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Economic costs of power interruptions: a consistent model and methodology

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Abstract

One of the most basic requirements in cost/benefit assessments of generation and transmission systems are the costs incurred by customers due to power interruptions. This paper provides a consistent set of cost of interruption data that can be used to assess the reliability worth of a power system. In addition to this basic data, methodologies for calculating the customer damage functions and the interrupted energy assessment rates for individual load points in the system and for the entire service area are also presented. The proposed model and methodology are illustrated by application to the IEEE-reliability test system (IEEE-RTS) [A Report Prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee, IEEE Reliability Test System, IEEE Trans. on PAS, Vol. PAS-98, No.6, pp. 2047-2054, November/December 1979. [1]].

Keywords: Power system economics; Reliability of power systems; Customer outage data

1. Introduction

Quantitative reliability evaluation is an important aspect of power system planning and operation. The indices produced in these applications are utilized in a wide range of management decisions throughout a utility. These techniques have also been used in reliability cost/reliability worth (sometimes referred to as the cost/benefit approach) assessments of electric power systems [2–4] and marginal outage costing [5].

Assessing the worth of reliability is a very difficult task to conduct directly. The difficulty comes from the fact that there are many intangibles involved in the process, which are not always amenable to monetary quantification. A number of approaches have been applied over the past few decades to quantify reliability worth. Most of these methods are based on the assessment of the effects and impacts of unreliability [6]. It is believed that quantifying the costs and losses incurred by electric customers as a result of power deficiencies is an easier task than attempting to directly assess reliability worth. The unreliability costs or the costs of interruption are not identical to the worth of reliability but are considered to be reasonably representative measures.

In order to generate a practical tool for reliability worth assessment, customer interruption costs must be related to the calculated indices utilized in system planning and operation. Factors that relate the customer losses caused by electric power interruptions to the worth of electric service reliability have been developed for generating systems [7] and composite generation and transmission systems [8]. Such factors are referred to as interrupted energy assessment rates (IEAR's).

This paper provides a consistent set of cost interruption data for the IEEE-RTS. The utilization of these data in calculating the interrupted energy assessment rate for an entire service area (HLI analysis) and at individual load points (HLII analysis) of a power system is illustrated.

2. Customer interruption cost data

The problem of estimating the economic costs incurred by customers due to power outages have been discussed extensively in the literature [9–17]. Refs. [18,19] provide a comprehensive background on the evolution of the

Abbreviations CCDF, composite customer damage function; CDF, customer damage function; COMREL, composite system reliability evaluation software; ECOST, expected cost of all system load curtailment events; EUE, expected unserved energy; F and D, frequency and duration; HLI, hierarchical level I; HLII, hierarchical level II; IEAR, interrupted energy assessment rate; IEEE-RTS, IEEE reliability test system; L.F., load factor; SCDF, sector customer damage function.

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Table 1
Sector interruption cost estimates (CDF's) expressed as $/kW of annual peak demand

User sector	Interruption duration				
	1 min	20 min	1 h	4 h	8 h
Large users	1.005	1.508	2.225	3.968	8.240
Industrial	1.625	3.868	9.085	25.163	55.808
Commercial	0.381	2.969	8.552	31.317	83.008
Agricultural	0.060	0.343	0.649	2.064	4.120
Residential	0.001	0.093	0.482	4.914	15.690
Govt. and inst.	0.044	0.369	1.492	6.558	26.040
Off and bldg.	4.778	9.878	21.065	68.830	119.160

methodologies used to estimate these costs. One of the most commonly used methods to gather this data is to survey electrical customers, sector by sector, to determine the costs or losses resulting from power interruptions. For the last decade, postal surveys of electric customers have been conducted [14,15,17].

The interruption cost estimates obtained from the survey respondents vary widely for different customers and with different interruption related characteristics, such as interruption duration, frequency, time of occurrence, etc. The interruption duration is usually considered to be the primary variable. The outage cost for a given type of customer, as a function of interruption duration, is referred to as a customer damage function (CDF). The CDF for a specific economic sector is designated as a sector customer damage function (SCDF). The SCDF's for the IEEE-RTS are given in Table 1. These costs are the raw data from which various cost models for the entire service area and for the individual load points of the IEEE-RTS can be developed.

The cost of interruption at a single customer load point is dependent entirely on the cost characteristics of that customer. As the supply point in question moves away from the actual customer load point, the consequences of an outage of the supply point involve an increasing number of customers. As the supply point becomes the generating system, potentially all system customers are involved. The customer cost associated with a particular outage at a specific point in the system involves an amalgamation of the costs associated with the customers affected by the interruptions at that point in the system. This amalgamation or consolidation of costs is known as a composite customer damage function (CCDF). The following sections in this paper illustrate the development of the CCDF and the IEAR for the generating system (HLI analysis) and the composite generation and transmission system (HLII analysis) of the IEEE-RTS.

3. HLI analysis

Conceptually, the CCDF for a particular service area is an estimate of the costs associated with power supply interruptions as a function of the interruption duration for the customer mix in the service area. Each customer or type of customer has a different cost for particular outage duration and the method for combining the individual costs is to perform a weighted average according to the annual peak demand or energy consumption of the individual customers or customer group. Weighting by annual peak demand is used for short duration interruptions and weighting by the energy consumption is used for interruptions longer than one-half hour [14]. The load composition of the IEEE-RTS service area is given in Table 2.

Table 2
Load composition of the IEEE-RTS service area, based on annual peak demand and annual energy consumption

User sector	Sector peak (%)	Sector energy (%)
Large users	30.0	31.0
Industrial	14.0	19.0
Commercial	10.0	9.0
Agricultural	4.0	2.5
Residential	34.0	31.0
Govt. and inst.	6.0	5.5
Off and bldg	2.0	2.0
Total	100.0	100.0

In order to calculate the CCDF, the user sector costs given in Table 1 are weighted in accordance with the load composition of the service area given in Table 2. The weighted costs are then summed for each duration and the results are presented in Table 3. Despite the uncertainties affecting the development of a CCDF, it is the most suitable function available for determining monetary estimates of reliability worth. The CCDF can be tailored to reflect the individual nature of the system, a region within it and in the limit, any particular customer.

The detailed description of the concepts involved in calculating an IEAR at HLI using a basic frequency and duration (F and D) approach or Monte Carlo simulation is presented in [7] and a brief description of the F and D approach is given here to illustrate the salient features. The estimation of the IEAR at HLI involves the generation of a capacity margin model [20] which indicates the severity, frequency and duration of the expected negative margin states. This model can be used in conjunction with the CCDF for the service area to estimate the IEAR. The generation model is developed from the capacities, forced outage rates, failure rates and repair rates of the generating units. An exact-state load model is used which represents the actual daily system load cycle by a sequence of discrete load levels [20]. The expected unserved energy (EUE) for the estimated loss of load events within the period of study is given by:

$$\mathrm{EUE} = \sum_{i=1}^{N} m_i f_i d_i \quad (\mathrm{kWh/day}), \tag{1}$$

where

Table 3
Composite customer damage function for the IEEE-RTS service area

Service area of system	Interruption duration				
	1 (min)	20 (min)	1 (h)	4 (h)	8 (h)
Interruption cost ($/kW)	0.67	1.56	3.85	12.14	29.41