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RELIABILITY EVALUATION OF POWER DISTRIBUTION SYSTEMS CONSIDERING THE MOMENTARY INTERRUPTIONS

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Abstract: In this paper, we propose the reliability evaluation method of power distribution systems considering the momentary interruptions. The results of research are concentrated on two parts. One is the reliability evaluation method of power distribution system considering the momentary interruptions and the other is the reliability cost evaluation that unifies the sustained and momentary interruption costs. These proposed evaluation methodologies are divided into the analytic and probabilistic method. Time Sequential Monte Carlo method is used for the probabilistic methodology. The proposed methods are tested using the modified RBTS (Roy Billinton Test System) form and historical reliability data of KEPCO (Korea Electric Power Corporation) system. Through the case studies, it is verified that the proposed reliability cost evaluation can be used to evaluate the actual reliability. *Copyright © 2003 IFAC*

Keywords: Reliability evaluation, distribution systems, quadratic performance indices, reliability test system, Monte Carlo simulation.

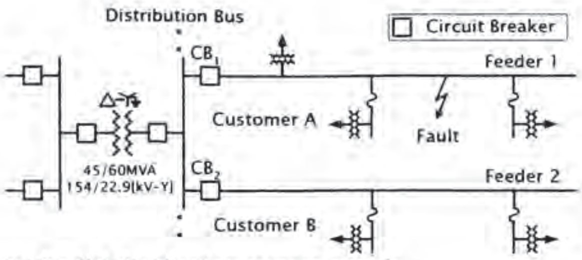
1. INTRODUCTION

The goal of reliability evaluation of power distribution systems is to predict the service security of electric customer based on the topologies and information of system components. It has been mainly determined by the frequency and duration of sustained interruption. In resent, the damage of short duration voltage disturbances has been progressively increased because the electronic and precision devices are used in customer-side and the topology of distribution systems becomes shorter and more high dense. Above of all, momentary interruptions occur more frequently than sustained interruptions, and the adverse effects of the former on certain customers are also greater than those of the latter.

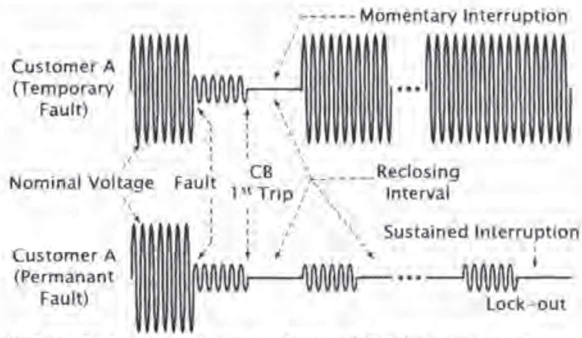
Up to these date, the methodology of reliability evaluation for power distribution system is divided into the evaluation of system reliability indices (customer-oriented indices and energy-oriented indices) and the reliability cost/worth evaluation. These two parts can be evaluated into the analytic and probabilistic method. The analytic method is used to decide the average value or expected value of system reliability (Billinton and Allan, 1996) and the probabilistic method is used to decide the probability distribution of one (Billinton and Li, 1994; Billinton and Wang, 1988). Studies of momentary interruptions are concentrated on the reduction of its occurrence and the development of evaluation methods (Warren, 1992; Brown, 1997; Brown, 1998). The reliability indices, which contain the momentary interruptions on power distribution system, have been authorized to a standard (IEEE Standard 1366, 1998). MAIFI (Momentary Average Interruption Frequency Index) and $MAIFI_E$ (Momentary Average Interruption Event Frequency Index) that is related to the momentary interruption are proposed.

The evaluation parameters of both conventional analytic and probabilistic reliability methods did not consider the frequency and duration of momentary interruptions. For the case of MAIFI and $MAIFI_E$, it can be hardly applied to actual distribution systems because it needs a specific evaluation methodology.

In this paper, a new reliability evaluation methodology to facilitate a quantitative evaluation of momentary interruptions and its damage in a power distribution system is proposed. The main contents of this paper compose three parts and it is summarized as follows. Section 2 outlines the occurrences and characteristics of sustained and momentary interruptions in a power distribution system and the proposed reliability evaluation method of momentary interruptions are summarized. In Section 3, the unified reliability cost evaluation method is proposed that considering the sustained and momentary interruptions. In Section 2 and 3, the proposed evaluation methods are divided into the analytic and probabilistic approaches and Time Sequential Monte Carlo simulation is used for the probabilistic method. In Section 4, we examine the case studies for the modified RBTS (Roy Billinton Test System) and historical reliability data in KEPCO (Korea Electric Power Corporation).



(a) Radial distribution system sample



(b) Voltage waveform on faulted feeder customer

Fig. 1. Occurrence of sustained and momentary interruption

2. MECHANISM OF MOMENTARY INTERRUPTION AND RELIABILITY EVALUATION OF DISTRIBUTION SYSTEMS

In this section, we examine the behavior of sustained and momentary interruptions and propose the analytic and probabilistic evaluation methodology of momentary interruptions.

2.1 Mechanism of Momentary Interruption

Interruptions (sustained and momentary) are usually associated with a fault somewhere on a distribution system. When a fault occurs as shown in Fig. 1(a), the circuit breaker opens to clear the fault and automatically recloses after a time delay. This reclosing behavior can take place several times in an effort to establish continuous service for a temporary fault. If the fault is temporary in nature, a reclosing operation on the breaker should be successful and the interruption will only be temporary. The customer *A* on faulted feeder experiences a momentary interruption. However, if it is the permanent fault, reclosing operations on the breaker should be failed and the reclosing device will be locked-out. The customer *A* on faulted feeder experiences a sustained interruption. As shown in this example, the momentary interruptions are originated to the reclosing behaviors by protective devices. The dead time is the direct source of momentary interruptions.

2.2 Reliability Evaluation of Sustained Interruptions

Reliability Indices of Sustained Interruptions

The basic parameters of conventional reliability evaluation are divided into the average permanent failure rate, average permanent outage time, and average annual permanent outage time Billinton and Allan, 1996). Although the three primary indices are fundamentally important, they do not always give the complete indices of the system performance. In order to reflect more actual system severity then them, additional reliability indices are used. The additional reliability indices that are called to the SAIFI, SAIDI, CAIFI, CAIDI, ASAI, ASUI, and etc. are defined in the IEEE Std. 1366 (1998).

The methodologies of distribution system reliability evaluation are generally divided into the analytic and probabilistic methods. The analytic method is used to decide the average or expected value (Billinton and Allan, 1996) and the probabilistic methods can be applied to decide the probability distribution of its impact (Billinton and Allan, 1983; Billinton and Li, 1994). The average values of each load point or feeder can be used to compare the magnitude of potential risk. However, the probability distributions are very important because the planners are generally required the most severe case.

2.3 Proposed Reliability Evaluation Methodologies of Momentary Interruptions

Reliability Indices of Momentary Interruptions

In this paper, two basic parameters for reliability evaluation of momentary interruptions are proposed. One is the average temporary failure rate, λ_M. The λ_M for a load point i is

$$\lambda_{Mi} = \sum_{j\in M(i)} \lambda_{Mj} \quad f/yr, \tag{1}$$

where λ_{Mj} denotes the momentary failure rate of a section j and $j \in M(i)$ means the all sections due to occur a momentary interruption for a load point i. The other is the duration of momentary interruption. As mentioned in Section 2.1, it is directly related to the reclosing dead-time and is defined as following equation.

$$t_{Mi} = Max(t_{r_1}, t_{r_2}, t_{r_3}, \ldots, t_{r_n}). \tag{2}$$

Here, t_{Mi} denotes the duration of momentary interruption and t_{r_n} is the nth reclosing dead-time due to a protective device (circuit breaker or recloser). As the case of sustained interruptions, the additional reliability indices of momentary interruptions are existed. The momentary average interruption frequency index (MAIFI) and the momentary average interruption event frequency index ($MAIFI_E$) are defined in the IEEE Std. 1366 (1998).

Analytic and Probabilistic Reliability Evaluation Method of Momentary Interruptions

The analytical reliability evaluations of momentary interruptions are used to decide the potential risk of momentary interruption using the average momentary failure rate(λ_M). The typical process of analytical reliability evaluation method of momentary interruptions summarizes as follows.

Step 1) Surveys the data of system topology: The line lengths and protective device types in sample system should be collected and the average momentary failure rates of each component are calculated.
Step 2) Calculate the reliability parameters of each load point: The average temporary failure rate of each load point is calculated. The operation schemes of system components and the types and characteristics should be also considered.
Step 3) Calculate the system reliability indices: MAIFI and $MAIFI_E$ are

$$\begin{aligned} MAIFI &= \frac{\sum_{i=1}^{N_{LP}} N_{Mi} NC_i}{\sum_{i=1}^{N_{LP}} NC_i} \\ &= \frac{\sum_{i=1}^{N_{LP}} \left(\sum_{k=1}^{N_r} (\lambda_{Mi} \times P_{r_k} \times k)\right) \times NC_i}{\sum_{i=1}^{N_{LP}} NC_i} \; int/cus \cdot yr \end{aligned} \quad (3)$$

$$\begin{aligned} MAIFI_E &= \frac{\sum_{i=1}^{N_{LP}} N_{MEi} NC_i}{\sum_{i=1}^{N_{LP}} NC_i} \\ &= \frac{\sum_{i=1}^{N_{LP}} \lambda_{Mi} \times NC_i}{\sum_{i=1}^{N_{LP}} NC_i} \; int/cus \cdot yr \end{aligned} \quad (4)$$

where N_{Mi} and λ_{Mi} are the number of momentary interruptions and momentary failure rate for load point i, respectively. P_{r_k} denotes the probability of k^{th} reclosing successful ratio and N_r is the number of reclosing attempts.

The probabilistic reliability evaluation of momentary interruptions is used to decide the probability distribution of the potential risk of it. Time Sequential Monte Carlo method is used for the probabilistic reliability evaluation. This method is composed as following steps.

Step 1) Generates a random number for each element and convert it into the TTTF (time to temporary failure) using the probability distribution function of the element.
Step 2) Determines the section with minimum TTTF.
Step 3) For the section with minimum TTTF, generates a random number and convert this number into the reclosing scheme (reclosing success (1^{st}, 2^{nd}, …) or failure)
Step 4) Records the temporary failure and the temporary outage time (reclosing dead time) of a load point that is affected with the failed section.
Step 5) Repeats Step 4 for all load points
Step 6) Generates a new random number for the repaired section and convert it into a new TTTF, and return to Step 2 if the simulation time is less than one year, otherwise, go to Step 7.
Step 7) Records the number and duration of momentary interruptions for all load points that are affected by the failed sections for a year.
Step 8) Calculate the system indices and record these system indices for a year.
Step 9) If the total simulation time is less than the specified simulation years, go to Step 2, otherwise, go to Step 10.
Step 10) Calculates the average number and duration of momentary interruptions for all load points.
Step 11) Calculate the average values of system indices.

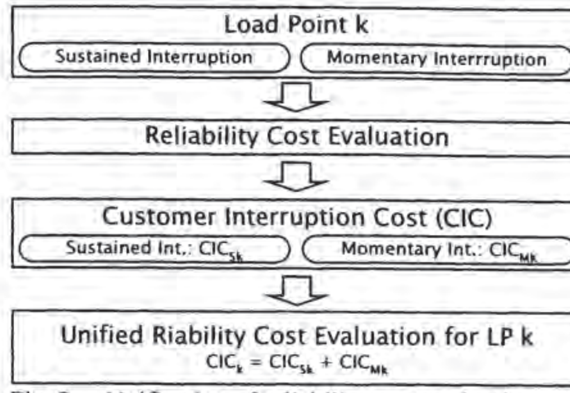


Fig. 2. Unification of reliability cost evaluation

3. RELIABILITY COST EVALUATION CONSIDERING THE MOMENTARY INTERRUPTION OF DISTRIBUTION SYSTEMS

In order to reflect the severity or significance of integrated system damages due to the sustained and momentary interruptions, the unified reliability evaluation method are proposed. The concept of unified reliability evaluation in distribution system is illustrated in Fig. 2. As shown in Fig. 2, the evaluation element are integrated into the customer interruption cost (CIC) for each sustained and momentary interruption.

One convenient way to display customer interruption costs is in the form of sector customer damage functions (SCDF). The SCDF is the function of interruption duration and cost for each customer type (Billinton, 2001). Therefore, the interruption cost for any duration can be calculated using the SCDF. The unified reliability cost evaluation is also proposed the analytic and probabilistic methodologies.

3.1 Proposed Analytic Method of Unified Reliability Cost Evaluation

The basic procedures used in the analytic reliability cost evaluation method can be summarized in the following steps:

Step 1) Finds the average permanent failure rate λ_{Sj}, the average temporary failure rate λ_{Mj}, the average outage time r_j, and the average switching time S_j for a failed section j. The line length and protective device type in sample system should be collected.

Step 2) Finds the permanent failure rate λ_{Sij}, the temporary failure rate λ_{Mij}, and the outage duration r_{Sij} for a load point i due to a failure section j.

Step 3) Determines the per unit (kW) interruption cost C_{Sij} and C_{Mij} for the sustained and momentary interruptions, respectively. Using the SCDF, $f(x)$, it is calculated to the interruption cost due to the each duration is calculated as following equations.

$$C_{Sij} = f(r_{Sij}). \tag{5}$$

$$C_{Mij} = f(\sum_{k=1}^{N_r} \lambda_{Mij} \times P_{r_k} \times t_{r_k}). \tag{6}$$

Step 4) Evaluates the expected interruption cost of the load point i caused by failure of section j is

$$ECOST_{ij} = L_i(C_{Sij}\lambda_{Sij} + C_{Mij}\lambda_{Mij}), \tag{7}$$

where L_i is the average load (kW) of load point i.

Step 5) Repeats Step 1 to Step 4 for all sections. The total expected cost of the load point i is calculated as following equation.

$$ECOST_i = \sum_{j=1}^{N_j} ECOST_{ij}. \tag{8}$$

Here, N_j is the total number of sections in the system.

Step 6) Evaluate the total system expected cost as following equation.

$$ECOST = \sum_{i=1}^{N_{LP}} ECOST_i, \tag{9}$$

3.2 Proposed Probabilistic Method of Unified Reliability Cost Evaluation

The basic procedures used in the probabilistic reliability cost evaluation method can be summarized in the following steps.

Step 1) Generates a random number for each element in the system and convert it into the TTF and TTTF corresponding the element failure probability distribution.

Step 2) Determine the elements with minimum TTF and TTTF

Step 3) Generate two random numbers for the element with minimum TTF and convert them into TTR and TTS

Step 4) Generates a random number for the element with minimum TTTF and convert it into reclosing scheme (reclosing success (1^{st}, 2^{nd}, ...) or failure).

Step 5) Find the load points that are affected by the failed sections.

Step 6) Finds the permanent failure rate, the temporary failure rate and the durations of permanent and temporary failure for the load points due to the failure sections. If the restoration time caused by the new permanent failure event is overlapped by the old restoration time caused by the old failure event, the overlapping time is deducted.

Step 7) Using the permanent and temporary failure duration (t_{Mi}), determines the per unit cost C_{Sij} and C_{Mij} for the sustained and momentary interruptions.

Step 8) Evaluates the interruption cost $COST_{ij}$ of the load point i caused by failure of section j as following equation.

$$COST_{ij} = L_i(C_{Sij} + C_{Mij}), \tag{10}$$

Step 9) Generate two new random numbers for the repaired sections and convert it into a new TTF and TTTF, and return to Step 2 if the simulation time is less than one year, otherwise, go to Step 10.

Step 10) Record the interruption costs of sustained and momentary interruptions for all load points that are affected by the failed sections for a year.

Step 11) If the total simulation time is less than the specified simulation time, go to Step 12, otherwise, go to Step 13.

Step 12) Generate two new random numbers for the repaired elements and convert it into the new TTF and TTTF, and go to Step 2.

Step 13) Calculates the interruption cost of a load point for the total simulation years as following equation.

$$COST_i = \sum_{s=1}^{N_S}(\sum_{j=1}^{N_j} COST_{ij}). \tag{11}$$

Here, where N_S is the total number of failure events in the specified simulation period.

Step 14) The expected interruption cost of a load point for a year is

$$ECOST_i = \frac{COST_i}{TST}, \tag{12}$$

where TST is the total specified simulation time in years.

Step 15) Calculates the system $ECOST$ using Eq. (9)

4. CASE STUDIES

This section examines case studies on the proposed reliability evaluation methodologies. We conducted case studies using the model distribution system, RBTS distribution bus 2. We further adjust the composition of systems, and the type and location of protective devices to match the practical systems in Korea. The whole result is simulated by analytic and probabilistic method. Time Sequential Monte Carlo simulation method is used for the probabilistic

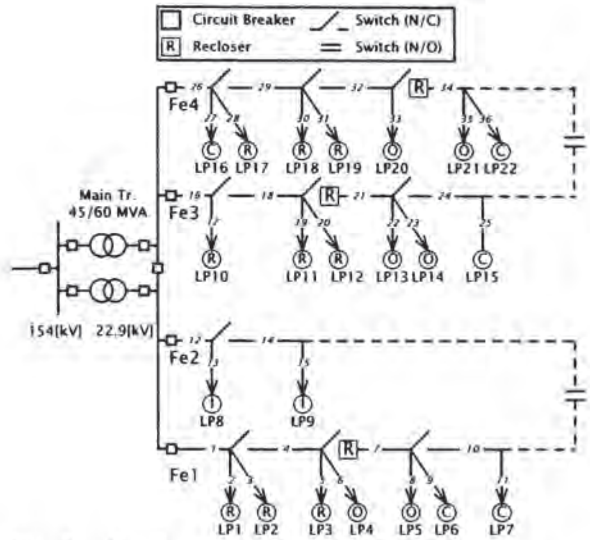


Fig. 3. Configuration of modified RBTS system

Table 1 Reliability data for case studies

Components \ Fault type	Sustained		Momentary
	Failure rate/yr	Repair time/fr	Failure rate/yr
Line	0.034/km	0.5 hr	0.160/km
Circuit Breaker	0.002	3 hr	-
Recloser	0.002	3 hr	-
Switch	0.002	3 hr	-

Table 2 Customer interruption cost for case study and customer load level

Customer Interruption Cost (US$/kW)

Customer Types	Momentary Interruption		Sustained Interruption				
	0.5 sec	15 sec	1 min	20 min	1 hr	4 hr	8 hr
Residential	0.00068	0.0052	0.021	0.093	0.482	4.914	15.69
Commercial	0.02932	0.2198	0.881	2.969	8.552	31.32	83.01
Office Building	0.15912	1.1923	4.778	9.878	21.06	68.83	119.2
Industrial	0.05412	0.4055	1.625	3.868	9.085	25.16	55.81

Customer Load Level

Load Points	Customer Type	Average Load Level per Load Point (MW)	Number of Customer per Load Point
1-3, 10, 11	Residential	0.535	210
12, 17-19	Residential	0.450	210
8	Industrial	1.000	1
9	Industrial	1.150	1
4, 5, 13, 14, 20, 21	Office building	0.566	1
6, 7, 15, 16, 22	Commercial	0.454	12

Table 3. Comparison of SAIFI and SAIDI

Feeders	SAIFI (int/yr·cus)		SAIDI (hr/yr·cus)	
	Analytic Method	Monte Carlo Method	Analytic Method	Monte Carlo Method
Feeder 1	0.4558	0.4567	0.1295	0.1291
Feeder 2	0.3039	0.3050	0.0917	0.0925
Feeder 3	0.3886	0.3891	0.1216	0.1217
Feeder 4	0.4501	0.4477	0.1282	0.1304

Table 4. Comparison of MAIFI and $MAIFI_E$

Feeders	MAIFI (int/yr·cus)		$MAIFI_E$ (int/yr·cus)	
	Analytic Method	Monte Carlo Method	Analytic Method	Monte Carlo Method
Feeder 1	2.5079	2.5004	2.1316	2.1275
Feeder 2	1.6638	1.6642	1.4160	1.4159
Feeder 3	2.1297	2.1345	1.8125	1.8161
Feeder 4	2.4697	2.4666	2.1019	2.0986

approach. The exponential type is selected for the random number generator of the frequency and duration of faults. The total simulation time is determined by 50,000 years.

4.1 Data for Case Studies

Test System and Historical Reliability Data

We use the modified RBTS (Roy Billinton Test System) distribution bus #2 (Allan et al., 1991) for the simulations. The modified parts of the original model follow the general operation principles in KEPCO (Yun et al., 2000). This system consists of two main transformers (2 bank), four overhead (or underground cable) 22.9kV feeders, and serves 22 load points (LP1-LP22). The test system topology is shown in Fig. 3.

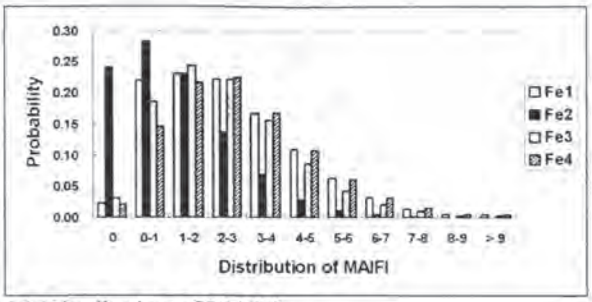
The historical reliability data used in the case studies are shown in Table 1. The annual distribution system reliability data of KEPCO in the Kyeong-in region of Korea is used.

Data for Calculation of Customer Interruption Costs

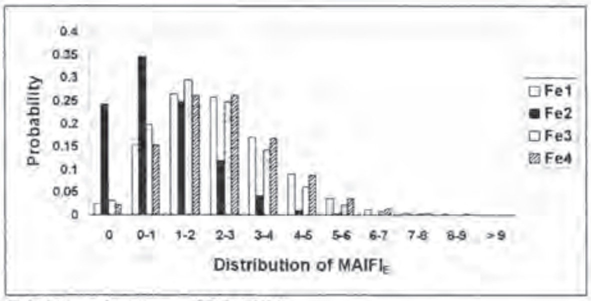
The data related to the customer interruption costs for sustained and momentary interruptions and customer load level are shown in Table 2. The customer interruption costs in Table 2 are calculated from the SCDF survey of Canada (Billinton and Allan, 1996). The durations of momentary interruption in Table 2 is shown in 0.5sec and 15sec. It is the reclosing dead-time of protective devices of distribution systems in Korea.

4.2 Results of Case Studies

The results of sustained interruptions for case studies summarize SAIFI and SAIDI. Table 3 shows the comparison of analytic method and Monte Carlo simulations of SAIFI and SAIDI for each feeder. In feeder 1, 3 and 4, SAIFI and SAIDI are higher than that in the feeder 2 because the line lengths are longer than the feeder 2. The results of momentary interruptions for case studies summarize MAIFI and $MAIFI_E$. To verifying the validation of simulation, we compare the results of analytical method with the average results of Monte Carlo method. The values of MAIFI and $MAIFI_E$ for all feeders are shown in Table 4. As shown in Table 4, the trend of simulation



(a) Distribution of MAIFI



(b) Distribution of $MAIFI_E$

Fig. 4. Probability distribution of momentary interruptions

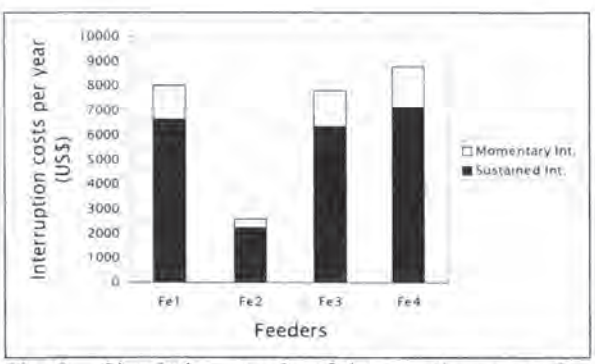
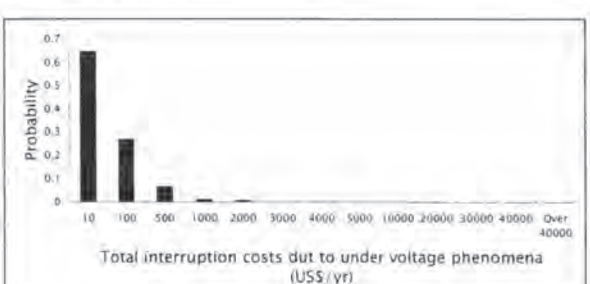
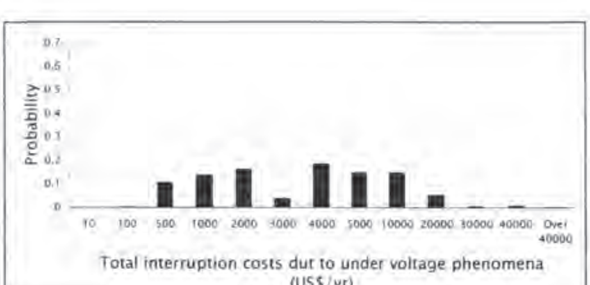


Fig. 5. Simulation result of interruption cost for each feeder



(a) Load point 1



(b) Load point 21

Fig. 6. Probability distribution of interruption cost for load point 1 and load point 21

results for momentary interruptions and momentary interruption events is similar to the sustained interruptions one. Fig. 4 shows the probability distribution of each momentary interruption and momentary interruption events for each feeder. The total average interruption costs of each load point are shown in Fig. 5. The probability distributions of total interruption costs for LP1 and LP21 are shown in Fig. 6.

CONCLUSION

In this paper, a novel approach to assess the reliability of distribution system is proposed. The proposed method is considered to the momentary interruption and the sustained interruption that is the element of conventional reliability analysis. An analytic and probabilistic reliability evaluation method for momentary interruptions are proposed and the unified method of reliability cost evaluation is proposed and it is integrated to the costs of sustained and momentary interruption. Through the case study, we verify that the proposed evaluation methodologies can be used to evaluate the actual reliability of distribution systems.

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