Evaluation of the Reliability of Distribution Power Systems Considering Composite Customer Interruption Cost

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Abstract - As the power industry moves towards open competition, there has been a call for methodology to evaluate power system reliability by using composite interruption cost. This paper presents algorithms to evaluate the interruption cost of distribution power systems by taking into consideration the failure source and the composite customer interruption cost. From the consumer's standpoint, the composite customer interruption cost is considered as the most valuable index to estimate the reliability of a power distribution system. This paper presents new algorithms that consider the load by customer type and failure probability by distribution facilities while calculating the amount of unserved energy by customer type. Finally, evaluation results of unserved energy and system interruption cost based on composite customer interruption cost are shown in detail.

Keywords: Composite customer interruption cost, power system reliability, probability of failure, unserved energy

1. Introduction

Ensuring reliability has, and will continue to be, a priority for suitable electricity industry restructuring. Reliable electric power delivered on demand is a cornerstone of electricity's ubiquitous adoption and use. A central feature in electricity's value to consumers, whether they are individual households or large industrial complexes, is the infrequent occurrence of outages or other power disturbances that interrupt the use of appliances, motors, electronics, or any of the other myriad of end uses for which electricity is the primary energy source.

While no one disagrees that customers seek dependable power, ensuring reliability is a complex and multi-faceted problem. The strategies available to meet that goal are numerous and the price tags associated with them vary greatly. Most important of all, reliability has always been a shared responsibility because it is a public good. Therefore, who pays and who benefits from increased reliability has always been a question of significance for both private and public decision makers.

The recent August 14th blackout in the Northeast - the largest blackout in U.S. history - has punctuated the importance of and at the same time difficulty in determining the best strategy or combination of strategies.

Accordingly, in relation to the restructuring of the power industry, service reliability has emerged as a major issue. In addition, severe competition among the energy industry demands energy suppliers to consider the conditions related to service reliability. In other words, as customers have the option to select an alternative energy source in consideration of price, enhancing service reliability is not necessarily a mandatory strategy. Therefore, to effectively deal with such an issue, it is necessary to investigate customers' response to service reliability and interruption costs. In the past, the issue of service consistency in the power industry was focused on ensuring high reliability at all times. However, as increased costs accompany high reliability, implementing flexible plans for consumers is emerging as a new trend within the industry.

For example, if distribution system facilities are expanded, customers will have a stable power supply due to improved service reliability, which is an advantage. However, the facility investment costs incurred will be passed on to customers through increased electric charges, which is a disadvantage. As the improvement of service reliability brings the reduction of interruption costs, it is possible to carry out an economic evaluation of a system facility plan from the consumers' standpoint by quantifying the interruption costs following the changes in service reliability([1][2][3]). Therefore, in Japan and other countries,

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researchers directed their attention to the evaluation of the service reliability of a power system by taking into account customer interruption costs.

For instance, researchers at Kitami Institute of Technology in Japan suggested a method of evaluating a power system's service reliability by taking into account the interruption costs ([4]). In general, various facilities are used as a distribution power system; including power lines, transformers, and switches. The failure probability of each facility might vary. In addition, the customer interruption costs are varied by customer type. As the method proposed by the researchers at Kitami Institute of Technology does not differentiate these factors and considers them inclusively, accuracy decreases when the interruption cost of a system is calculated.

In order to overcome this problem, this paper presents an alternate method involving a methodology to evaluate composite interruption costs by customer type weighing factors in proportion to interruption duration. For a distribution system, the composite interruption cost considering interruption duration by customer type was calculated using the amount of unserved energy. A method of totaling the composite interruption cost by customer type is then presented. In addition, a new algorithm takes into account the load by customer type and the failure probability by distribution facilities when calculating the amount of unserved energy by customer type.

2. Evaluation of System Interruption Cost

In recent years, to increase the efficiency of the power industry through competition and to ensure customer choice in power purchases, the opening of power markets, at home and abroad, has been on the rise. As a result, customer interest in the soundness between electric charges and the level of system reliability has increased. Due to this, when a power company wants to improve its service reliability by reducing interruptions, it is necessary to evaluate how much benefit will be produced. However, as the assessment of customer interruption costs varies from country to country, it is difficult to apply it uniformly. Therefore, in this paper, data of interruption costs by customer type is obtained through survey methodology of Korean customers, conducted by KERI [5]. The amount of unserved energy and the average system interruption time considering the failure source for a sample system were then calculated. Finally, system interruption costs were evaluated in consideration of composite customer interruption costs. A summarized flowchart is illustrated in Fig. 1.

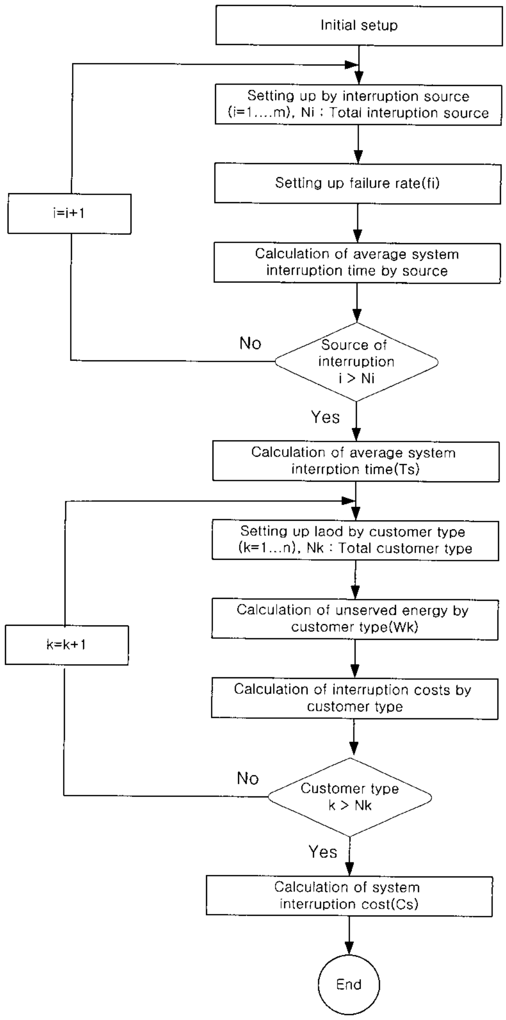

Fig. 1 Flowchart for the evaluation of system interruption costs considering probability of failure and interrupttion cost by customer type

2.1 Evaluation of the system interruption cost

In recent years, the level of power service reliability in advanced countries and in Korea is quite high. Accordingly, to raise the reliability level higher than the current level, the investment necessary to expand power facilities goes up drastically. However, the level of advantage the customers get from improved reliability is not as high compared to the amount of investment required. This is because the increase of investment for facility expansion increases the cost of power supply, which in turn causes the increase of electric charges to the customers. From that point, it is not advantageous to the customers. Therefore, it is important to plan and operate power facilities in consideration of a balance between the benefits the customers will get from the improved reliability and the cost increase the customers should bear. In other words, it is necessary to decide the size of power supply facilities that minimizes the total costs customers have to pay, which are the sum of power supply costs and customer interruption costs.

In other words, it is necessary to establish a plan in consideration of service reliability. For this, it is essential to review and evaluate the interruption costs from the customers' standpoint. Researches on the evaluation of interruption costs have been carried out in Britain, France, Italy, Canada, the U.S.A and Japan since they first started in Sweden. Various methods have been used to evaluate the interruption costs but they can be classified into two.

The first type is the macro method, which calculates the interruption costs in relation to national economy. The second type is the micro method, which estimates the interruption costs by customer type based on the survey of individual customers.

The former, the macro method, was conceived on the point that economic loss occurs after power interruption as economic activities are halted, that is justifiable economic value is lost due to power interruption. The simplest method is calculating the interruption cost macroscopically by dividing GNP by total power consumption. A more detailed method is also used.

By using tables related to economic activities, this method calculates the interruption costs of each economic sector by dividing the value added obtained in the sector by the power input of the sector. These methods are rough but have merits also. With these methods, it is possible to calculate the interruption costs of a country as a whole or by sector. However, evaluating the interruption costs of individual customers with the values obtained by these methods has some problems.

On the other hand, with the micro method, it is possible to calculate the interruption costs of customer groups but not individual customers. The result can be problematic from an objectivity standpoint. As a consequence, it is necessary to carry out large scale surveys.

Interruption costs are calculated based on large scale surveys in Sweden, Britain, France, the U.S.A, Canada and Japan and yet there has been no specific evaluation on this in Korea so far. In this paper, we carry out the customer interruption costs using the micro survey evaluation of Korean customers according to customer type

Also, in this paper, the evaluation of a composite for customer interruption costs for service areas is introduced to define the total customer interruption cost for that area as a function of the interruption duration. The composite interruption cost is a function of the various customer types and other variables such as duration of interruption, frequency of interruption, time of interruption (or day), season of interruption and regional difference. These costs are weighted in proportion to their respective power demand within the area. Weighing by the annual peak demand is used for short duration interruptions and weighing by the average demand is used for duration interruptions longer than half an hour. These costs are then summed to provide the total costs for the area for each duration period. The variation of this total cost with duration is considered to be the composite interruption costs for the service area.

Despite the uncertainties affecting the development of composite interruption costs, it is the most suitable tool available in determining monetary estimates of reliability worth. This paper presents methodology to calculate composite interruption costs in a service area, as illustrated in the following equations (1) & (2):

$$C_c = \Sigma\alpha_k \ C_k \tag{1}$$

where,

k = Customer type

C_k = Interruption cost by customer type (long duration)

α_k = Rate of average demand by customer type (%)

C_c = Composite interruption cost (long duration)

$$C_c = \Sigma \ \beta_k \ C_k \tag{2}$$

where,

k = Customer type

C_k = Interruption cost by customer type (short duration)

β_k = Rate of peak demand by customer type (%)

C_c = Composite interruption cost (short duration)

The following table presents data of this interruption cost per kW by main customer type obtained in Korea in 2002 using the detail micro survey procedure.

Table 1 Evaluation for interruption cost per kW by main customer type from interruption duration

(unit: $/kW)

Customer Type	Interruption Duration			
	1 minute	20 minutes	1 hour	4 hours
Apartment	0.1	2.1	6.2	23.6
Large Shopping Center	4.0	8.0	20.4	95.7
Small Stores	2.2	4.5	12.8	52.2
Restaurant	2.9	5.8	17.5	69.9
Government Organization	76.9	289.6	749.1	1,209.2
Educational Organization	31.4	90.2	143.0	248.9
Financial Organization	28.0	128.2	235.1	554.1
Sports Organization	62.7	106.2	224.7	490.8
Hospitals	19.3	41.4	89.0	268.2
Agriculture	1.3	76.0	349.5	683.0
Fishery	48.8	515.4	1,574.7	2,405.0
Stock Raising	3.2	49.4	264.8	886.0

Table 2 Calculation of average interruption time by source

Number of switches	Number of lines	Number of switches per line	Dispatch time (in minutes)	Average failure detection time (in minutes)	Average switch changing time (in minutes)	Average interruption time (in minutes)
①	②	③ = ①/②	④	⑤	⑥	⑦ = ④ + ⑤ + ⑥

2.2 Calculation of average system interruption time considering probability of failure

As the failure rate by source, the interruption time for repair and the number of customers experiencing interruption are different, the following equation (3) is used to calculate the average system interruption time.

$$Ts = \sum \frac{ti \times fi \times \text{Length(Number)} \times Ni}{Nt \times 60} \qquad (3)$$

where,

I = Failure source (power line, transformer, switch, etc.)
N_i = Number of customers experiencing interruption by failure source
N_t = Total number of customers
t_i = Interruption time by source (in minutes)
f_i = Failure rate by source

At this time, the average interruption time is calculated in Table 2 with consideration to dispatch time, failure detection time, and average switch changing time.

2.3 Calculation of the amount of unserved energy

In order to calculate the total amount of unserved energy of a system for the evaluation of service reliability from the customers' standpoint, the amount of unserved energy by customer type needs to be calculated. By using the load characteristics by customer type in the respective area, the amount of unserved energy by customer type is defined by the following equation:

$$W_k = P_k \times T_s \qquad (4)$$

where,

k = Customer type
W_k = Amount of unserved energy by customer type
P_k = Load by customer type
T_s = Average system interruption time (h)

2.4 Evaluation of system interruption cost

From the amount of unserved energy (W_k) by customer type and the estimate of composite interruption cost (C_c), the interruption cost of a system according to system configuration is calculated as in the following equation:

$$C_s = \Sigma\, C_c \times W_k \qquad (5)$$

where,

k = Customer type
C_c = Composite customer interruption cost
W_k = Amount of unserved energy by customer type
C_s = System interruption cost

3. A Case Study

3.1 Conditions of case study

To apply the algorithm that evaluates service reliability taking into account the customer interruption costs presented above, a distribution system of a dual supply system consisting of mostly high voltage customers, as shown in Fig. 2, is used. In this study, for the model system illustrated in Fig. 1, the average system interruption time and the amount of unserved energy by customer type was calculated for the failure by distribution facilities type. The system interruption cost was then evaluated in consideration of the composite interruption cost by customer type.

For distribution systems, related regulations require that loads over 100kW should be supplied by high voltage and loads under 100kW should be supplied by low voltage through transformers. Therefore, in this study, we hypothesized that the model system supplies high voltage of over 100 kW to 8 customers and low voltage of under 100kW to residential customers. In Table 3, load characteristic data including the load amount by switch and customer type are presented.

3.2 Results of the case study

For the model system, we calculated the average system interruption time in consideration of the failure probability by distribution facilities consisting of power lines, switches, and transformers, by using equation (3) and based on the following assumptions. The results are presented in Table 4.

- The average switch changing time is 3 minutes per switching station. Also, the time taken to move for repair is considered to be 10 minutes (considering the site situation).
- Calculates the number of lines for the system supply method.

- Number of average switch stations = Number of switch stations ÷ Number of lines.
- n = (Number of average switch stations ÷ 2^n) ≤ 1.
- Average failure detection time = (n - 1) × 10 minutes / per move.
- Average switch changing time = (2n - 1) × 3 minutes / per switch station.
- Transformer changing time is considered to be 120 minutes.

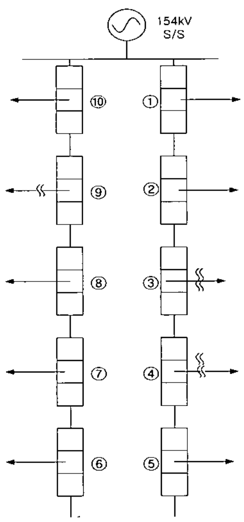

Fig. 2 Configuration of model power system

Table 3 Load characteristic data of the model system

Switch Number	Load (kw)	Customer Type
①	800	Apartment
②	3,000	Large shopping Center
③	700	Small Stores
④	500	Restaurant
⑤	500	Government
⑥	2,000	Organization
⑦	3,000	Education Organization
⑧	1,000	Financial Organization
⑨	900	Sports Organization
⑩	300	Hospital Organization
		Agriculture

By using the average system interruption time calculated with equation (3), the amount of unserved energy by customer type was calculated with equation (4) and the results are indicated in Table 5.

In this case study, the rate between peak and average demand in each service area by using load characteristics in the model system is shown in Table 6. The data presented in Table 6 is calculated with a ratio between peak and average demand in urban areas in Korea. By using the rate between average and peak demand, which is presented in Table 6, composite customer interruption costs by customer type is calculated in equation (1) and equation (2). The results are shown in Table 7.

Table 4 Calculation of system average interruption time

Interruption Source	Failure Rate	Length (Number)	Total Customer	Interruption Time (min.)	Number of Customers Experiencing Interruption (by interruption source)	Number of Customers Experiencing Interruption (annual)	Customer Interruption Time (for the year - min.)	Average System Interruption Time(min)
	①	②	③	④	⑤	⑥=①*②*⑤	⑦=④*⑥	⑧=⑦/③
Lines	0.00754	50	28	24.15	7.0	2.639	63.7319	2.2761
Switches	0.00102	10	28	24.15	7.0	0.0714	1.7243	0.0616
Transformers	0.00084	10	28	120.0	2.8	0.0235	2.8224	0.1008
Total	-	-	-	-	-	2.7339	68.2786	2.4385

Table 5 Calculation of unserved energy

Customer Type	Load (kW)	Number of Customers	Load Per Customer (kW)	Interruption Time Per Customer (Hr)	Unserved energy (kWH)
	①	②	③=①/②	④=Average system interruption time*②/60	⑤=③*④
Apartment	800	1	800	2.4385	1,950.82
Large Shopping	3,000	1	3,000	2.4385	7,315.56
Small Store	700	7	100	17.0696	1,706.96
Restaurant	500	5	100	12.1926	1,219.26
Government	500	1	500	2.4385	1,219.2
Education	2,000	1	2,000	2.4385	4,877.04
Financial	3,000	1	3,000	2.4385	7,315.56
Sports	1,000	1	1,000	2.4385	2,438.52
Agriculture	900	9	100	2.1947	2,194.67
Hospitals	300	1	300	2.4385	731.56
Total		28			30,969.20

Table 6 The proportion of average load to peak load for each customer sector

Customer Type	Average Demand (%)	Peak Demand (%)
Apartment	16.0	15.0
Large Shopping	8.0	13.0
Small Store	9.0	9.0
Restaurant	10.0	10.0
Government	12.0	15.0
Education	11.0	5.0
Financial	10.0	15.0
Sports	13.0	10.0
Agriculture	5.0	4.0
Hospitals	6.0	4.0

Next, to evaluate system interruption costs taking into account the composite interruption cost from the amount of unserved energy calculated in Table 5, the final system interruption cost in each service area was calculated by summing and multiplying the amount of unserved energy and customer interruption costs by customer type. The results are presented in Table 8.

Table 7 Composite customer interruption costs

Interruption Duration	Composite Customer Interruption Cost ($/kW)	Composite Customer Interruption Cost ($/kWH)
1 minute	25	1,500
20 minutes	85	255
1 hour	187	187
4 hours	365	91

Table 8 Assessment of system interruption costs

Customer Type	Amount of Unserved Energy (kWH)	Composite Interruption Cost Per Customer ($/kWH)	System Interruption Cost ($/year)
	①	②	③=①*②
Apartment	32.51	1,500	48,770
Large Shopping	121.93	1,500	182,888
Small Store	28.45	255	7,255
Restaurant	20.32	1,500	5,182
Government	20.32	1,500	30,481
Education	81.28	1,500	121,925
Financial	121.93	1,500	182,888
Sports	40.64	1,500	60,963
Agriculture	32.92	1,500	49,381
Hospitals	12.19	1,500	18,289
Total	512.49	-	708,022

4. Conclusion

Methods of evaluating service reliability have been presented, part of which involves a method of evaluating service reliability based on the interruption cost by converting the loss customers suffer due to interruptions into currency. In this paper, breaking away from the traditional method of power supply, in which the supplier alone decides the level of acceptable service reliability, a means of supply reliability evaluation reflecting the customers' side was introduced. In addition, to evaluate the system interruption costs more accurately, the amount of unserved energy by customer type was calculated considering the failure probability by distribution facilities and the evaluation of a composite customer interruption cost for service areas defining the total system interruption cost considering interruption duration. Then, the final system interruption cost was calculated by using the interruption cost by customer type.

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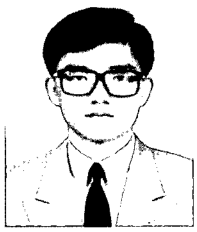

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