Sensitivity Study of Well-Being Based Reliability Worth for Different Customer Outage Cost Functions in Subtransmission Systems

R. GUPTA, L. GOEL* and M. F. ERCAN

School of Electrical & Electronic Engineering
Singapore Polytechnic
500 Dover Road
SINGAPORE
http://www.sp.edu.sg

*School of Electrical & Electronic Engineering
Nanyang Technological University
50 Nanyang Avenue
SINGAPORE
http://www.ntu.edu.sg

Abstract: - The evaluation of the costs and benefits of competing investments has now become a standard practice in power system planning. Customer interruption costs, which serve as surrogates for the perceived worth of supply reliability, have been determined for several jurisdictions, areas, provinces and countries as diverse as Canada, United Kingdom, Nepal and Thailand, among others. This paper uses the well-being framework to include the societal worth of electric service reliability in subtransmission systems associated with the above four outage cost functions. System well-being is defined in terms of the system being in the healthy, marginal, and at risk states, thus combining the deterministic and probabilistic approaches into a single framework. The main objective of the paper is to present results of reliability worth indices such as expected cost of interruptions (ECOST) and interrupted energy assessment rate (IEAR), for the healthy and at risk states in terms of the well-being framework. The concepts are illustrated by application to a small reliability test system designated RBTS.

Key-Words: - Customer interruption cost, Interrupted energy assessment rate, Healthy, Risk, Reliability

1 Introduction

The fundamental function of an electric energy system is to provide electricity as economically as possible, and with a reasonable assurance of quality and reliability. The major difficulty faced by power system managers and planners is in justifying new facilities and equipment (and the associated investment cost) to improve service reliability vis-a-vis the benefits accruing to the society due to these facilities. Power system planners strive to determine the optimum balance between investment costs and system reliability to meet the ever-increasing customer load requirements. The basic question "what is an acceptable level of service reliability?” is difficult to address as what constitutes an "acceptable" level could vary from one utility to another. This issue can best be examined in terms of the costs and the worth (benefits). This form of evaluation is sometimes also designated as value-based reliability (VBR) evaluation [1-7].

The economic evaluation of reliability requires the determination of "benefit (worth)" from the customers' perspective, and its explicit incorporation into the planning process. A number of general approaches have been used to assess reliability worth, most of which are based on indirect methods of customer outage costs. Many such surveys have been undertaken by various research groups. The Power Systems Research Group at the University of Saskatchewan has been instrumental in conducting many such surveys since 1980. This paper utilizes the research findings of this group [8] for four countries, namely Canada, United Kingdom, Nepal and Thailand, in a reliability worth evaluation of subtransmission systems with well-being considerations.

The main objective of this paper is to include the customer interruption costs of the above four countries in a reliability well-being assessment of subtransmission systems, and to compare the results in the form of reliability worth indices of expected cost of interruptions (ECOST) and interrupted energy assessment rates (IEAR). This assessment is expected to assist planners in further understanding the application of reliability cost vis-à-vis reliability worth.

2 Customer Damage Functions of the Study Systems

The traditional interruption cost model is known as a composite customer damage function (CCDF), which defines the overall average costs of interruptions as a function of the interruption duration in a given service area that was used in the surveys. These data can be used to create customer damage functions (CDFs) for specific customer classes (sectors). Data collected from the University of Saskatchewan surveys [10] are shown in Table 1 for three customer classes (residential, small industrial, and commercial) for Canada - these data were normalized with respect to the sector peak load (using a 1991C$ base). Sector interruption cost data for United Kingdom, Nepal and Thailand are shown in Tables 2, 3 and 4 respectively. The interruption cost data shown in Table 3 are demand normalized (Thai Baht / kW) using the average loads, whereas the outage data presented in Tables 1, 2 and 4 are demand normalized using the peak loads. In addition, Table 3 data have assumed that category SGS (small general sevice) and MGS (medium general sevice) [9] are replaced by commercial and small industrial (Sm. Ind.) users respectively for the RBTS [9, 10] bus-4 subtransmission system – the reliability test system used to describe all studies reported in this paper.

Table 1 CCDF (in 1991 C$/kW) for the RBTS Bus 4 Supply Points (Canada)

Duration	SP1	SP2	SP3
2 sec	0.3447	0.4188	0.4617
1 min	1.0197	1.147	1.1756
20 min	1.927	1.993	1.862
1 hr	4.65	4.65	4.1735
2 hr	8.88	8.706	7.57
4 hr	20.903	19.998	16.997
8 hr	36.08	35.112	30.662
24 hr	55.972	55.685	51.3675

Table 2 CCDF (in 1992 British Pounds/kW) for the RBTS Bus 4 Supply Points (UK)

Duration	SP1	SP2	SP3
Less than 1 min	2.215	2.753	3.095
1 min	2.327	2.893	3.255
20 min	5.467	10.193	7.341
1 hr	10.402	12.316	13.326
4 hr	32.205	37.217	39.577
8 hr	52.596	60.714	63.85
24 hr	66.09	76.194	80.03

Table 3 CCDF (in 1995 Thai Baht/kW) for the RBTS Bus 4 Supply Points (Thailand)

Duration	SP1	SP2	SP3
1 min	10.486	11.546	11.6281
5 min	12.761	13.796	13.645
10 min	19.4306	19.645	18.859
30 min	57.2385	58.709	56.746
1 hr	84.576	84.231	78.623
2 hr	160.327	154.822	143.702
4 hr	336.671	316.707	294.233

Table 4 CCDF (in 1996 Nepal Rupees/kW) for the RBTS Bus 4 Supply Points (Nepal)

Duration	SP1	SP2	SP3
1 min	7.747	6.707	4.768
20 min	25.103	20.882	13.843
1 hr	55.52	45.739	30.178
2 hr	116.556	92.123	53.475
4 hr	221.192	181.318	119.425
8 hr	341.028	287.163	202.209
24 hr	657.215	609.075	520.443

The RBTS subtransmission system at bus 4, shown in Figure 1, consists of three 11kV supply points (SP) connected through a 33kV subtransmission network and station equipment. The CCDF for the customer mix of the RBTS for the above four systems are presented in Tables 1 through 4 respectively.

3 Evaluation of Reliability Worth Indices

In order to predict future interruption costs using collected data, it is necessary to estimate the system reliability indices [1-7] in a suitable form. The unserved energy, or expected energy not supplied (EENS), provides the severity associated with capacity deficiencies in terms of the energy not supplied when demand exceeds the available capacity.

A reliability worth factor (index) designated interrupted energy assessment rate (IEAR) has been developed using the reliability index EENS and the outage cost data [4-6]. The IEAR, obtained in $/kWh (or any other local currency per kWh) of unsupplied energy, can be used in a managerial assessment of reliability worth, and in any consideration of assigning customer tariffs for different reliability levels. The basic formulation of IEAR at any system level is as follows:

$$EENS = \sum_{i=1}^{N} m_i f_i d_i \quad (kWh\ /\ period) \tag{1}$$

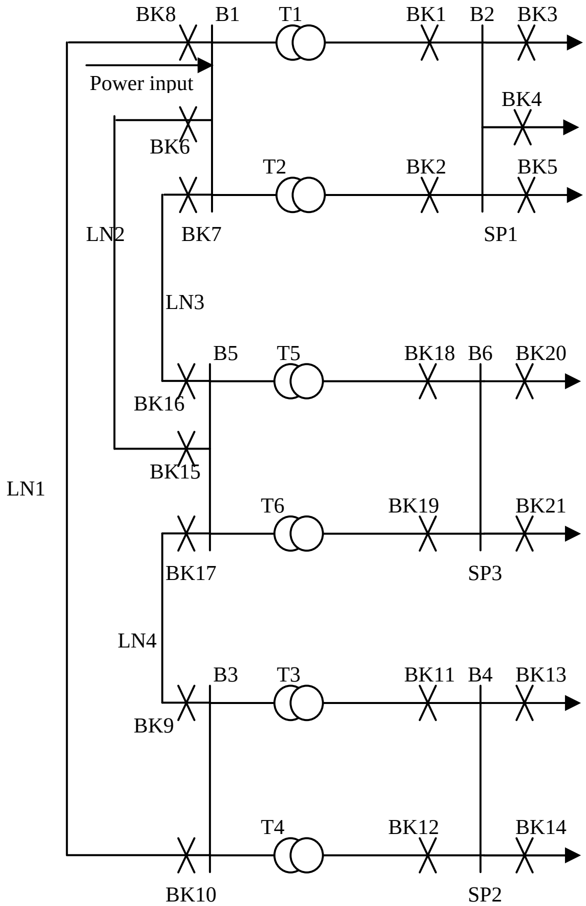


Fig. 1. SLD of the RBTS-Bus4 Subtransmission System

$$ECOST = \sum_{i=1}^{N} c_i(d_i)\, f_i m_i \quad (\$/\ period) \qquad (2)$$

$$IEAR = \frac{ECOST}{EENS} \quad (\$/\ kWh\ ) \qquad (3)$$

where:
m_i = load curtailed (kW) due to capacity shortfall
f_i = frequency of outage event i
d_i = duration of outage event i
$c_i(d_i)$ = cost in \$/kW of outage duration d_i using the cost function SCDF or CCDF
EENS = expected unserved energy due to all possible load curtailment events
ECOST = expected interruption costs due to all possible load curtailment outage events, and
N = the total number of load loss events.

4 Well-Being Indices

The criteria and techniques first used in practical applications were based on deterministic (rule-of-thumb) methods. A typical deterministic criterion used for planning of sub-transmission systems is to construct a minimum number of circuits to a load group, the minimum number being dependent on the maximum demand of the group. Although these and other similar criteria have been developed in order to account for randomly occurring failures, they are inherently deterministic. Their essential weakness is that they do not and cannot account for the probabilistic or stochastic nature of system behavior, of customer demands or of component failures. These factors can only be considered through probabilistic criteria.

The most commonly-used load point reliability indices that are used in sub-transmission systems are the load point failure rate, the load point unavailability, and the load point outage duration. The gap between deterministic and probabilistic methods can be bridged by using a well-being framework in which the deterministic techniques are embedded in the conventional probabilistic indices. The well-being framework is designated as healthy, marginal and at risk [11-12]. The well-being of the system is quantified in terms of system health and margin states which incorporate the pre-determined deterministic criterion / criteria, in addition to a system risk index that provides the system inadequacy. The system operates in the healthy state when it meets a pre-defined deterministic criterion such as the presence/outage of a transmission line or the presence/outage of a transformer. In the marginal state, the system is not in any difficulty but does not have sufficient “margin” to meet the specified deterministic criterion. The probability of risk (annual unavailability/8760.0), is the probability of finding the system in the at risk state. It can be seen from the state definition that the system well-being indices can be used to assess a system from a deterministic point of view in addition to recognizing its stochastic behavior. The main emphasis in this paper is on conducting comparative studies on the four diverse systems and to discuss the findings.

5 Selected Studies Using the RBTS

The RBTS Bus-4 as shown in Figure 1 is utilized to illustrate the concepts of system well-being in this paper. Probabilistic as well as deterministic (well-being) indices were determined for all these three supply points, and the following sections describe in detail the study results.

The conventional risk index used in this paper is the average annual unavailability (in terms of the probability of failure of the supply point). Annual unavailability of a particular load/supply point is the expected time in a year that the load/supply point will be on outage. First and second order overlapping permanent outages and active failures that lead to supply point failure were considered in the studies. The probability at risk for SP2 was determined as 1.1309E-05. The probability of the healthy state was determined using a contingency enumeration approach. The probability of the marginal state is the complementary value of the summation of the healthy and risk states' probabilities. As previously noted, the system should be able to tolerate the outage of any single component contingency (deterministic criterion, DC) in the healthy state. Two deterministic criteria were considered for the reliability worth and well-being studies described in this paper:

- Transmission line as DC, or
- Transformer as DC

The reliability worth indices of ECOST and IEAR using the well-being framework were evaluated using equations (2) and (3) respectively, and selected study results are presented herein.

Figures 2 and 3 show the variation in the ECOST and IEAR indices respectively for the four interruption cost scenarios (Canada, Nepal, Thailand and UK) for all three RBTS Bus 4 supply points under three distinct conditions: base case (BC), deterministic criterion of transformer (TR), and deterministic criterion of transmission line (TL). Figure 4 shows the IEAR for the four countries on separate bar charts, to make the comparison more meaningful. The costs shown in these figures were normalized in terms of US dollars so as to give the evaluation a common reference. The conversion rates used for the four currencies were as follows:

1 US$ = 1.3138 C$
1 US$ = 75.421 Nepal Rupee
1 US$ = 39.22 Thai Bhat
1 US$ = 0.5465 UK Pound

The expected interruption costs due to all possible load curtailment outage events, ECOST, for all the three supply points of the RBTS Bus 4 are the highest using the UK data, followed by Canada, Thailand and Nepal in a descending order, as illustrated in Figure 2. This is due to the fact that, in general, the overall average cost of interruption as a fuction of the interruption duration or CCDF for UK is highest as compared to the other three countries. It can also be observed from Figure 2 that for all four countries SP2(TL) and SP2(TR) ECOST values are significantly higher in comparison to corresponding values for other supply points / conditions. The ECOST values are as follows: for UK, SP2(TL) = US$391,832, SP2(TR) = US$376,747; for Canada, SP2(TL) = US$93,351, SP2(TR) = US$89,278; for Thailand, SP2(TL) = US$28,937, SP2(TR) = US$27,812; and for Nepal, SP2(TL) = US$13,482, SP2(TR) = US$12,800. The higher ECOST values for SP2(TL) and SP2(TR) for all countries can be attributed to the high unavailabilities resulting from contingencies considering the well-being framework.

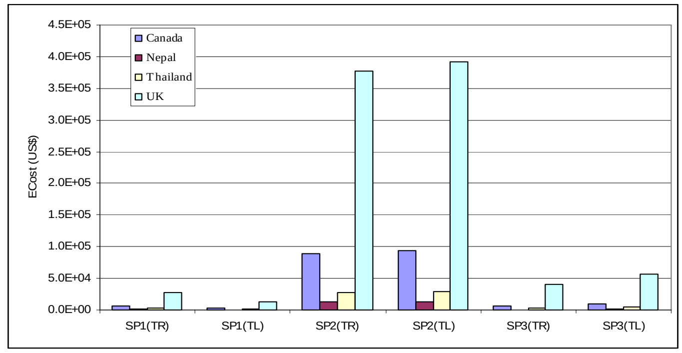


Fig. 2 ECOST variation for the 4 countries at the Bus 4 supply points

Figure 3 shows that, in general the IEAR values for UK are significantly greater than those for other countries. The EENS values for SP1, SP2 and SP3 are fixed, regardless of the country used. In other words, the EENS for SP1 (for instance) will have a single value corresponding to a fixed DC (or the Base Case), and this value will be the same for all four countries as it is independent of the interruption cost data and it depends only on the network configuration.

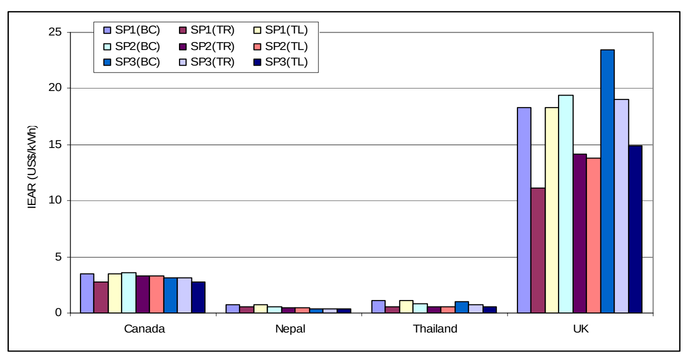
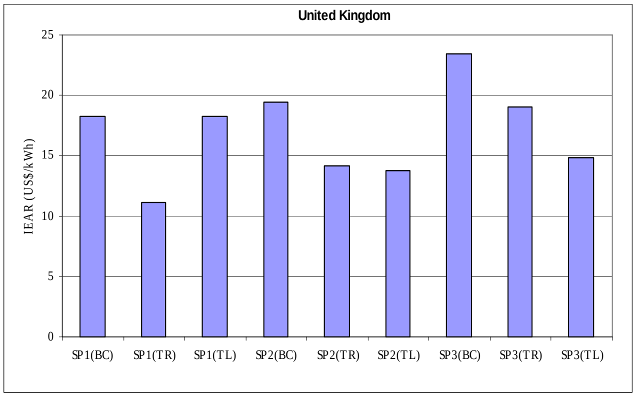
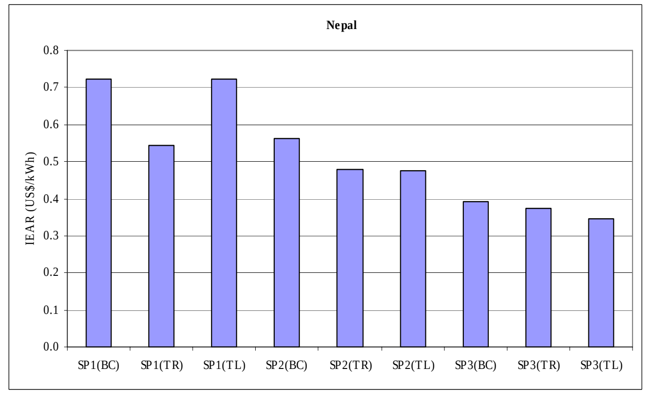


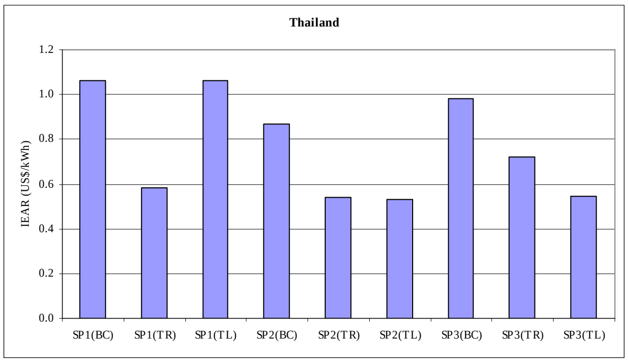
Fig. 3 IEAR variation for the 4 countries for two supply points of the RBTS



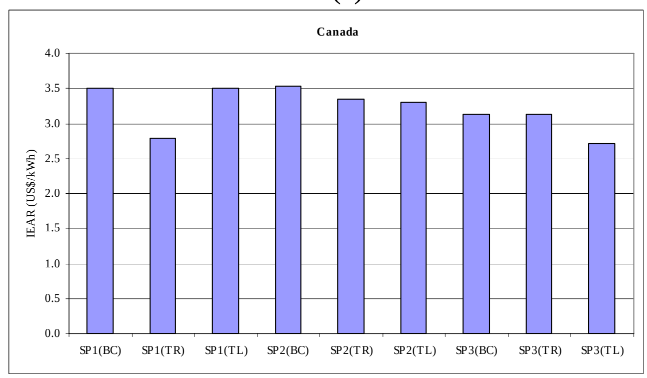
(a)



(c)



(b)



(d)

Fig. 4 IEAR for the three supply points for (a) United Kingdom, (b) Thailand, (c) Nepal, and (d) Canada.

This means that the IEAR values are simply driven by the ECOST values, and since the UK data provide the highest ECOST values, the IEAR for the UK data will be the highest. For example, as depicted in Figure 4(a), the IEAR value for UK is highest (US$ 23.42/kWh) in the case of SP3(BC). Similary, Figures 4 (b) and (c) show that the highest IEAR values for Thailand and Nepal are obtained for the cases of SP1(BC) (US$1.06/kWh and US$0.72/kWh respectively) and SP1(TL) (US$1.06/kWh and US$0.72/kWh respectively). The highest value of IEAR for Canada is obtained for SP2(BC) (US$3.54/kWh).

6 Conclusions

Reliability worth factors such as interrupted energy assessment rates (IEAR) can be used in an overall assessment of the monetary worth of system reinforcements. This paper presents a comparative study of reliability worth indices including well-being considerations in electric subtransmission systems. The reliability worth indices evaluated are expected interruption costs (ECOST) and IEAR. Interruption cost data collected by the University of Saskatchewan from customer surveys for four countries – Canada, Thailand, Nepal, and United Kingdom – are utilized for the comparative study of reliability worth indices. The IEAR were obtained for a small reliability test system, and a comparison of the worth indices indicates that for all the three supply points of the test system, the United Kingdom has significantly higher reliability worth indices as compared to the other three countries. Customer surveys indicate the interruption costs as a function of duration, but this paper has converted those estimates into more meaningful indices of ECOST and IEAR that can be used directly in system planning and reinforcement.

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