# A Combined Bulk Electric System Reliability Framework Using Adequacy and Static Security Indices

**Roy Billinton**[†] **and Wijarn Wangdee***

**Abstract** – Deterministic techniques have been applied in power system planning for many years and there is a growing interest in combining these techniques with probabilistic considerations to assess the increased system stress due to the restructured electricity environment. The overall reliability framework proposed in this paper incorporates the deterministic N-1 criterion in a probabilistic framework, and results in the joint inclusion of both adequacy and security considerations in system planning. The combined framework is achieved using system well-being analysis and traditional adequacy assessment. System well-being analysis is used to quantify the degree of N-1 security and N-1 insecurity in terms of probabilities and frequencies. Traditional adequacy assessment is incorporated to quantify the magnitude of the severity and consequences associated with system failure. The concepts are illustrated by application to two test systems. The results based on the overall reliability analysis framework indicate that adequacy indices are adversely affected by a generation deficient environment and security indices are adversely affected by a transmission deficient environment. The combined adequacy and security framework presented in this paper can assist system planners to realize the overall benefits associated with system modifications based on the degree of adequacy and security, and therefore facilitate the decision making process.

**Keywords**: Bulk electric system (BES), Combined reliability framework, Traditional adequacy assessment, System well-being analysis, Generation and transmission deficiencies

## 1. Introduction

The term reliability when applied to a composite generation and transmission system can be divided into the two distinct aspects of adequacy and security. Adequacy assessment relates to the existence of sufficient facilities in the system to meet the customer load requirements within acceptable operating limits and at an appropriate level of reliability. A composite generation and transmission system is usually designated as a bulk electric system (BES) as it includes the facilities necessary to generate sufficient energy and the associated transmission to move energy to the actual bulk supply points. Considerable material has been published on the adequacy assessment of BES using probabilistic techniques [1]-[4]. Research has also been conducted and published [5]-[7] on security evaluation using the concept of system operating states designated as normal, alert, emergency, and extreme emergency states. Security evaluation in a BES is normally conducted using the traditional N-1 deterministic criterion [8], [9], which states that the system should be able to withstand the loss of any single BES element without violating any system constraints. The system is assumed to be operating in the normal state prior to the disturbance. Security analysis can be divided into the two domains of transient (dynamic) and steady-state (static) assessment. Transient stability analysis and large scale disturbance assessment are major elements in transient security assessment. Static security assessment is focused on the determination of the existence of a steady-state secure operating point where the system can reside after the dynamic perturbations have subsided. Acceptable deterministic criteria such as the N-1 approach can be incorporated in static security assessment using the well-being approach [10]-[12]. This method provides the ability to embed the deterministic criterion in the probabilistic framework used in conventional adequacy assessment. This approach is employed in this paper using system operating states designated as healthy, marginal and at risk. The degree of system security is quantified in terms of the probabilities and frequencies associated with the secure state (N-1, healthy) and the insecure state (marginal) Conventional system adequacy assessment is focused on the system failure states and estimates the severity of failure in physical and monetary terms. Quantitative

---

[†] Corresponding Author: Power System Research Group, Department of Electrical Engineering, University of Saskatchewan, Saskatoon, Canada. (roy.billinton@usask.ca)

* System Planning and Performance Assessment, British Columbia Transmission Corporation (BCTC), Vancouver, Canada. (wijarn.wangdee@bctc.com)

Received July 15, 2006 ; Accepted October 12, 2006

evaluation of the degree of system security is not normally included in a traditional adequacy assessment.

The combined reliability framework considering both the adequacy and static security perspectives utilized in this paper is achieved using system well-being analysis and traditional adequacy assessment. Selected adequacy-based and security-based indices are used to create a combined reliability framework. Two test systems are used and various case studies are illustrated based on different system conditions involving generation and transmission deficient situations. The combined adequacy and security framework presented in this paper can assist system planners to assess system modifications based on the degree of adequacy and security, and therefore facilitate the decision making process. Various possible reinforcement alternatives considering the overall reliability analysis framework are also demonstrated in this paper.

## 2. Sequential Simulation Process for Bulk Electric System Reliability Analysis

### 2.1 Traditional Adequacy Assessment Procedure

The BES reliability assessment studies described in this paper were conducted using sequential Monte Carlo simulation [2], [13]-[15]. In this approach, the initial state of each relevant element (generation and transmission components) are specified, following which the chronological up and down states for each element are determined for a given time period. This is usually a year. The element state durations are obtained using the inverse transform method and the distribution functions associated with the element failure and repair rates. Chronological hourly load models for each system load point and for the overall system are incorporated in the analysis. The system operation is assessed on an hourly basis and if required, corrective actions are incorporated to alleviate constraints and curtail load if needed. System reliability indices are calculated and accumulated at the end of each year as the simulation progresses. The simulation is terminated when the coefficient of variation of a specified index is less than a specified tolerance level. The fast decoupled AC power flow technique [16] is used and linear programming methods [7], [17] are utilized for corrective actions such as generation rescheduling, line overload alleviation, operating constraint corrections (i.e. real and reactive power, voltage violations), and load curtailment solutions are considered.

The basic bulk electric system adequacy indices are related to load curtailment. The following indices are used in the studies described in this paper.

*PLC = Probability of load curtailment (/year)*
*EFLC = Expected frequency of load curtailment (occurrences/year)*
*ECOST = Expected customer interruption cost (M$/year)*
*DPUI = Delivery point unavailability index (system.minutes)*

### 2.2 System Well-Being Analysis

System well-being can be categorized into the three states of healthy, marginal and at risk as shown in Fig. 1. The state definitions in the well-being approach are as follows:

***Healthy state*** – all equipment and operating constraints are within limits and there is sufficient margin to serve the total load demand even with the loss of any element, i.e. generator or transmission line.

***Marginal state*** – the system is still operating within limits, but there is no longer sufficient margin to satisfy the acceptable deterministic criterion.

***At Risk state*** – equipment or system constraints are violated and load may be curtailed.

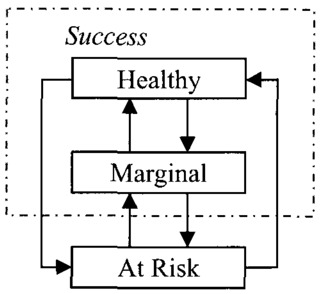

**Fig. 1.** Well-Being Framework

The basic procedure described above using sequential Monte Carlo simulation for BES adequacy assessment has been modified and extended to include system well-being considerations. The detailed process is described in [12], [18].

The basic system well-being indices are the probabilities and frequencies of the healthy, marginal and risk states, and are designated as follows:

*Prob{H} = Probability of the healthy state (/year)*
*Prob{M} = Probability of the marginal state (/year)*
*Prob{R} = Probability of the at risk state (/year)*
*Freq{H} = Frequency of the healthy state (occurrences/year)*
*Freq{M} = Frequency of the marginal state (occurrences/year)*
*Freq{R} = Frequency of the at risk state (occurrences/year)*

The bulk electric system reliability indices associated with the at risk state in system well-being analysis (static security assessment) are identical to the predictive reliability indices related to load curtailment in adequacy assessment. These relationships are as follows: Prob{R} = PLC and Freq{R} = EFLC.

In this analysis, Prob{R}, Freq{R}, DPUI and ECOST are designated as adequacy indices and Prob{H}, Prob{M}, Freq{H} and Freq{M} are designated as security indices in the studies presented in this paper.

The effectiveness of the proposed overall framework for bulk electric system reliability analysis considering both adequacy and static security are examined and illustrated by application to several practical case studies involving different systems and conditions. The case studies are presented in the following sections using two basic scenarios. The first scenario is focused on bulk electric systems with generation deficiencies. The second scenario is focused on bulk systems with transmission deficiencies. The RBTS [19] and the IEEE-RTS [20] are used as test systems.

## 3. Study Systems

### 3.1 The Reinforced RBTS (R-RBTS)

The original RBTS [19] is a 6 bus system composed of 2 generator buses, 5 load buses (delivery points), 9 transmission lines and 11 generating units. The system peak load is 185 MW and the total generation is 240 MW. The peak demands occurring at each individual delivery point may not be coincident when using chronological load models. The system peak demand, therefore, is lower than that of a load model in which all the delivery points reach their peak loads at the same time. In this case, the system peak is 179.28 MW rather than 185 MW. In this paper, the original RBTS described above has been reinforced by adding a transmission line (Line#10) between Bus 5 and Bus 6 in order to support the original single circuit delivery point at Bus 6. The reinforced RBTS is designated as the R-RBTS and is shown in Fig. 2.

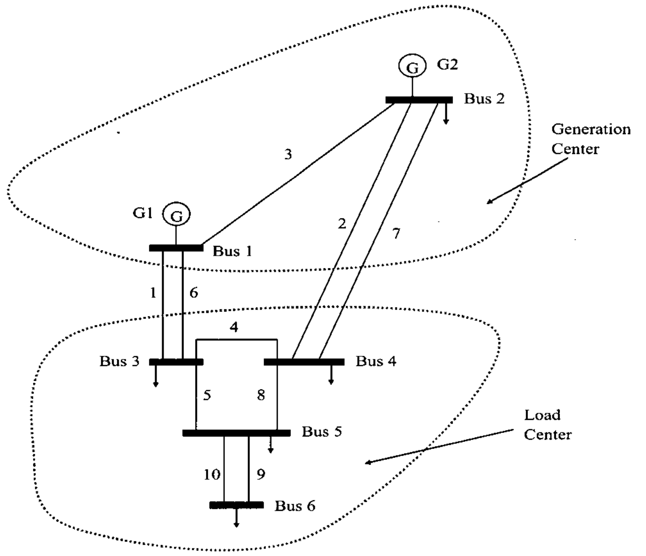

**Fig. 2.** Single line diagram of the reinforced RBTS (R-RBTS)

### 3.2 The Modified R-RBTS (MR-RBTS)

The R-RBTS described in Section 3.1 and shown in Fig. 2 has been modified as follows:

- Add 3×20MW generating units at Bus 1.
- Increase the system peak load by 20% (from 179.28 MW to 215.14 MW).

This modified system is designated as the modified R-RBTS (MR-RBTS) in this paper. In this system, the total generation is 300 MW and the system peak demand is 215.14 MW (39.4% reserve margin). The utilization of Lines # 1 and 6 is approximately 85% of the line rating for the system peak condition. Losing one of these parallel lines will create an overload on the remaining line during high load periods and may result in load curtailments. The system under this condition has an abundance of generation, but tends to be transmission deficient.

### 3.3 The Original IEEE-RTS

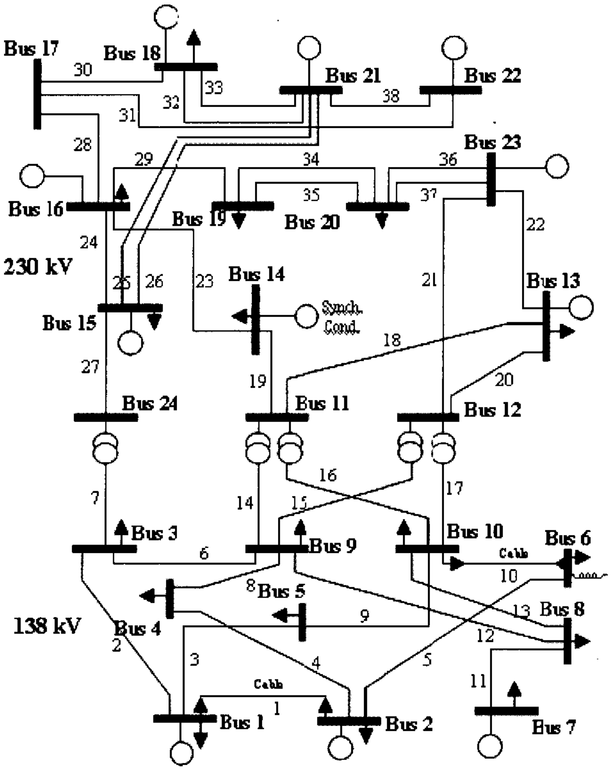

**Fig. 3.** Single line diagram of the original IEEE-RTS

The original IEEE-RTS [20] is a 24 bus system with 10 generator buses, 17 load buses, 33 transmission lines, 5 transformers and 32 generating units. The system peak load is 2,850 MW and the total generation is 3,405 MW. In this study, the system peak is 2,754.75 MW rather than 2,850 MW due to a non-coincidence of the chronological load models for the individual delivery points. The original IEEE-RTS has a very strong transmission network and a weak generation system. A single line diagram of the original IEEE-RTS is shown in Fig. 3.

### 3.4 The Modified IEEE-RTS

The original IEEE-RTS described in Section 3.3 is modified as follows:

- The load levels of all the delivery points are increased to 1.5 p.u. of the original values. The peak load for the modified system is 1.5×2,850 = 4,275 MW. (When considering the coincidence of the chronological loads at all the buses, the actual system peak load is 4,132.13 MW.)
- The generation at the five following generator buses is doubled: Buses 16, 18, 21, 22 and 23 (12 generating unit additions). The total number of generating units in the modified system is 32+12 = 44 units with a total system capacity of 3,405+1,915 = 5,320 MW.
- The line rating of Line # 10 (an underground cable between Buses 6 and 10) is increased to 1.5 p.u. of the original rating. The capacities of the synchronous condenser at Bus 14 and the reactor at Bus 6 are increased to 1.5 p.u. of the original capacities.

There is significant transmission utilization in the modified IEEE-RTS as a considerable amount of power is transferred from the north to the southern system. Even though the overall system reserve margin is 24%, the southern part (138 kV) of the modified system has both generation and transmission deficiencies. Both the northern and southern areas have transmission constraints. The system under this condition is similar to many current systems in which electricity competition has resulted in increased numbers of independent power producers and heavy increases in transmission utilization.

## 4. Case Studies on Generation Deficient Systems

Generation deficient environments exist in both the reinforced RBTS (R-RBTS) and the original IEEE-RTS by increasing the load in each system.

### 4.1 Case Study on the R-RBTS

The R-RBTS described in Section 3.1 is used in this study. In this system, a transmission line has been added between Bus 5 and Bus 6 in order to support the single circuit delivery point at Bus 6. This system, therefore, has a relatively strong transmission network. The total generation is 240 MW and the original system peak load is 179.28 MW. The combined system reliability indices considering both adequacy and security for the R-RBTS associated with different system peak demands are shown in Table 1. The results shown in Tables 1 are based on 4,000 simulation years and have a coefficient of variation of expected energy not supplied (EENS) that is less than 2.5%.

**Table 1.** Overall system reliability indices (adequacy and security) of the R-RBTS for various system peak demands

| System Indices | System peak load demand in MW | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 179.28 MW | 182.87 MW | 186.45 MW | 190.04 MW | 193.62 MW | 197.21 MW | 200.79 MW | 204.38 MW |
| Prob{H} | 0.9313 | 0.9237 | 0.9174 | 0.9126 | 0.9090 | 0.9058 | 0.8988 | 0.8859 |
| Prob{M} | 0.0683 | 0.0757 | 0.0818 | 0.0864 | 0.0896 | 0.0924 | 0.0990 | 0.1110 |
| Prob{R} | 0.0004 | 0.0006 | 0.0008 | 0.0010 | 0.0014 | 0.0018 | 0.0022 | 0.0031 |
| Freq{H} | 91.59 | 93.89 | 98.69 | 101.43 | 104.98 | 108.74 | 145.55 | 195.54 |
| Freq{M} | 92.37 | 94.96 | 100.27 | 103.54 | 107.73 | 111.90 | 149.49 | 202.54 |
| Freq{R} | 0.83 | 1.15 | 1.68 | 2.24 | 2.91 | 3.37 | 4.23 | 7.44 |
| DPUI | 15.61 | 21.25 | 28.80 | 38.75 | 51.91 | 69.12 | 88.92 | 116.32 |
| ECOST | 0.195 | 0.263 | 0.358 | 0.484 | 0.651 | 0.872 | 1.120 | 1.454 |

Table 1 shows that the system reliability indices gradually degrade as the system peak load progressively increases. When the system peak load is greater than 197.21 MW, the generation is not able to meet the demand when the largest generating unit (40 MW unit) is on outage. It is important to note that the system peak demand shown in Table 1 excludes transmission losses. The transmission loss in the R-RBTS is in the range of 3 – 4%. The total system demand (load + loss) for the 197.21 MW peak load is therefore slightly in excess of 200 MW. The DPUI increases significantly when the system load grows beyond this level. This observation is also applicable to the frequency indices such as Freq{H}, Freq{M} and Freq{R}. The Prob{H}, however, behaves in a somewhat different manner, as it gradually decreases as the load grows. The Prob{H} does not dramatically decrease under the condition when the N-1 security criterion (an outage of the largest generating unit) is violated (at the peak load). Security indices such as Prob{H} and Prob{M} are less sensitive than adequacy indices such as DPUI in a generation deficient environment. The utilization of Prob{H} as a single security index does not provide a valid indicator of the overall system well-being and should be used in conjunction with the other indices. The results based on a combined reliability framework indicate that the adequacy indices tend to be more adversely affected in a generation deficient environment than the security indices.

### 4.1 Case Study on the Original IEEE-RTS

The original IEEE-RTS described in Section 3.3 is used in this study. The total generation is 3405 MW and the system peak load is 2754.75 MW. The original IEEE-RTS has a very strong transmission network and a weak generation system. The combined system reliability indices considering both adequacy and security for the original IEEE-RTS with different system peak demands are shown in Table 2. The results are based on 3,000 simulation years and have a coefficient of variation of EENS that is less than 2.5%.

**Table 2.** Overall system reliability indices (adequacy and security) of the original IEEE-RTS for various system peak demands

| System Indices | System peak load demand in MW | | | | |
|---|---|---|---|---|---|
| | 2699.66 MW | 2754.75 MW | 2809.85 MW | 2864.94 MW | 2920.04 MW |
| Prob{H} | 0.9589 | 0.9478 | 0.9341 | 0.9197 | 0.9038 |
| Prob{M} | 0.0383 | 0.0480 | 0.0600 | 0.0721 | 0.0852 |
| Prob{R} | 0.0028 | 0.0041 | 0.0059 | 0.0082 | 0.0110 |
| Freq{H} | 72.22 | 89.67 | 102.91 | 120.18 | 145.46 |
| Freq{M} | 75.88 | 93.99 | 109.10 | 129.03 | 156.30 |
| Freq{R} | 6.55 | 9.24 | 12.09 | 15.99 | 21.85 |
| DPUI | 66.23 | 98.39 | 144.17 | 207.24 | 290.97 |
| ECOST | 14.430 | 21.517 | 31.622 | 45.582 | 64.221 |

Table 2 shows that the overall system reliability indices degrade as the system peak load progressively increases. As discussed earlier, the system peak demand levels shown exclude transmission losses. The total system consumption in each case is therefore slightly higher than that shown in Table 2. In a similar manner to the results shown in Table 1, the adequacy indices of DPUI and ECOST increase dramatically at the high peak loads while the security indices of Prob{H} and Prob{M} gradually deteriorate. Generation deficiencies have a significant adverse effect on the system adequacy indices as the severity of supply interruptions increase rapidly as the system peak load increases. Generation deficient environments, however, tend to have relatively less effect on the system security indices than on the system adequacy indices. Case studies on transmission deficient environments are examined in the following section.

## 5. Case Studies on Transmission Deficient Systems

Electric power systems are moving towards restructured regimes by creating competition and commercialization of power supply among the relevant participants under a transmission open access paradigm. This restructured environment results in an increased utilization of transmission networks which were not originally designed for competition and heavy utilization. The case studies presented in this section are focused on heavily utilized transmission conditions in order to examine these impacts on both the adequacy and security indices. The system reliability behavior in the transmission deficient cases is compared with that under the generation deficient environments described in the previous section. The MR-RBTS and modified IEEE-RTS described respectively in Sections 3.2 and 3.4 are used for the case studies on transmission deficient systems.

### 5.1 Case Study on the MR-RBTS

The combined delivery point and system reliability indices considering both adequacy and security for the MR-RBTS are shown in Table 3. The coefficient of variation of EENS is less than 2.5% for 4,000 simulation years. The delivery point indices are influenced by the load curtailment philosophy used and the contingency selection process employed. The main focus is on the security of the system as a whole rather than on the individual delivery points, as violations of a delivery point are considered to be a system security operating problem. The delivery point indices shown in Table 3, however, provide supplementary information to the overall system well-being indices, and are useful when selecting system reinforcements for specific areas.

Table 3 indicates that the system under this condition has an acceptable probability of the at risk state (Prob{R} = 0.00079) and an acceptable DPUI (19.97 sys.mins). The Prob{M} is, however, quite high, which indicates the potential for the system to encounter the at risk state. The Prob{H} is relatively low under this system condition. The acceptable healthy probability level for a given system is one component in its reliability criteria and can vary from one system to another. The results shown in Table 3 illustrate an example of a system that satisfies the adequacy criteria, but has considerable potential risk (high Prob{M}) for system security problems. This illustrates that security indices are adversely affected in a transmission deficient environment more than are the adequacy indices.

Table 4 shows the Prob{H} and DPUI for the R-RBTS at the peak load of 204.38 MW as presented in Table 1 and the MR-RBTS results previously illustrated in Table 3. The

**Table 3.** Overall delivery point and system reliability indices (adequacy and security) of the MR-RBTS

| Bus No. | Prob{H} | Prob{M} | Prob{R} | Freq{H} | Freq{M} | Freq{R} | DPUI | ECOST |
|---|---|---|---|---|---|---|---|---|
| 2 | 0.99975 | 0.00024 | 0.000005 | 1.69 | 1.73 | 0.02 | -- | 0.001 |
| 3 | 0.89733 | 0.10190 | 0.000768 | 158.47 | 158.13 | 1.75 | -- | 0.161 |
| 4 | 0.90336 | 0.09656 | 0.000069 | 211.21 | 211.34 | 0.19 | -- | 0.028 |
| 5 | 0.88756 | 0.11236 | 0.000080 | 196.96 | 197.08 | 0.30 | -- | 0.012 |
| 6 | 0.99535 | 0.00464 | 0.000004 | 8.98 | 8.98 | 0.01 | -- | 0.001 |
| **Sys.** | **0.86200** | **0.13721** | **0.00079** | **172.01** | **173.36** | **1.80** | **19.97** | **0.203** |

R-RBTS is in a generation deficient condition but its Prob{H} is higher than the Prob{H} of the MR-RBTS which is in a transmission deficient condition. The DPUI of the R-RBTS is, however, considerably higher than that of the MR-RBTS. This indicates that two systems with similar degrees of system security can have quite different levels of system adequacy. This situation can also occur in reverse, as two systems can have similar adequacy indices and quite different levels of security.

**Table 4.** Comparisons of the Prob{H} and DPUI for the R-RBTS at the 204.38 MW peak load and for the MR-RBTS

| System | Prob{H} | DPUI |
|---|---|---|
| R-RBTS | 0.88592 | 116.32 |
| MR-RBTS | 0.86200 | 19.97 |

### 5.2 Case Study on the Modified IEEE-RTS

The overall delivery point and system reliability indices considering both adequacy and security are shown in Table 5. The coefficient of variation of the EENS is less than 5% with 3,000 simulation years. The delivery point indices shown in Table 5 provide supplementary information to the overall system indices, and are useful in system reinforcement planning. This issue is addressed later.

The results shown in Table 5 indicate that the modified IEEE-RTS has a very high marginal state probability (Prob{M}= 0.30656). The system under this condition is not healthy even though the system adequacy indices are reasonable. System security analysis provides the opportunity to appreciate future potential risks (marginal state) in situations in which the adequacy indices of a system appear acceptable. The combined reliability framework provides an overall appreciation of both system security and adequacy under a particular condition. Freq{H} indicates that the system under this condition is expected to depart from the healthy state 335.15 times in a year. The average system residence time in the healthy state before moving to the marginal or at risk states is 18.47 hours, which is less than one day. System operators may, therefore, have to be prepared to encounter an alert condition every day.

**Table 5.** Overall delivery point and system reliability indices (adequacy and security) for the modified IEEE-RTS

| Bus No. | Prob{H} | Prob{M} | Prob{R} | Freq{H} | Freq{M} | Freq{R} | DPUI | ECOST |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.98795 | 0.01198 | 0.00007 | 65.06 | 65.60 | 0.39 | -- | 0.020 |
| 2 | 0.98890 | 0.01102 | 0.00008 | 55.73 | 53.59 | 0.35 | -- | 0.044 |
| 3 | 0.96296 | 0.03670 | 0.00034 | 76.13 | 76.30 | 0.90 | -- | 0.859 |
| 4 | 0.95635 | 0.04320 | 0.00044 | 113.12 | 113.26 | 1.07 | -- | 0.774 |
| 5 | 0.93537 | 0.06436 | 0.00027 | 171.42 | 171.23 | 0.83 | -- | 0.428 |
| 6 | 0.90084 | 0.09876 | 0.00040 | 206.12 | 206.02 | 1.14 | -- | 0.828 |
| 7 | 0.98988 | 0.01002 | 0.00010 | 56.25 | 55.85 | 0.55 | -- | 0.041 |
| 8 | 0.94524 | 0.05440 | 0.00036 | 151.16 | 150.88 | 0.99 | -- | 1.043 |
| 9 | 0.97941 | 0.02019 | 0.00040 | 58.26 | 57.63 | 0.87 | -- | 0.621 |
| 10 | 0.85015 | 0.14957 | 0.00028 | 246.61 | 246.72 | 0.81 | -- | 0.642 |
| 13 | 0.99669 | 0.00317 | 0.00014 | 15.72 | 15.86 | 0.45 | -- | 0.414 |
| 14 | 0.99640 | 0.00354 | 0.00006 | 16.69 | 16.60 | 0.19 | -- | 0.137 |
| 15 | 0.99817 | 0.00177 | 0.00006 | 10.99 | 10.68 | 0.20 | -- | 0.155 |
| 16 | 0.98895 | 0.01092 | 0.00013 | 63.20 | 60.04 | 0.49 | -- | 0.166 |
| 18 | 0.98319 | 0.01596 | 0.00085 | 92.45 | 90.08 | 2.48 | -- | 2.593 |
| 19 | 0.80146 | 0.19811 | 0.00043 | 205.77 | 205.98 | 1.43 | -- | 1.346 |
| 20 | 0.84962 | 0.15017 | 0.00021 | 153.77 | 153.85 | 1.08 | -- | 0.793 |
| **Sys.** | **0.69183** | **0.30656** | **0.00161** | **335.15** | **341.15** | **4.03** | **51.90** | **10.903** |

As shown in Table 5, the modified IEEE-RTS under the specified conditions is vulnerable to violating the N-1 security criterion. Transmission system reinforcement should therefore be considered and is illustrated in the following section. It is again important to note that generation deficiencies tend to have more significant impacts on system adequacy than on system security. In contrast, transmission deficiencies have more significant impacts on system security rather than on system adequacy. The overall system reliability can be examined by utilizing a combined framework analysis that incorporates both adequacy and security perspectives.

## 6. Transmission Reinforcement Considerations Using Combined Adequacy and Security Framework

This section illustrates the utilization of a combined adequacy and security framework in system reinforcement consideration. The modified IEEE-RTS is used for transmission reinforcement illustration. Two criteria are used in order to select effective locations for transmission reinforcements. The first criterion is based on line overload analysis of the base case (number of average overload hours in a year). This criterion can help to identify the critical transmission facilities from a system adequacy perspective. The second criterion is based on Freq{H} of all the delivery points of the base case shown in Table 5. Freq{H} is the number of times that each delivery point leaves the healthy state. This criterion can be used to identify critical locations from a security perspective. The following five possible reinforcement alternatives were selected for investigation using the two selection criteria.

*Alternative 1: A one line addition between Buses 2 and 6*

*Alternative 2: A one line addition between Buses 14 and 16*

*Alternative 3: A one line addition between Buses 2 and 6, and a one line addition between Buses 3 and 9*

*Alternative 4: A one line addition between Buses 14 and 16, and a one line addition between Buses 11 and 14*

*Alternative 5: Combining Alternatives 3 and 4 (four lines in total)*

In order to incorporate the deterministic security cost in the transmission planning process, the N-1 insecure state (marginal) is translated into a monetary form and used as a security cost factor in the decision making procedure. The expected potential insecurity cost (EPIC) is therefore proposed and expressed in (1), and is a surrogate for the preventive cost associated with system insecure conditions. The total monetary loss in the combined adequacy and security framework can therefore be expressed in (2) and designated as the expected overall reliability cost (EORC).

$$\text{Expected Potential Insecurity Cost (EPIC)} = \text{Prob}\{M\} \times \text{ECOST} \quad (1)$$

$$\text{Expected Overall Reliability Cost (EORC)} = \text{ECOST} + \text{EPIC} \quad (2)$$

The overall system reliability indices together with the proposed monetary costs for the modified IEEE-RTS with the five system reinforcement alternatives and the base case values are shown in Table 6.

The results shown in Table 6 indicate that Alternative 1 (adding a line between Bus 2 and Bus 6) effectively relieves the N-1 security problem and improves the overall system security, as Prob{H} increases from 0.69183 to 0.96491. This reinforcement option is, however, not very effective in improving the system adequacy as DPUI only reduces to 47.35 sys.mins compared to 51.90 sys.mins in the base case. Alternative 2 does not effectively improve the system security as Prob{H} only slightly increases from 0.69183 to 0.70561. This alternative, however, considerably improves the system adequacy as DPUI reduces to 38.50 sys.mins. Alternative 1 was selected based on the high value of Freq{H} which is a security based indicator and Alternative 2 was selected based on the highest average overload hour on Line # 23, which is an adequacy based indicator. As expected, Alternative 1, therefore, improves the system security while Alternative 2 improves the system adequacy.

**Table 6.** Overall system reliability indices for the modified IEEE-RTS with the five different system reinforcement alternatives.

| System Indices | Base case | Alter. 1 | Alter. 2 | Alter. 3 | Alter. 4 | Alter. 5 |
|---|---|---|---|---|---|---|
| Prob{H} | 0.69183 | 0.96491 | 0.70561 | 0.96755 | 0.70562 | 0.98036 |
| Prob{M} | 0.30656 | 0.03352 | 0.29296 | 0.03123 | 0.29304 | 0.01868 |
| Prob{R} | 0.00161 | 0.00158 | 0.00143 | 0.00122 | 0.00134 | 0.00096 |
| Freq{H} | 335.15 | 80.57 | 321.80 | 75.05 | 324.12 | 38.60 |
| Freq{M} | 341.15 | 82.29 | 327.43 | 76.40 | 329.27 | 39.28 |
| Freq{R} | 4.03 | 4.13 | 3.50 | 3.58 | 3.47 | 2.65 |
| DPUI | 51.90 | 47.35 | 38.50 | 30.48 | 30.06 | 20.74 |
| ECOST | 10.903 | 9.913 | 8.073 | 6.267 | 6.343 | 4.341 |
| EPIC | 3.342 | 0.333 | 2.365 | 0.196 | 1.859 | 0.081 |
| EORC | 14.245 | 10.246 | 10.438 | 6.463 | 8.202 | 4.422 |

Alternative 3 is intended to improve both system security and system adequacy. Line # 6 (between Buses 3 and 9) encounters an average overload of 3 hrs/yr. This alternative, which is an extension of Alternative 1, improves both the system security and the system adequacy. The Prob{H} is slightly better than that of Alternative 1 and the DPUI reduces from 47.35 sys.mins to 30.48 sys.mins. This results in an ECOST reduction of almost 3.5 M$/yr.

Alternative 4 is considered in order to further reduce DPUI from that obtained with Alternative 2, by adding one more line between Bus 11 and Bus 14. The reason for adding this line is that the addition of a second line between Bus 14 and Bus 16 will increase the power flow through this path creating an average overload on Line # 19 of 1.0 hr/yr. The line addition between Bus 11 and Bus 14 in Alternative 4 decreases the potential of an overload on this path. Table 9.10 shows that Alternative 4 results in a reduction of the DPUI from 38.50 sys.mins in Alternative 2 to 30.48 sys.mins. The Prob{H} for these two alternatives are basically the same and indicate that the line addition between Bus 11 and Bus 14 does not improve system security.

Alternative 5 is a combination of Alternatives 3 and 4, and involves a total of four additional lines. Alternative 5 should provide considerable improvement in both the system security and system adequacy. As shown in Table 6, the overall reliability indices are considerably better than those for Alternatives 3 and 4, and are a considerable improvement over those of the base case. This alternative provides the best reliability benefit of the selected transmission reinforcement schemes, but involves significant investment. Reliability cost/worth analysis should be conducted on the five transmission reinforcement options to examine the optimum option. This additional process can be achieved by minimizing the accumulated cost of the investment cost and the EORC.

## 7. Conclusions

An overall reliability analysis framework considering both adequacy and security perspectives is demonstrated in this paper using system well-being analysis and traditional adequacy assessment. Selected adequacy-based and security-based indices are used to create a combined reliability framework. Various case studies are illustrated based on different system conditions involving generation and transmission deficient situations. The results based on overall reliability analysis indicate that adequacy indices are adversely affected by generation deficient environments and security indices are adversely affected by transmission deficient environments. A system planning process using combined adequacy and security considerations offers an additional reliability-based dimension, and can assist system planners to appreciate the overall benefits of possible reinforcement options. The concept of a combined reliability framework demonstrated in this paper should prove useful in the present electric utility environment where system stress is becoming increasingly important.

## References

[1] R. Billinton and R. N. Allan, *Reliability Evaluation of Power Systems*, 2nd Edition, Plenum Press, New York, 1996.

[2] R. Billinton and W. Li, *Reliability Assessment of Electrical Power Systems Using Monte Carlo Methods*, Plenum Publishing, New York, 1994.

[3] IEEE Task Force, "Reliability Assessment of Composite Generation and Transmission Systems", *IEEE Tutorial Course 90EHO311-1-PWR*, February 1990.

[4] M. V. F. Pereira and N. J. Balu, "Composite Generation/Transmission Reliability Evaluation", *Proceedings of the IEEE*, Vol. 80, No. 4, pp. 470-490, April 1992.

[5] L. H. Fink and K. Carlsen, "Operating Under Stress and Strain", *IEEE Spectrum*, Vol. 15, No. 3, pp. 48-53, March 1978.

[6] EPRI Final Report, "*Composite-System reliability Evaluation: Phase 1 – Scoping Study*", Tech. report EPRI EL-5290, Dec 1987.

[7] R. Billinton and E. Khan, "A Security Based Approach to Composite Power System Reliability Evaluation", *IEEE Transactions on Power Systems*, Vol. 7, No. 1, pp. 65-71, February 1992.

[8] *North American Electric Reliability Council Planning Standards*. Available at: http://www.nerc.com.

[9] *Union for the Co-ordination of Transmission of Electricity (UCTE), Policy 3: Operational Security (final policy 1.3 E, 20.07.2004)*, Association of Transmission System Operators in Continental Europe. Available at: http://www.ucte.org.

[10] R. Billinton and G. Lian, "Composite Power System Health Analysis Using a Security Constrained Adequacy Evaluation Procedure", *IEEE Transactions on Power Systems*, Vol. 9, No. 2, pp. 936-941, May 1994.

[11] R. N. Allan and R. Billinton, "Probabilistic Assessment of Power Systems", *Proceedings of the IEEE*, Vol. 88, No. 2, pp. 140-162, February 2000.

[12] W. Wangdee and R. Billinton, "Bulk Electric System Well-Being Analysis Using Sequential Monte Carlo Simulation", *IEEE Transactions on Power Systems*, Vol. 21, No. 1, pp.188-193, February 2006.

[13] R. Ubeda and R. N. Allan, "Sequential Simulation Applied to Composite System Reliability Evaluation", *IEE Proceeding-C*, Vol. 139, No. 2, pp.81-86, March 1992.

[14] A. Sankarakrishnan and R. Billinton, "Sequential Monte Carlo simulation for composite power system reliability analysis with time varying loads", *IEEE Transactions on Power Systems*, Vol. 10, No. 3, pp. 1540-1545, August 1995.

[15] R. Billinton and W. Wangdee, "Delivery Point Reliability Indices of a Bulk Electric System Using Sequential Monte Carlo Simulation", *IEEE Transactions on Power Delivery*, Vol. 21, No. 1, pp.345-352, January 2006.

[16] B. Stott and O. Alsac, "Fast Decoupled load flow", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-93, No. 3, pp. 859-869, May/June 1974.

[17] A. J. Wood and B. F. Wollenberg, *Power System Generation, operation and control*, 2nd Edition, Wiley, New York, 1996.

[18] W. Wangdee, *Bulk Electric System Reliability Simulation and Application*, Ph.D. Thesis, University of Saskatchewan, 2005. Available at: http://library.usask.ca/theses/available/etd-12152005-133551.

[19] R. Billinton and et al, "A Reliability Test System for Educational Purposes- Basic Data", *IEEE Transactions on Power Systems*, Vol. PWRS-3, No. 4, pp. 1238-1244, August 1989.

[20] IEEE Task Force, "IEEE Reliability Test System", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, pp. 2047-2054, Nov/Dec 1979.

**Roy Billinton**

He obtained the B.Sc. and M.Sc. degrees from University of Manitoba, and the Ph.D. and D.Sc. degrees in electrical engineering from the University of Saskatchewan, Saskatoon, SK, Canada. He was with the System Planning and Production Divisions of Manitoba Hydro. He joined the University of Saskatchewan in 1964. He is the author and coauthor of eight books on reliability evaluation and over 850 papers on power system reliability evaluation, economic system operation and power system analysis.

Dr. Billinton is a Fellow of the CAE and the Royal Society of Canada and a Registered Professional Engineer in the Province of Saskatchewan, Canada.

**Wijarn Wangdee**

He obtained the B.Eng. degree in electrical engineering from Chulalongkorn University, Bangkok, Thailand, in 1999. He obtained the M.Sc. and Ph.D. degrees in electrical engineering from the University of Saskatchewan, Canada in 2002 and 2005 respectively.

He is currently with the System Planning and Performance Assessment Department of the British Columbia Transmission Corporation (BCTC), Vancouver, British Columbia, Canada.