Assessment of Reliability in the Distribution System of an Industrial Complex

Sang-Bong Choi†

Abstract – As the power industry moves towards open competition, there has been a need for methodology to evaluate distribution power system reliability by using customer interruption costs, particularly in power supply zones under the competitive electricity market. This paper presents an algorithm to evaluate system average interruption duration index, expected energy not supplied, and system outage cost taking into consideration failure rate of the distribution facility and industrial customer interruption cost. Also, to apply this algorithm to evaluate system outage cost presented in this paper, the distribution arrangement of a dual supply system consisting of mostly high voltage customers in an industrial complex in Korea is used as a sample case study. Finally, evaluation results of system interruption cost, system average interruption duration index, and expected energy not supplied in the sample industrial complex area are shown in detail.

Keywords: Competitive Electricity Market, Failure Rate, Industrial complex, System Expected Energy Outage Cost, System Interruption Cost, System Average Interruption Duration Index

1. Introduction

For the restructuring of the power industry, assurance of supply reliability is one of the most important factors. In addition, providing highly reliable power service can be a foundation for the ubiquitous application and use of electricity. Whether for a residential customer or an industrial customer, one important characteristic of electricity is the interruption that prevents the use of numerous devices using electricity as the energy source, such as electric equipment, motors, and electronic devices. No one would disagree with the fact that customers want high reliability. But assuring reliability is very complex and related to many factors. Since reliability is a public good, the most important factor is sharing the responsibility. As a result, deciding who should benefit from improved reliability level and who should pay for the cost is a very important matter. The massive power outage recently occurred in the Northeastern part of the U.S. highlighted the importance of reliability in system planning. It also implied how difficult it is to set an optimal strategy.

It can be said that a strategy is an assumption of the value of supply reliability to customers. The general assumption on the short duration accidents, such as the massive power outage in the Northeastern part of the U.S. and the 2001 outage in California, is that customers must pay higher cost for adequate supply reliability. On the other hand, during the power supply period accompanied by higher electric rate, the cost is caused because the system is designed and constructed for higher reliability than the customer paid.

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 consumer standpoint by quantifying the interruption costs following the changes in service reliability [1-3]. Therefore, in Japan and other countries, researchers directed their attention to the evaluation of the service reliability of a power system by taking into account

† Corresponding Author: Power Technology Team, Power System Division, KERI, Korea (sbchoi@keri.re.kr)
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customer interruption costs.

For instance, researchers at the 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 the 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 system average interruption duration index, expected energy not supplied considering failure source, and interruption costs by industrial customer type at load point.

For a distribution system, the interruption cost considering interruption duration by industrial customer type was calculated using the amount of unserved energy. A method of totaling the system 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 industrial customer type.

2. Evaluation of Interruption Cost by Industrial Customer Type

2.1 Survey of the interruption cost by customer type

In recent years, the level of power service reliability in advanced countries and in Korea has been 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 raises 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 customer 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 were first initiated in Sweden. Various methods have been used to evaluate the interruption costs but they can be classified into three groups, analytic method, case studies of actual interruption, and survey.

The first type is the analytic method, which can be classified into several categories but in general these methods are assessments of outage costs from theoretical and economic perspectives. Most analytic methods use market-based data but some methods use secondary data such as economic indices. One of these methods assesses the outage cost based on the ratio of GDP and power consumption. The advantage of this method is that assessment is relatively simple. However, this analytic method is usually applied only to places where the assessment of outage cost is impossible and not to actual customer needs.

The second type is case studies of actual interruption. These Case studies of actual interruption assess the actual damages from interruption. Direct and indirect costs can be assessed. For example, in the case of the New York City Blackout of 1977, the outage cost was assessed taking into account the direct and indirect social and structural impacts due to the blackout. A very interesting result was found from this case study. The indirect cost (3.45$/kWh) was higher than the direct cost (0.66$/kWh). It was also found that the outage cost was higher when the blackout area was wide than when it was localized. Valuable information can be obtained from the case studies of actual interruption. Unfortunately, such information is limited to individual blackout case and locality. Thus, this information cannot be generalized to other blackout cases and localities.

The last type is the customer survey assessment method. To realistically assess the outage costs using analytic methods and case studies of actual interruption, specific information on customers is needed. The customer cost means the loss of production or service suffered by the customers due to interruption. It is based on the assumption that customers can best assess the loss they suffered from interruption. The customer survey questionnaire can be created in various forms based on customer type, location, and production type, etc. The customer survey method can be classified into contingent valuation method, direct assessment method, and indirect assessment method as follows. Most of the customer survey methods can be organized into one of these three and which method to use depends largely on customer type.

2.1.1 Contingent valuation method

The contingent valuation method is based on 2 basic concepts of power use. The first concept implies that customers use power according to power use patterns by season, week, and day. In other words, customers develop power use patterns that are most beneficial to them. The second concept implies that power use is more valuable to customers than other things. In other words, there is a difference between the electric rate and the value of loss due to interruption. The value of power use can be quantified into people's willingness to pay (WTP) to avoid interruption or people's willingness to accept (WTA) the deprivation of the benefits of power use.

Theoretically, WTP and WTA should have the same value, but in actuality, they do not. It may be because electric rates are different by customer type, or it may be the reflection of the difference between the bidding rate and the demanding rate. They can be considered as two boundaries for the value of reliability by customer type. Firstly, as this approach is based on the basic concepts of power use, it is applicable to all types of customers. And secondly, compared to other assessment methods, this method brings out a relatively approximate assessment.

2.1.2 Direct assessment method

The direct assessment method asks the customers to appraise the impact of a certain interruption scenario and assess monetary loss. For example, customers can be asked to assess the impact of production loss, overtime work expense, raw material loss, production restart cost, and the cost of emergency power supply device operation in monetary terms. This assessment method is appropriate for industrial or commercial customers, for whom power interruption can lead to actual economic loss.

2.1.3 Indirect assessment method

The indirect method is based on the economic principle of alternative uses. An alternative is an indicator of the value of a product or service that it replaces. This approach is appropriate when most of the loss due to interruption is intangible or only social impact is expected like the case for residential customers. One form of this assessment method is to ask the customers to select various preparative actions for interruption. These preparative actions could range from doing nothing to obtaining an emergency power supply device to fully cover the necessary load. The value of the preparative actions is a way to evaluate up to what extent the customer will pay to lessen the effect of interruption. From the results the customer selected, the value of power use can be assessed.

2.2 Evaluation and analysis of the interruption cost by industrial customer type

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 related to interruption costs by industrial customer type have been obtained through survey methodology of Korean customers, conducted by KERI [5]. The amount of expected energy not supplied and the average system interruption time considering the failure source for a sample system were then calculated. Finally, system interruption costs in an industrial complex in Korea were evaluated in consideration of customer interruption costs. A summarized flowchart is illustrated in Fig. 1. Accordingly, in this paper, reliability indices such as system average interruption duration index (SAIDI), system expected energy not supplied due to power outage (EENS), and system expected outage cost to customers due to supply outages (ECOST) can be calculated in distribution power systems.

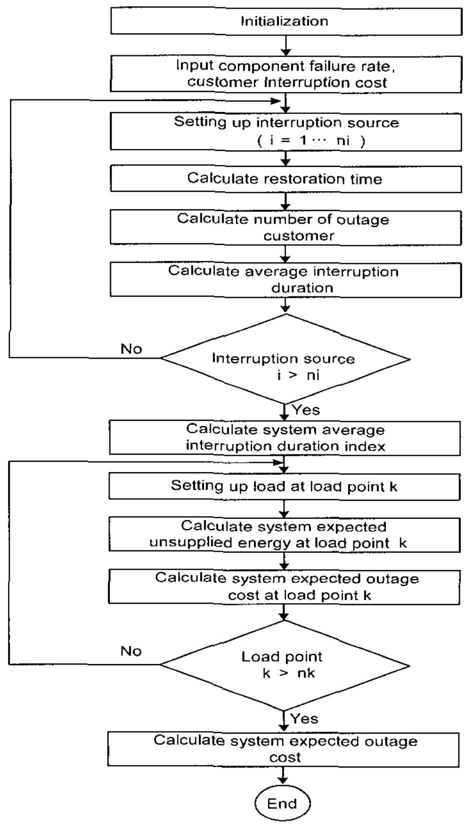

Fig. 1. Flowchart for the evaluation of system interruption costs considering probability of failure and interruption cost by industrial customer type.

2.2.1 Calculation of System Average Interruption Duration Index (SAIDI)

As the failure rate by source, the interruption time for repair and the number of customers experiencing interruption are different, the following equation (1) is used to calculate the system average interruption duration index (SAIDI).

$$SAIDI = \sum_{i} \sum_{j} \frac{t_i \times h_i \times length(number) \times N_j}{N_t \times 60} \quad (1)$$

where,

i = Outage source (power line, transformer, switch, etc.)
j= Customers experiencing interruption by outage source
N_j = Number of isolated customers due to outage source i
N_t = Total number of customers
t_i= Interruption duration by outage source i (in minutes)
h_i = Failure rate by outage source i

2.2.2 Calculation of system Expected Energy Not Supplied due to power outage (EENS)

In order to calculate system expected unsupplied energy due to power outage, the amount of expected energy not supplied by industrial customer type at load point needs to be calculated. By using the load characteristics by industrial customer type in the load point, the amount of expected energy not supplied is calculated as in the following equation (2)

$$EENS = \sum_{i} \sum_{k} L_k \times t_i \times h_i \quad (2)$$

where,

i = Outage source (power line, transformer, switch, etc.)
k = Load point
L_k = Load at load point k
t_i= Interruption duration by outage source i (in minutes)
h_i = Failure rate by outage source i

2.2.3 Calculation of system Expected Outage Cost

From the amount of system expected energy not supplied and the estimate of interruption cost by industrial customer type, system total interruption cost based on distribution system configuration is calculated as in the following equation (3)

$$ECOST = \sum_{i} \sum_{k} L_k \times C_{ik}(t_i) \times h_i \quad (3)$$

where,

i = Outage source (power line, transformer, switch, etc.)
k = Load point
L_k = Load at load point k
t_i= Interruption duration by outage source i (in minutes)
h_i = Failure rate by outage source i
$C_{ik}(t_i)$ = Customer interruption cost due to outage source i with interruption duration t_i

The following Table 1 presents data of industrial interruption cost per kW by industrial customer type obtained in Korea in 2005 using the detail micro survey procedure.

Table 1. Interruption cost for average power consumption according to the interruption duration by industrial customer type

Type	Monthly average power use(kWh)	Interruption cost per average kW (unit : $/kW)			
		3sec below	1min below	5min below	30min below
Textile and apparel	1,233,844	8.421	8.724	9.500	13.935
Pulp and paper products	3,093,209	1.650	1.678	1.781	2.100
Chemicals and chemical products	5,046,603	39.806	50.284	52.042	61.505
Electric and electronic equipment	1,087,592	80.335	120.718	174.493	230.076
Food and beverage	43,927	22.783	44.747	78.020	128.504
Basic/fabricated metal	69,283	12.886	18.706	33.359	63.288
Other machinery and equipment	107,437	11.594	15.950	26.605	59.443
Electric machinery	158,957	7.700	13.634	21.470	45.794
Audio visual equipment	94,041	9.647	12.709	23.045	53.517
Motor vehicles	184,107	23.699	36.683	49.706	83.612
Other transport equipment	103,562	9.316	12.862	15.782	39.420

Type	Monthly average power use(kWh)	Interruption cost per average kW (unit : $/kW)			
		1hour below	4hour below	8hour below	8hour above
Textile and apparel	1,233,844	16.952	22.881	34.388	39.768
Pulp and paper products	3,093,209	2.619	9.017	15.381	22.055
Chemicals and chemical products	5,046,603	70.181	84.372	98.950	115.854
Electric and electronic equipment	1,087,592	229.500	299.389	405.556	430.514
Food and beverage	43,927	182.430	410.426	896.906	1,103.595
Basic/fabricated metal	69,283	111.716	210.649	420.882	554.733
Other machinery and equipment	107,437	106.757	229.865	399.013	619.161
Electric machinery	158,957	86.786	226.114	388.452	604.103
Audio visual equipment	94,041	92.411	215.753	337.946	448.962
Motor vehicles	184,107	120.061	206.528	351.617	560.296
Other transport equipment	103,562	66.047	142.871	253.682	298.673

3. Case Study

3.1 Conditions of case study

To apply the algorithm that evaluates service reliability taking into account the industrial customer interruption costs presented above, the distribution system of a dual supply system consisting of mostly high voltage customers in an industrial complex in Korea, as shown in Fig. 2, is used.

In this study, for the model system illustrated in Fig. 2, the system average system interruption duration and the amount of expected energy not supplied by industrial customer type was calculated for the failure by distribution facilities type.

The system interruption cost was then evaluated in consideration of the interruption cost by industrial customer type. For distribution systems in industrial complexes in Korea, 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 13 customers and low voltage of under 100kW to food & beverage and textile & apparel customers. In Table 2, load characteristic data including the load amount by switch and customer type are presented.

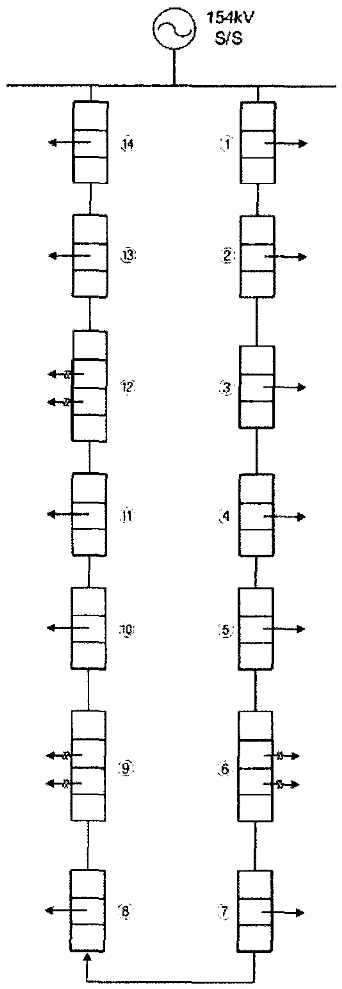

Fig. 2. Configuration of model power system

Table 2. Load characteristic data of the model system

Switch Number	Load (kw)	Customer Type
①	900	Basic/fabricated metal
②	1500	Chemical & Chemical products
③	800	Other machinery & equipment
④	450	Audio visual equipment
⑤	850	Other transport equipment
⑥	90, 95	Food & beverage
⑦	300	Pulp & paper products
⑧	850	Electric machinery
⑨	95, 85	Textile and apparel
⑩	700	Motor vehicles
⑪	1700	Chemical & chemical products
⑫	80, 90	Food & beverage
⑬	800	Basic/fabricated metal
⑭	600	Other machinery & equipment

3.2 Results of the case study

For the model system, we calculated the average system interruption duration in consideration of the failure probability by distribution facilities consisting of power lines, switches, and transformers, by using equation (1) and based on the following assumptions. The results are presented in Table 3.

- 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 = $(n - 1) \times 10$ minutes / per move.
- Average switch changing time = $2(n - 1) \times 3$ minutes / per switch station.
- Transformer changing time is considered to be 120 minutes.

By using the average system interruption duration calculated with equation (1), the amount of expected energy not supplied by industrial customer type was calculated with equation (2) and the results are indicated in Table 4.

Table 3. Calculation of system average interruption duration

Interruption Source	Failure Rate	Length (Number)	Total Customers	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
Line	0.00754	50km	17	44..92	8.5	3.0245	143.9461	8.4674
Switch	0.00102	14	17	44.92	8.5	0.12138	5.4524	0.3207
Transformer	0.00084	17	17	120.0	1.0	0.01428	1.7136	0.1008
Total	-	-	-	-	-	3.34016	151.1121	8.8889

Table 4. Calculation of expected energy not supplied

Customer Type	Load (kW)	Number of Customers	Load Per Customer (kW)	Interruption Time Per Customer (Hr)	Expected Energy Not Supplied(kWH)
	①	②	③=①/②	④=Average system interruption time*②/60	⑤=③*④
Basic/fabricated metal	900	1	900	0.1481	133.29
Chemical & products	1,500	1	1,500	0.1481	222.15
Other machinery & equipment	800	1	800	0.1481	118.48
Audio visual equipment	450	1	450	0.1481	66.65
Other transport equipment	850	1	850	0.1481	125.89
Food & beverage	185	2	92.5	0.2963	27.41
Pulp & paper products	300	1	300	0.1481	44.43
Electric machinery	850	1	850	0.1481	125.89
Textile and apparel	180	2	90	0.2963	26.67
Motor vehicles	700	1	700	0.1481	103.67
Chemical & products	1,700	1	1,700	0.1481	251.77
Food & beverage	170	2	85	0.2963	12.59
Basic/fabricated metal	800	1	800	0.1481	118.48
Other machinery & equipment	600	1	600	0.1481	88.86
Total	9,985	17			

Table 5. Assessment of system interruption costs in industrial complex

Customer Type	Amount of Expected Energy Not Supplied(kWH)	Interruption Cost by Industrial Customer($/kWH)	System Interruption Cost ($/year)
	①	②	③=①*②
Basic/fabricated metal	133.29	1.0548	140.6
Chemical & products	222.15	1.0250	227.7
Other machinery & equipment	118.48	0.9907	117.4
Audio visual equipment	66.65	0.8920	59.5
Other transport equipment	125.89	0.6570	82.7
Food & beverage	27.41	2.1417	58.7
Pulp & paper products	44.43	0.0350	1.6
Electric machinery	125.89	0.7632	96.1
Textile and apparel	26.67	0.2323	6.2
Motor vehicles	103.67	1.3935	144.5
Chemical & products	251.77	1.0250	258.1
Food & beverage	12.59	2.1417	27.0
Basic/fabricated metal	118.48	1.0548	125.0
Other machinery & equipment	88.86	0.9907	88.0
Total			1,433.1

Next, to evaluate system interruption costs taking into account the industrial interruption cost from the amount of expected energy not supplied calculated in Table 4, the final system interruption cost in each service area was calculated by summing and multiplying the amount of expected energy not supplied and customer interruption costs by industrial customer type. The results are presented in Table 5.

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 in 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 customer side was introduced. In addition, to assess the system interruption costs more accurately, the amount of expected energy not supplied by customer type was calculated considering the failure probability by distribution facilities and the evaluation of a customer interruption cost by industrial customer type 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 industrial customer type.

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Sang-Bong Choi
He received his Ph.D. in Electrical Engineering from Yonsei University. His primary research interests are transmission/distribution planning and operation.