CUSTOMER OUTAGE COST EVALUATION IN ELECTRIC POWER SYSTEMS

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ABSTRACT

In order to relate investment costs to the resulting levels of supply reliability, it is required to quantify supply reliability in a monetary basis which can be achieved by calculating the expected interruption costs (EIC). Customer interruption costs (CIC) are used as substitute in the assessment of reliability worth in electric power systems. In order to determine an optimal and reliable level of customer service, reliability cost/worth is to be assessed by calculating the costs associated with different system configurations and assessing the corresponding reliability worth at the respective system load points. This paper presents the utilization of a practical radial distribution system of APCPDCL /APTRANSCO database in the development of individual sector and customer damage functions. Customer interruption costs due to failure in electrical energy supply depend on many factors. A composite customer damage function is created for combinations of all customer classes. The main objective of the paper is to assess reliability cost /worth indices of expected energy not supplied (EENS), expected cost of interruptions (ECOST) and interrupted energy assessment rate (IEAR) of a typical radial practical distribution system using a generalized analytical technique. The effects on customer interruption cost indices associated with alternate supply, protection devices, different switch fuse, and breaker are included in the analysis and also compared with the results of reinforcement of system by disconnect switch additions. The results presented in this paper will be useful for the electric power utilities, designers and planners in the decision-making stage.

Keywords: electric power systems, cost analysis, expected interruption cost, customer outage cost, reliability, energy assessment rate.

1. INTRODUCTION

The most important function of a recent electric power system is to provide electric power to its customers at the lowest possible cost with acceptable reliability levels. The two aspects of economics and reliability often conflict and present power system managers, planners, designers and operators face with a wide range of challenging problems. The price that a customer is willing to pay for higher reliability is directly connected to the interruption costs created by power failures. Some customers may be willing to pay more to receive higher reliability and others may be willing to pay less for lower reliability. Utilities may also be willing to provide higher reliability of power supply at no increased customer cost because of competition. Decision-making depends on many aspects such as social, economic, environmental and government considerations etc. and is a difficult task. System customer interruption cost analysis provides the opportunity to incorporate cost analysis and quantitative reliability assessment into a common structured framework, which can assist the decision making process. The highest level of efficiency can only be reached by comparing the increase of performance with the required investment costs. The assessment of expected performance indicators in respect to supply reliability is the task of the reliability assessment. This task can be divided into the calculation of non-monetary interruption indices and the calculation of reliability cost/worth indices. The calculation of non-monetary interruption statistics is more established [1-6]. One possible way to accommodate for customer importance is to use the costs for the energy not supplied (money/kWh) and/or a cost per interrupted power (money/kW) as an adjustable measure for interruption severity. This can produce useful indices, but it is often insufficient for more detailed planning or selection of alternatives. This linearization of the costs with the duration of the interruption does not consider the fast increase with duration that occurs for individuals as well as for aggregated loads [7]. An acceptable method of assessing the worth of power system reliability is to evaluate the customer losses due to service interruptions, i.e. the cost of unreliability [8]. The basic concept associated with power system reliability cost/worth evaluation is shown in Figure-1. The total public cost, which is ultimately borne by the customers, is the sum of the two curves. The optimum level of reliability occurs at the point R_{opt}, i.e. at the point of lowest total cost. Thus CIC can be used as an estimate of the worth of reliable electric service. The customer survey approach, [7] in which customers are specifically contacted, is the most practical and reliable process to obtain these costs.

Customer interruption costs are a function of both interruption and user characteristics. The costs incurred due to power supply interruptions can be presented as a function of outage duration, and when expressed in this form is known as a customer damage function (CDF).The CDF can be determined for a group of Customers belonging to particular standardized industrial classifications (S1C). In these cases, the interruption cost vs. duration plots are referred to as an individual customer damage functions (ICDF).

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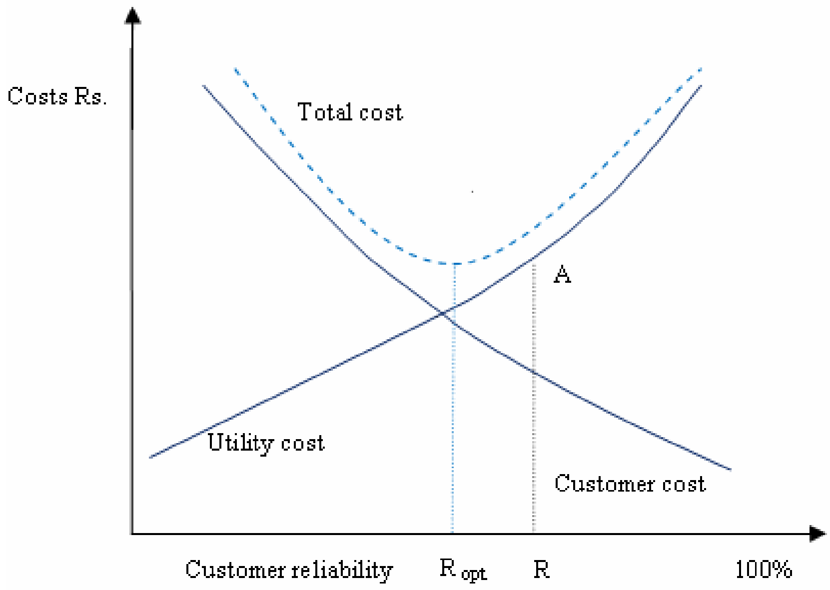

Figure-1. The basic concept associated with power system reliability cost/worth evaluation.

2. INTERRUPTION DAMAGE FUNCTIONS (IDF)

The consequences of an interruption are quantified by a so-called "interruption damage function" (IDF), which gives the consequences in monetary units as a function of the characteristics of the interruption. The interruption damage functions for a single point interruption and for multipoint interruptions. The single point load will be interrupted as soon as the supply to the bus bar to which it is connected is interrupted. A multi-point damage model describes the interruption damage for an area or a large industrial process which are supplied by more than one bus. The multi-point model has an additional trigger condition which defines the combinations of bus bars that must be interrupted in order for the damage function to apply. In [10], the impacts of interruptions are classified as direct vs. indirect and economic vs. otherwise (social). Short interruptions in a small residential area will normally only cause direct damage, such as food spoilage or inconvenient building temperatures. More wide-spread interruptions with a longer duration will also cause indirect damage such as civil disobedience, breakdown of logistic chains, etc. Interruption damage functions are often abstract estimations of the actual interruption damage. Actual interruption damage may depend on the type of interrupted customers, duration of the interruption and the situation in which the interruption occurs: day of week, time of day, and customer's activities at the moment of interruption, etc. All the ICDF of a given sector (i.e. commercial, industrial, residential etc.) can be combined into a representative cost function for that sector designated as a sector customer damage function (SCDF). The costs can be calculated in various ways, but demand normalize (Rs/kW) values calculated on an aggregated basis are common indices [7]. The survey has been conducted in APCPDCL/APTRANSCO; for a typical radial feeder that created a practical data base, which is utilized to demonstrate the development of ICDF, SCDF, and CCDF. SCDF are developed by weighting the ICDFs using the energy utilized by each customer group. A similar procedure is used to create a CCDF.

3. SECTOR CUSTOMER DAMAGE FUNCTION (SCDF)

The "raw" data from the customer surveys has to be processed and transformed in order to create customer damage functions (CDF) which can also be projected upon customers which have not been surveyed. The first step in the data transformation is performed by grouping all raw damage functions according to some customer classification, for instance the SIC (Standard Industrial Classification). Typical customer classes, or sectors, are "residential", "industrial", "commercial", "government", etc. Creating Sector Customer Damage Functions, when the affected service area contains more than one type of customer; the cost functions for the different customers must be combined to obtain a representative CDF for that service area. This is done on the basis of respective utilization by the constituent groups. A similar approach can be used to create a sector customer damage function (SCDF) which can be used to represent the entire sector. Only the commercial, industrial, Govt. and Institutions, Office and buildings and residential sectors are considered in this paper. In order to exhibit the sensitivity of the SCDF to changes in energy utilization, the share for a specific SIC was increased by an additional share which has the effect of decreasing the energy utilization of all other SIC'S within that sector. The resulting SCDF is a weighted average of the applicable SIC group damage functions. The weighted sector damage function is obtained by summing the products of the SIC weighting factors and their respective cost values for each interruption durations. This was done for each SIC in the high, medium and low interruption cost ranges. The

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ICDFs were combined to form a resultant SCDF using an equal weighting factor for all constituent SIC groups (ICDF's). Not surprisingly the higher cost ICDF's have a much more profound effect on the resultant SCDF than do the lower cost ICDF.

4. COMPOSITE CUSTOMER DAMAGE FUNCTION (CCDF)

The SCDF is not used in the actual reliability assessment itself. It is only used to create damage functions for single customers or for mixes of customers. The normalization process leads to SCDFs which have units like Rs. /kWh or Rs. /kW. In some cases these units have been misinterpreted as costs per energy not supplied or per interrupted power. If we need to create damage functions for a mix of customers, then we have to create a composite customer damage function (CCDF). The CCDF is basically the sum of the individual customer damage functions in the customer mix. The SCDF of the residential, commercial and industrial sectors etc. can be combined to create a composite customer damage function (CCDF) for a large region using a similar procedure to that noted above. In this case, the SCDF can he combined using the sector customer mix information in the region. The customer composition at a particular load point may only contain a few different customer types [10] and therefore the CCDF should be based, if possible, on the actual ICDF for that composition.

5. ASSESSMENT OF RELIABILITY COST /WORTH INDICES

A distribution system is the segment of an overall power system which links the bulk system to the individual customers. The basic distribution system reliability indices are the three load point indices of average failure rate (λ), the average outage duration (r) and the annual outage duration (U). These three basic indices are important individual load point parameters. The system indices of SAIFI, SAIDI, CAIDI, ASAI and ASUI along with three basic load point indices are assessed for a typical radial distribution system in APCPDCL/APTRANSCO [4]. The reliability cost/worth indices of expected energy not supply (EENS), expected interruption cost (ECOST) and interrupted energy assessment rate (IEAR) can also be calculated using the three basic load point indices and customer interruption costs. The equations used to calculate these indices are described in a generalized Analytical Approach. In order to predict future interruption costs using collected data, it is necessary to estimate the system reliability indices [4] in a suitable form. The outage 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. The IEAR, obtained in Rs. /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.

5.1 A generalized analytical approach

The generalized analytical method to assess the interruption or outage cost indices is described in the following steps.

i) Find the average failure rate λ_y, the average outage duration $\mathbf{r}_y$ and the average annual outage duration $\mathbf{U}_y$ for each failed element y contributing to its outage for load point p connected to the chosen typical distribution network.

ii) Find the affected Load Points (LPs) using a direct search technique accord to the network configuration. The failure rate λ_{xy}, failure duration $\mathbf{r}_{xy}$ for an affected load point x can be calculated using Eq. (1) and Eq. (2).

$$\lambda_{xy} = \lambda_y \prod_{k=1}^{N_{pr}} (1 - p_k) \qquad \text{Eq…1}$$

Where p_k the probability that fuse (or breaker) k is operates successfully. N_{pr} is the total number of breakers and fuses between the load point x and the failed element y .

$$\mathbf{r}_{xy} = p_a u_y + (1 - p_a) r_y \qquad \text{Eq…2}$$

Where p_a is the probability of being able to transfer load for a LP that can be isolated from the failed element. p_a is zero for the LPs that can be isolated by disconnect switches from the failed element y .

iii) Using the outage time $\mathbf{r}_{xy}$ and the customer type at load point x determine the per unit (kW) interruption cost $\mathbf{c}_{xy}$ using the corresponding sector customer damage function (SCDF).

$$\mathbf{c}_{xy} = f(\mathbf{r}_{xy}) \qquad \text{Eq…3}$$

Where $f(\mathbf{r}_{xy})$ is the SCDF

iv) Evaluate the expected energy not supply $EENS_{xy}$ expected interruption cost $ECOST_{xy}$, of the load point x caused by failures of element y .

$$EENS_{xy} = \lambda_{xy} \mathbf{L}_x \mathbf{r}_{xy} \qquad \text{Eq…4}$$

$$ECOST_{xy} = \mathbf{c}_{xy} \lambda_{xy} \mathbf{L}_x \qquad \text{Eq…5}$$

Where $\mathbf{L}_x$ is the average load of load point x .

v) Repeat i-iv for all elements in order to assess load point $EENS_x$,$ECOST_x$ and $IEAR_x$, for load point x , using the following equations:

$$EENS_x = \sum_{y=1}^{N_e} \mathbf{L}_x \lambda_{xy} \mathbf{r}_{xy} = \mathbf{L}_x \sum_{y=1}^{N_e} \lambda_{xy} \mathbf{r}_{xy} \qquad \text{Eq…6}$$

$$ECOST_x = \sum_{y=1}^{N_e} \mathbf{c}_{xy} \mathbf{L}_x \lambda_{xy} = \mathbf{L}_x \sum_{y=1}^{N_e} \mathbf{c}_{xy} \lambda_{xy} \qquad \text{Eq…7}$$

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$$IEAR_x = (ECOST_x / EENS_x) = \left(\sum_{y=1}^{N_e} c_{xy}\,\lambda_{xy}\right) / \left(\sum_{y=1}^{N_e} \lambda_{xy}\, r_{xy}\right) \quad \text{Eq…8}$$

Where N_e is the total number of elements in the distribution system.

vi) Repeat v till the $EENS_x$,$ECOST_x$ and $IEAR_x$, of the entire load points are assessed.

vii) To assess the total system EENS, ECOST and IEAR following equations are used:

$$EENS = \sum_{x=1}^{N_p} EENS_x = \sum_{x=1}^{N_p} L_x \sum_{y=1}^{N_e} \lambda_{xy}\, r_{xy} \quad \text{Eq...9}$$

$$ECOST = \sum_{x=1}^{N_p} ECOST_x = \sum_{x=1}^{N_p} L_x \sum_{y=1}^{N_e} \lambda_{xy}\, c_{xy} \quad \text{Eq10}$$

$$IEAR = (ECOST/EENS) = \left\{\left(\sum_{x=1}^{N_p} ECOST_x\right) / \left(\sum_{x=1}^{N_p} EENS_x\right)\right\} \quad \text{Eq...11}$$

Where N_p is the total number of' load points in the system.

It can be seen from Equation (8) that the load point interrupted energy assessment rate is independent of the average load.

5.2 Models used in the analysis:

A number of different models are required to assess customer interruption cost indices. These include the equipment operating models for lines, breakers, fuses, isolators and standby back feed alternate supplies, the load models and the customer sector interruption cost models. The equipment element model uses a two state up/down representation to model the operation/repair cycle. A probability model is used to represent the operation of fuses, breakers and alternate supplies in which probabilities represent the likelihood of successful device or facility operation. The average load at each load point is used as the load model. A Standard Industrial Classification (SIC) can be used to divide customers into industrial, commercial, residential, government and institutions and office and buildings categories. The surveys show that the cost of an interruption depends on the type of customer interrupted, and on the magnitude and the duration of the interruption [6, 7, and 9]. The survey data has been analyzed to give the sector customer damage functions (SCDF) which are used as the customer interruption cost models. The SCDF are shown in Table-1.

Table-1. Sector interruption cost estimates (CDF) in kW of annual peak demand (Rs. /kW). Sector interruption cost (Rs. /kW).

User sector	Interruption duration (Min) and cost (Rs. /kW)				
	1 min	**20 min**	**1 hr**	**4 hr**	**8 hr**
Industrial	1.050	2.455	6.005	18.125	37.250
Commercial	0.125	0.985	3.850	16.125	42.750
Residential	0.0005	0.048	0.250	2.809	9.750
Govt. and Inst.	0.015	0.145	0.725	4.985	19.150
Office and bldg.	1.025	2.119	6.450	22.250	40.250

5.3 System analysis

These indices can be used to evaluate the reliability of an existing distribution system and to provide useful planning information regarding improvements to existing systems and the design of new distribution systems. This paper is focused on the development and utilization of the cost/worth indices for individual load points and for the system. The following illustrates applications a typical distribution system in the APCPDCL /APTRANSCO. The basic reliability parameters required in the analysis are presented in [4].

5.4 Application to a typical distribution system

A typical practical radial distribution system in the APCPDCL/APTRANSCO connected as show in Figure-2 is taken as case study to evaluate the reliability cost indices and analysis. There are five types of customer: residential, commercial, industrial, govt. and inst., and office and bldg. [11].

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Fig: 2 A typical practical radial distribution systems in APCPDCL /APTRANSCO

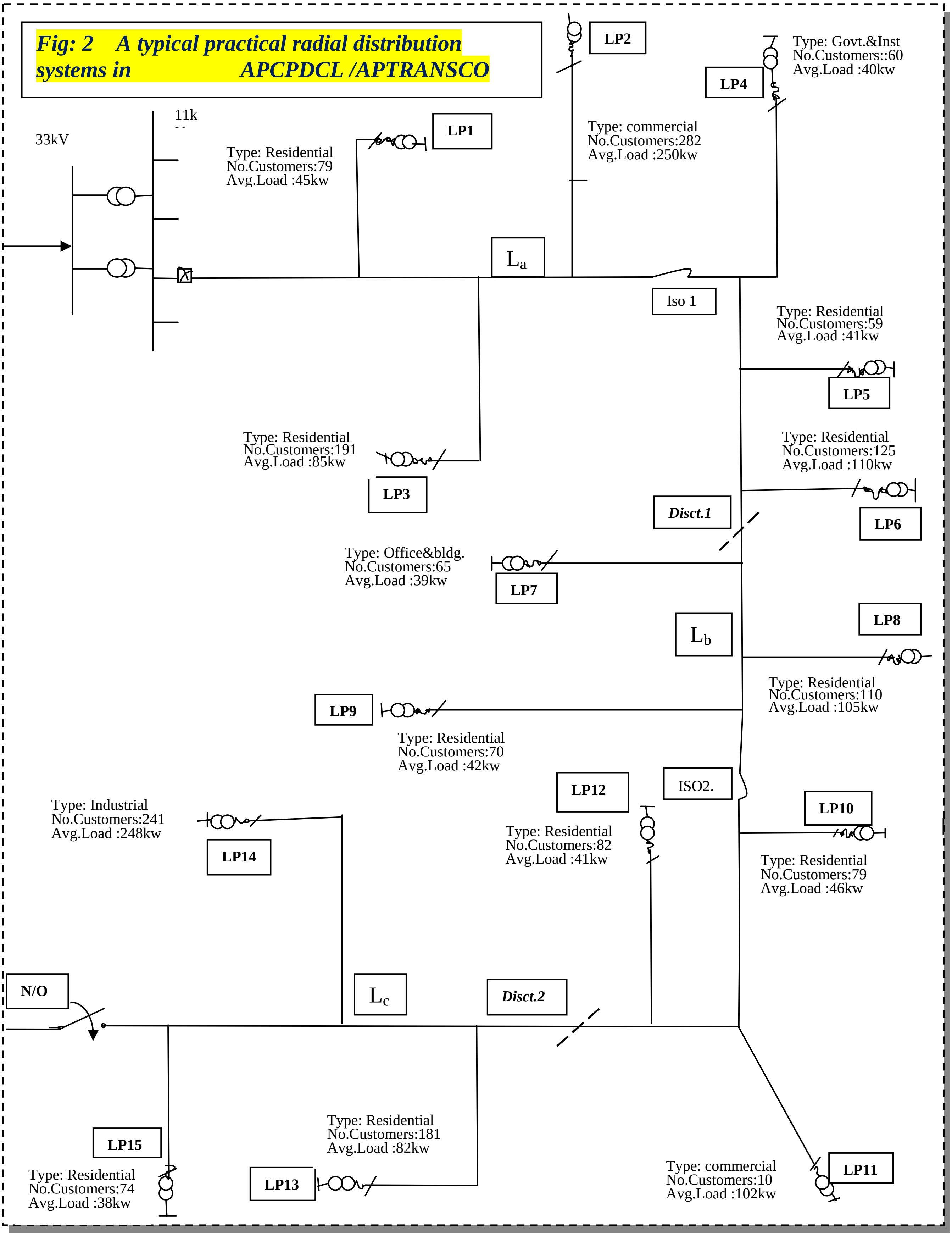

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Table-2. Load comparison for the chosen feeder service area, based on the annual peak demand and annual energy consumption.

User sector	**Sector peak** (MW)	**Sector peak** (%)	**Sector energy** (%)
Industrial	0.250	19.0	21
Commercial	0.210	16.0	17
Residential	0.736	56.0	55
Govt. and inst.	0.085	6.5	5
Office and bldg.	0.033	2.5	2
Total	**1.314**	**100**	**100**

The composite customer damage function (CCDF) in a radial distribution system are assessed as per Table-3.

Table-3. System CCDF (Rs. /kW) assessed from the sector Interruption durations.

Interruptions durations	**CCDF** (Rs. /kW)
1 min	0.25
20 min	0.71
1 hr	2.22
4 hr	8.79
8 hr	22.22

The system composite customer damage function is indicated in the Figure-3.

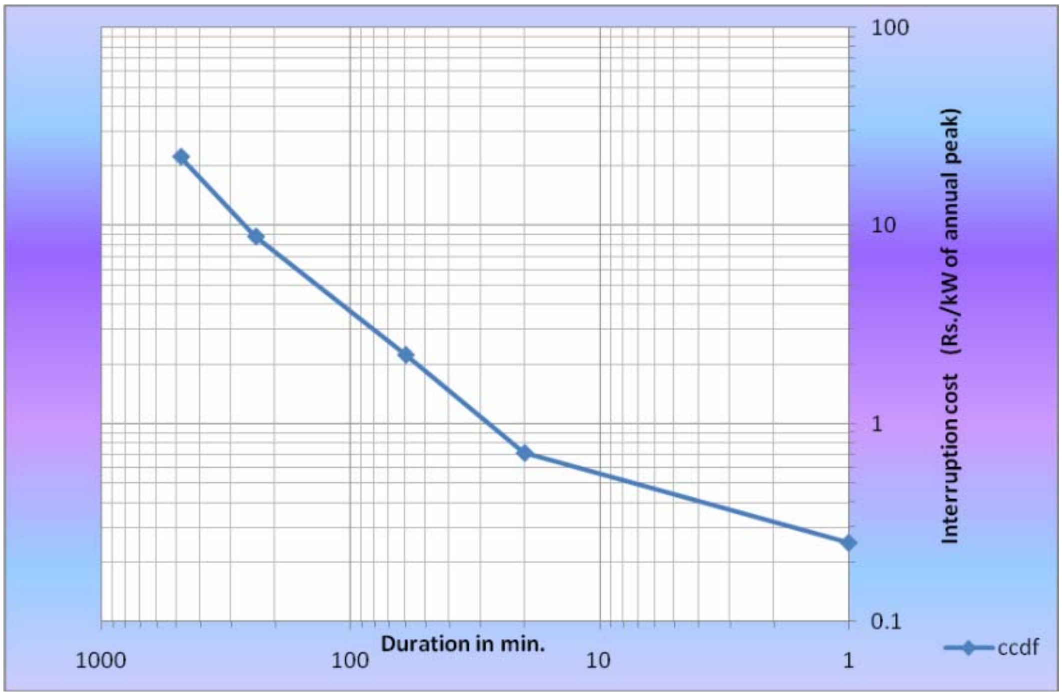

Figure-3. System composite customer damage function.

5.5 Case-I: Assessment of cost indices for load points and system of the present system:

Based on the component reliability parameters and load point reliability indices for the chosen radial distribution feeder, the assessed system reliability indices are shown in Table-4.

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Table-4. Interruption costs of load points (For the present feeder).

Load point	λ_L **(f/yr)**	r_L (hrs)	U_L (hrs/yr)	**EENS** (MWh/yr)	**ECOST** (Rs. / yr.)	**IEAR** (Rs. /kWh)
LP_1	287.62	0.17	49.70	2.123	7.288	3.433
LP_2	272.6	0.16	44.85	10.581	37.925	3.584
LP_3	284.6	0.17	49.61	4.002	13.698	3.423
LP_4	280.0	0.17	47.70	1.705	6.167	3.617
LP_5	270.0	0.14	38.66	1.557	5.928	3.807
LP_6	268.4	0.14	38.05	4.110	15.751	3.833
LP_7	261.2	0.13	25.14	1.344	5.346	3.978
LP_8	275.8	0.15	42.25	4.364	16.041	3.676
LP_9	265.8	0.14	37.48	1.545	5.980	3.870
LP_{10}	284.6	0.16	45.58	2.044	7.287	3.565
LP_{11}	293.2	0.17	50.24	5.008	17.143	3.423
LP_{12}	263.2	0.14	37.00	1.470	5.739	3.903
LP_{13}	275.2	0.16	43.37	3.463	12.760	3.685
LP_{14}	292.6	0.16	46.52	11.253	39.674	3.526
LP_{15}	275.4	0.15	42.41	1.568	5.752	3.668
			Total	56.137	202.479	3.607

Case-II: Reliability worth of network reinforcement with disconnect switch additions (RWSA):

The function of disconnect switches in the main feeder is to isolate failed elements and affected load points and to restore other loads to service if a failure occurs in the main section. The reliability worth of the disconnect switch additions (RWSA) using reinforcement of network with 2 no.s DSA. The RWSA for some load points is marginal and considerable for some other DSA's. The assessed reliability cost indices for Load points and System are indicated in the Table-5.

Table-5. Interruption costs of load points (after reinforcement).

Load point	**Type**	**EENS** (MWh/yr)	**ECOST** (KRs. / yr.)	**IEAR** (Rs./kWh)
LP1	Residential	1.797	6.420	3.573
LP2	commercial	8.768	33.102	3.775
LP3	Residential	3.386	12.059	3.561
LP4	Govt. and Inst.	1.472	5.463	3.712
LP5	Residential	1.318	5.206	3.951
LP6	Residential	3.468	13.813	3.983
LP7	Office and bldg.	1.150	4.698	4.085
LP8	commercial	3.842	14.298	3.721
LP9	Residential	1.337	5.283	3.952
LP10	Residential	1.788	6.477	3.624
LP11	commercial	4.439	15.347	3.458
LP12	Residential	1.241	5.017	4.042
LP13	Residential	2.945	11.262	3.824
LP14	Industrial	9.688	35.142	3.627
LP15	Residential	1.328	5.057	3.808
Total		47.965	178.643	3.724

The comparison of ECOST values as per Case-I and Case-II are graphically represented in Figure-4.

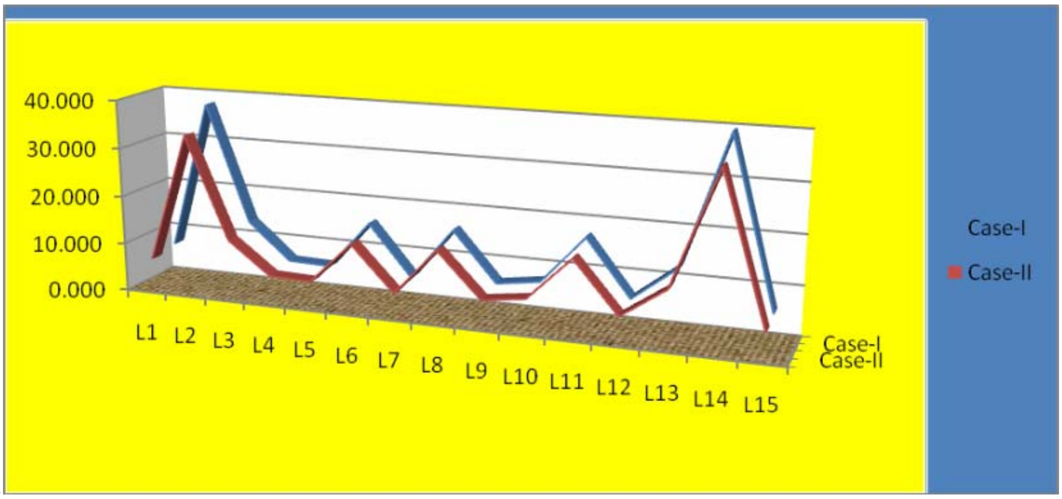

Figure-4. Load point ECOST values for case-I and case-II.

The EENS, ECOST and IEAR cost indices for all the load points of the chosen feeder and the system using the generalized analytical method technique for different configurations have been assessed, and tabulated in the Tables 4, 5 and 6.

Table-6. System costs indices; ECOST, EENS and IEAR comparisons.

Case	Present system	After reinforcement
ECOST (kRs./yr)	202.479	178.643
EENS (MWh/yr)	56.137	47.965
IEAR (Rs./kWh)	3.607	3.724

From the above assessed interruption Costs indices at all load points and system vide Table-4, Table-5 and Table-6, it can be concluded that the reliability worth indices of the system with disconnect switch additions of reinforced network i.e. IEAR (Interrupted Energy Assessment Rate)) have increased marginally, EENS is reduced by more than 14% and ECOST is reduced by more than 11% with respect to the present system. Switching devices affect the customer interruption durations which will affect the customer interruption costs. Figure-4 shows the effect on the load point customer interruption costs of the system with additional 2 nos. of isolating switches. Therefore, the total customer interruption costs of Feeder 2 is reduced by Rs. 23,836/yr after reinforcement of the system. The Switches used in the simple system are all pad mounted sectionalizing switches, at the present cost of Rs.7420/ A.B switch each. The switches used in the complex distribution system are all pole top gang operated, at a total cost of Rs.7420/- for each A.B switch including the installation cost. The annual maintenance cost was assumed to be 2% of the annual investment cost and the interest rate 8%. The life of the switch was assumed to be twenty years. The above assessed reduced CIC of Rs.23,836 is larger than the general annual investment cost of providing 2no.s.disconnecting switch additions and therefore providing the additional disconnecting switches is justified.

CONCLUSIONS

The results of the different ICDF, SCDF, and CCDF cost functions provide the numerical data required to explicitly consider reliability worth in the economic evaluation of distribution segments of an electric power system. And a generalized analytical technique is developed to evaluate load point and system customer interruption cost indices of EENS, ECOST and IEAR for comparative study of reliability worth indices in a practical radial electric distribution system. The reliability costs/ worth indices EENS, ECOST and IEAR are evaluated and can be used in an overall assessment of the monetary worth of system reinforcements. 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. The results assessed from the analysis conducted in this research paper of reduced CIC of Rs.23,836 is larger than the general annual investment cost of providing 2no.s.disconnecting switch additions and therefore providing the additional disconnecting switches for reinforcement is justified, which shows that the reliability cost/worth analysis provided is having an importance to include customer concerns in to system planning, operation and expansion. Based on the assessed reliability cost/worth analysis, the assessed interruptions/outage costs can be used and there is a need to be considered in system feeder optimum design, planning and reconfiguration.

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Nomenclature

CIC	Customer Interruption Costs
SIC	Standardized Industrial Classifications
CDF	Customer Damage Function
ICDF	Individual Customer Damage Functions
SCDF	Sector Customer Damage Function
CCDF	Composite Customer Damage Functions
LP or L	Load Point
DSA	Disconnect Switch Additions
EENS	Expected energy not supplied due to all possible load curtailment events
ECOST	Expected interruption costs due to all possible load curtailment outage events
IEAR	Interrupted energy assessment rate
N	Total no. of load loss events
IDF	Interruption Damage Functions
RWSA	Reliability worth of the disconnect switch additions
A.B Switch	Air Break switch