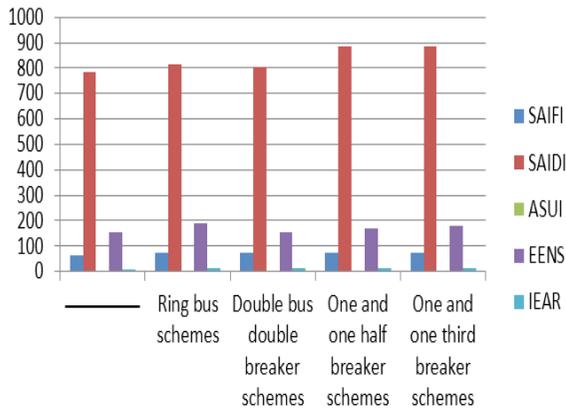


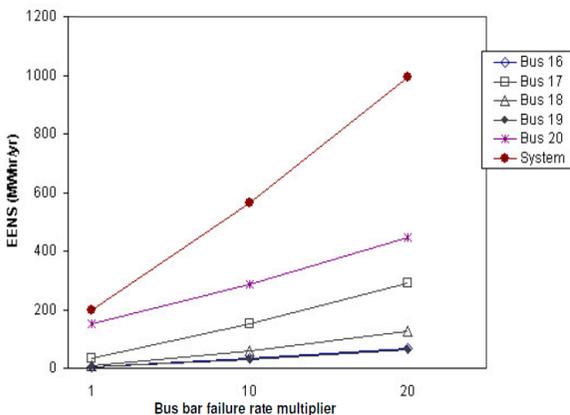
Figure 7: Relative impact on the system reliability indices for the RBTS due to the four different station configurations

The results show that station related outages are important factors in the system assessment and significantly affect the predicted indices. The comparisons shown in Figure 7 are based on the parameters shown in the basic reliability data for major station components, circuit breakers, bus bars and transformers shown in the above section. The most significant increase in the system indices is associated with the ring bus configuration. This is the least expensive configuration in terms of capital cost. The double bus double breaker configuration results in the lowest system ENLC and EENS and is the most expensive configuration.

Sensitivity analysis on the RBTS with stations

The RBTS basic system and the RBTS with four different station configurations are used in the sensitivity studies. The EENS index is an important indicator of system performance and is used for assessing the RBTS performance.

The single line diagram of the RBTS with ring bus schemes is shown in Figure 3. The effect on the RBTS performance of varying the bus bar failure rate can be seen in Figure 8. The load bus and system indices increase with an increase in the bus bar failure rates. The effect is quite significant at all the buses and for the system, as the bus bars are important components in a ring bus configuration.



The effect on the EENS index of varying the circuit breaker fail-

ure rates can be observed from Figure 9. It can be seen that the system EENS of the RBTS with ring bus schemes is relatively less sensitive to increases in the circuit breaker failure rate as compared to that of varying the bus bar failure rate.

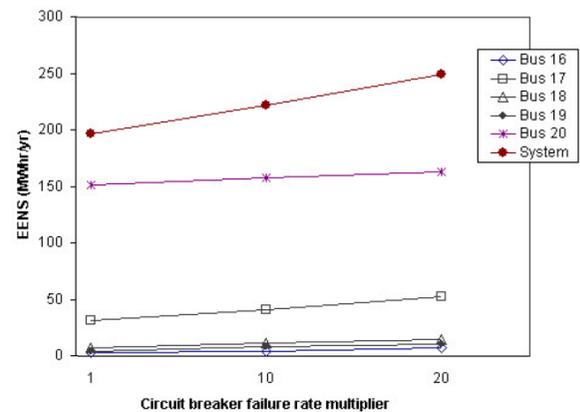


Figure 9: Effect of varying the circuit breaker failure rates in the RBTS withring bus schemes

The effect of varying the failure rates of the double bus double breaker station Figure 4 components can be observed from Figures 10 and 11. There is no significant increase in the EENS values at the load buses and for the system, when the bus bar failure rates are varied.

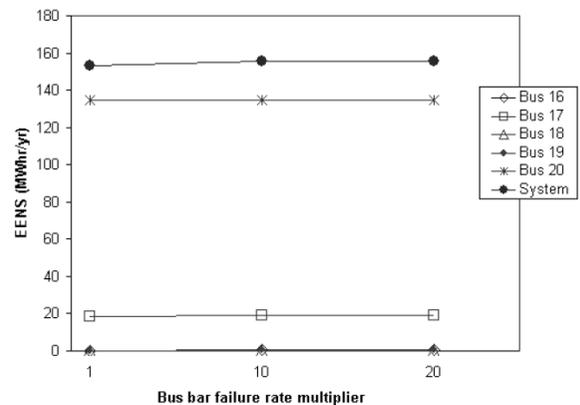


Figure 10: Effect of varying the bus bar failure rates in the RBTS with double bus double breaker schemes

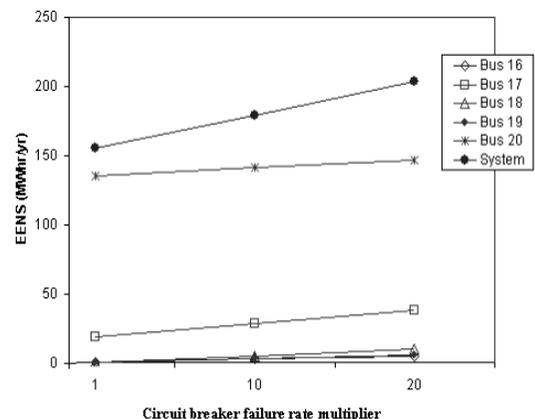


Figure 11: Effect of varying the circuit breaker failure rates

in the RBTS with double bus double breaker schemes

The RBTS with one and one half circuit breaker schemes figure 5, this station configuration is widely used in composite power systems. Figure 12 show the response to variations in the bus bar failure rates is not very sensitive. Figure 13 show the response to variations in circuit breaker failure rates is similar to Figure 11.

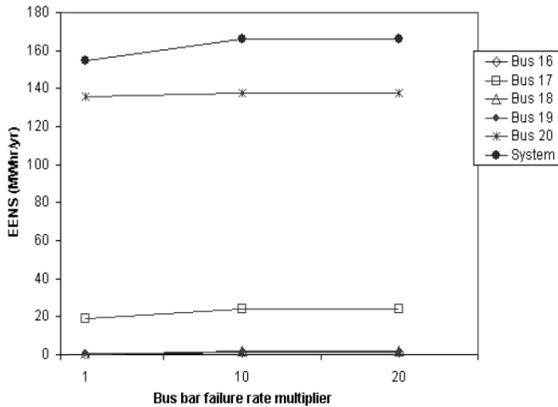


Figure 12: Effect of varying the bus bar failure rates in the RBTS with one and one half breaker schemes

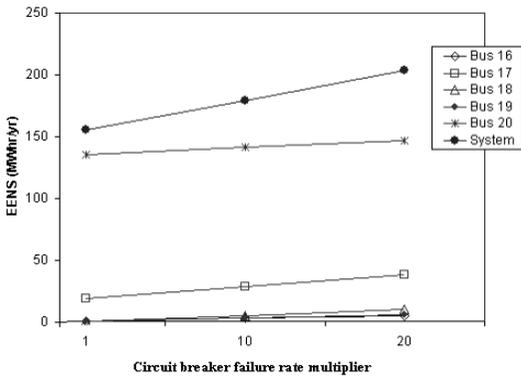


Figure 13: Effect of varying the circuit breaker failure rates in the RBTS with one and one half breaker schemes

The RBTS with one and one third circuit breaker schemes Figure 6 has fewer breakers per terminal compared to the one and one half breaker configuration and is shown in Figure 5. The effect on the performance of the RBTS with one and one third breaker configurations of varying the bus bar failure rate can be observed from Figure 14. It can be seen that the load bus and system EENS indices are relatively insensitive to variations in the bus bar failure rates. The effect on the performance of the RBTS of varying the circuit breaker failure rates can be observed from Figure 15.

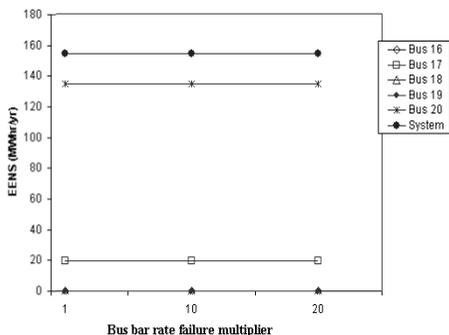


Figure 14: Effect of varying the busbar failure rates in the RBTS with one and one third circuit breaker schemes

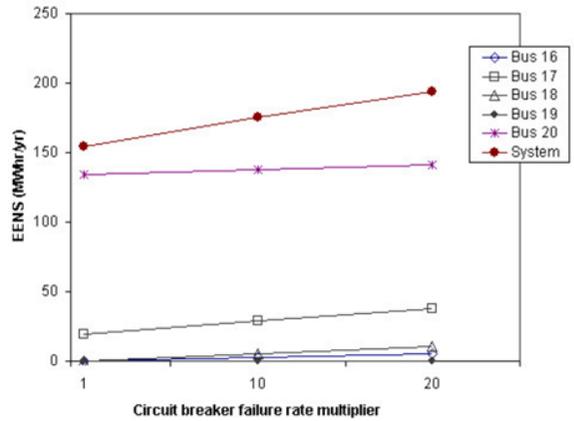


Figure 15: Effect of varying the circuit breaker failure rates in the RBTS with one and one third circuit breaker schemes

The system EENS values are sensitive to variations in the circuit breaker failure rates and are similar to those shown in Figures 11 and 13. Load bus 17 is more sensitive to variations in the circuit breaker failure rates compared to the other load buses. The studies did on the RBTS with one and one third circuit breaker configurations shows that this configuration is more reliable than the ring bus scheme. The performance of the RBTS with one and one third stations is similar to that of the RBTS with one and one half circuit breaker stations and the RBTS with double bus double breaker configurations. It should be noted, however that the behavior of the RBTS with different station configurations could change with different station components failure parameters.

Comparison of variations in the circuit breaker failure rate Figure 16 shows the increase rate in the system EENS due to includ-

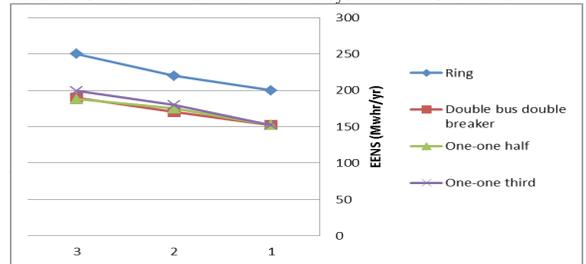


Figure 16: Increase rate of system EENS as a function of the circuit breaker failure rates for the modified RBTS with the four station schemes.

The RBTS with double bus double breaker configurations is slightly more sensitive to variations in the circuit breaker failure rates as compared to the RBTS with one and one half breaker configurations and one and one third breaker configurations.

CONCLUSIONS

This paper has presented a test system, RBTS, which includes all the basic data required for fundamental reliability studies at HLII. The station components present in a composite system play a significant role in system performance. The station related outages are important factors in the system assessment and significantly affect the predicted indices. RBTS was augmented with different configurations of substations and reliability analysis was run for each configuration. The system reliability was measured through reliability indices output of ETAP and NEPLAN software. As was expected reliability level of the

system are ordered in ascending order as follows RBTS with ring bus , one and one third circuit breaker , one and one half circuit breaker and double bus double breaker substation. The sensitivity analysis was run and shows the reliability indices of the RBTS with ring bus schemes are sensitive to variations in the bus bar failure rates, and are relatively less sensitive to increases in the circuit breaker failure rates. The EENS index for the RBTS with double bus double breaker configurations, one and one half breaker configurations and one and one third breaker configurations are insensitive to variations

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