Reliability Assessment of Metropolitan Electricity Authority's Distribution System with Optimal Restoration Strategies

P. Boonpan and S. Sirisumrannukul

Abstract— *Reliability assessment of a complex radial distribution system with optimal restoration strategies is presented in this paper. A typical distribution system is often designed and constructed as a radial feeder system and can be represented by a tree-like diagram. For any single outage events in the system, a fault-traversal technique, consisting of parent-search and breadth-first search and offspring search, are used to find affected areas classified by types of switch, switching actions for fault isolation and system configuration with the objective to minimize the customer interruption cost. The associated interruption duration of each load point can be determined from multi-state Markov models classified as series, parallel and series-parallel. The developed reliability model is tested with a distribution system of MEA consisting of 35 load points, 28 manual switches, 12 manual tie-switches and 2 auto tie-switches. The study results indicate that the methodology can identify the restoration time of each affected area and locations that are most vulnerable to a single failure in the system. Therefore, it can be served as a practical guideline in decision making for operation and planning for reliability improvement in MEA.*

Keywords— **Distribution system reliability, Disconnecting switch, Fault-traversal search, Optimal restoration time.**

1. INTRODUCTION

Reliability is an important measure of the adequacy of electric power supply. It is statistically known from most utilities that distribution system reliability makes the greatest individual contribution to the unavailability of supply to a customer [1]. This emphasizes the need to improve the system reliability by a number of alternatives for network reinforcements and decision making for supply restoration. Performance of distribution system is quantitatively evaluated in terms of customer-oriented reliability indices, such as system average interruption duration index (SAIDI), average service availability index (ASAI) or expected energy not served (EENS). One of the key system parameters that greatly affects these reliability indices is the restoration time that involves, for example, fault isolation, switching and reparing actions. Practically speaking, keeping restoration time as low as possible offers an effective means to minimize economical impacts from electricity interruption of customers.

Supply restoration becomes crucial for reliability improvement. In general, speed of restoration process for each individual load depends on system configuration, the types and locations of switches and alternative supplies, decision making for restoration, and available manpower [2]. Most distribution systems either have only manually operated devices (no automated devices) or are partially automated with a combination of manual and automated devices. Fast restoration can be achieved by automated devices, which can be remotely activated (minute or less) using a high-speed communication system and line sensors after a fault has occurred. Remote monitoring and control equipment can isolate faulted sections from healthy sections through alternative routes, thus having a significant effect on the system reliability.

The main emphasis of this paper is paid toward reliability assessment in an distribution system with optimal restoration strategies by the use of a fault-traversal technique [3]. The distribution system is viewed as tree-like diagram. Contingency enumeration technique is used to system states. Parent search, off-spring search and breadth-first search techniques are used to identify the consequence of the faulted component and affected areas. Service restoration strategies are modelled by sequential, parallel and hybrid switching Markov models. The restoration is prioritized by customer reliability described in forms of customer interruption cost, multistate-stage service restoration series, parallel and hybrid, types of switch in the system and restoration time described in terms of traffic condition. The methodology is demonstrated by a distribution system of Metropolitan Electricity Authority(MEA).

2. DETERMINATION OF AFFECTED AREA AND RESTORATION SUB-AREAS

Any single failure in a radially-operated distribution system, where there are a series of lines, cables, disconnecting switches, busbars, etc., can cause all load points to be disconnected. The restoration time for each of the load points in a complex system configuration and a variety of components may be difficult to be identified due to the required knowledge of network topology,

P. Boonpan was financially supported by Metropolitan Electricity Authority.

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protection scheme and types of component. A fault-traversal technique is a search that can be used to calculate the restoration time of a load point. In this technique, the distribution system is viewed as a tree on which there are a number of devices are installed between nodes such as switches, breakers, feeders, fuses and transformers. The technique consists of parent-search and breadth-first search and offspring search.

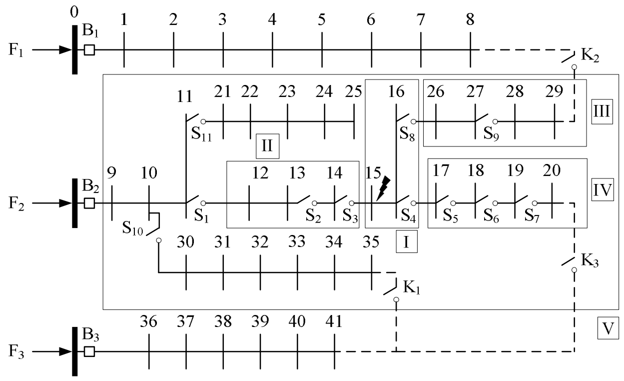

Fig.1. Sample Radial System

Figure 1 shows a sample distribution system for illustration of the fault-traversal technique. In the figure, S1-S11 are normally closed switches and K1-K9 are normally open switches. Of the switches, only S1, S4 and K3 are automated switches and the rest are manual switches. For a fault between buses 15 and 16, a search begins at the parent node of the failed component. The types of component connected to the parent node will be searched. The search stops when the first upstream circuit breaker B2 is found. Therefore, the affected load points interrupted by breaker B2 include load points 9-35.

After the affected load points have been identified, the associated affected areas will be divided into subareas by the breadth-first search technique. In the breadth-first technique, the first switch is identified by the failed component in each direction. In fact, a first switch is also a fault isolating switch. The vicinity of upstream and downstream switches that isolate the fault is classified as upstream and downstream areas. The area covered by the switches is restored after the failed component has been repaired (Area I of Figure 1). The upstream area, located between the upstream switches and the circuit breaker, can be restored by the main supply while the downstream area, located between the downstream switches and tie switches, can be restored through an alternative supply.

For the upstream area, the parent search technique is used to find the first automated switch. For the downstream area, the offspring search technique is employed to find a first automated switch and tie switches. After a fault occurs, the system can be classified as follows:

Class A: There is no affected area by the fault.

Class B: Upstream areas are restored by automated switches

Class C: Upstream areas are restored by manual switches

Class D: Downstream areas are restored by automated switches

Class E: Downstream areas are restored by manual switches

Class F: Areas are restored after the fault section has been replaced or repaired.

The upstream area between the first automated switch and the CB is in class B (area V excluding areas I, II, III and IV of Figure 1). If the first switch is manually operated, the area between the first automated switch and first switch is classified as class C (area II of Figure 1). If the first automated switch is also the first switch, no area in the system belongs to class C. If no automated switch has been found, no area in the system belongs to class B. The downstream area between the first automated switch and an automated tie switch is classified as class D (area IV of Figure 1). If the first switch is manually operated, that area is classified as class E (area III of Figure 1). If the first switch is also the first automated switch, the area from the first switch downwards belongs to class D. If no automated switch has been found, the area from the first switch is considered as class E. If a tie-switch has been found and is manually operated, the area belongs to class E. If no tie-switch has been found, the area belongs to class F. Each of the subareas classified by the fault shown in Figure 1 will be used to evaluate its restoration time.

3. PROCESSES/MODELS OF RESTORATION

Steps of restoration consist of fault isolation by the circuit breaker, determination affected area, decision making process, switching actions and repair process. Some affected load points can be restored by automated switches, others can by manual switches, and the others need to wait until the faulted components have been repaired or replaced [4].

Restoration time for customers in each area is used in switching/repair models and distribution system reliability models. In general, a two-stage Markov model for a system component is shown in Figure 2, where a switching action is not taken into account. A simple switching action is included in Figure 3 [2].

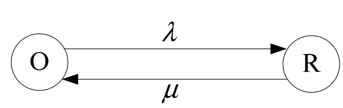

Fig.2. Two Stage Repairing Model

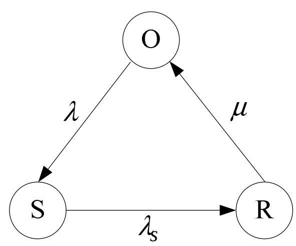

Fig.3. Three State Switching and Repairing Model

where

O	=	operating state
S	=	switching state
R	=	repairing state
λ	=	component failure rate
μ	=	repair/ replacement rate
λ_s	=	switching rate

Restoration time for each load point depends on fault location, type of switch and the number of switches, available manpower. The number of switching action depends on network configuration and fault location. The restoration procedure can be classified as:

A. Fault Isolation Process

Any failure on in a main feeder in the system will cause the circuit breaker to operate to isolate the fault. This operation leaves the system into healthy areas and affected areas. The isolation time (T_i) for this process is so short that it can be neglected.

B. Decision-making Process

After a fault has been cleared, the relevant fault information data are collected and analyzed to restore the supply to customers such as fault type, fault location, affected areas and number and location of switches. The restoration sequence is based on available resources and customer requirement. The duration for decision making (T_d) depends upon the complexity of failure.

C. Switching Actions

A switching action generally begins with feeder inspection to identify the failed component. Once the failed component is found, it will be isolated from the system. Switching sequence depends on types of switch, number of switches, crew resource, switching orders (i.e., parallel, sequential or combination of both). Hence, different fault locations give different switching actions.

For a sequential switching, the total switching time (T_S^s) is the summation of switching times of all switches involved.

$$T_S^s = \sum_{k\in N} T_{Sk} \tag{1}$$

where T_{Sk} is the switching time for switch k and N is the set of switches are involved in switching actions.

For parallel switching, total switching time (T_S^p) is the longest one of all the switching times.

$$T_S^p = \max(T_{s_1},\ T_{s_2},\ ....,\ T_{s_N}) \tag{2}$$

For hybrid switching, the total switching (T_S^h) time is

$$T_S^h = T_S^s + T_S^p \tag{3}$$

D. Repairing/replacing process

The time spent on this process depends on the type of the fail component and the available repairing resource. Different failed components may require different repair time (T_r).

E. Restoration models

Three restoration models are considered: series, parallel and hybrid switching. A sequential switching model is shown in Figure 4 [2].

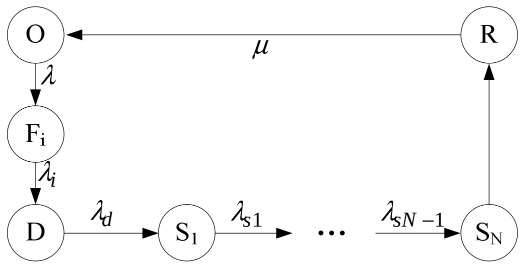

Fig.4. Multi-state Model with Sequential Switching

This type of switching action is suitable for manual operation or limited manpower resource. In general, the sum of restoration time for load point j after a failure at location h for sequential switching is

$$T_{hj} = T_{hi} + T_{hd} + T_{hr} + \sum_{k\in N_{hj}} T_{Sk} \tag{4}$$

where N_{hj} is the number of switches required for restoration of load point j.

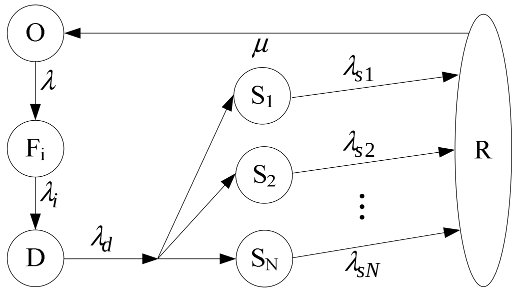

Fig.5. Multi-state Model with Parallel Switching

Figure 5 [2] shows a parallel switching. In a practical distribution system, the parallel model is usually implemented to the areas with automated switches or sufficient manpower. For an area with manual switches, parallel restoration means that members of the utility staff need to be dispatched at the same time. Therefore, the restoration time is calculated from

$$T_{hj} = T_{hi} + T_{hd} + T_{hr} + \max(T_{s_1},\ T_{s_2},\ ....,\ T_{s_N}) \tag{5}$$

For hybrid operation between series and parallel as shown in Figure 6, the switching time is

$$T_{hj} = T_{hi} + T_{hd} + T_{hr} + \sum_{k \in N_{hj}} T_{Sk} + \max(T_{s_1}, T_{s_2}, \ldots, T_{s_N}) \quad (6)$$

Note that muti-state models include a repairing/replacing process. Therefore, for a load where such a process is not involved, T_{hr} will not be included in Eq. 6.

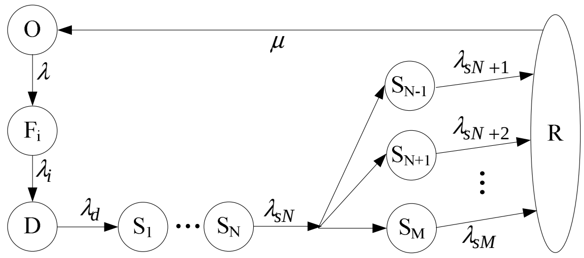

Fig.6. Multi-state Model with Sequential/parallel Switching

4. LOAD POINT AND SYSTEM RELIABILITY INDICES

A. *Load Point Indices*

Reliability indices for load point j is obtained from

$$\lambda_j = \sum_{i \in M} \lambda_i \quad (7)$$

$$U_j = \sum_{i \in M} \lambda_i T_{ji} \quad (8)$$

$$r_j = \frac{U_j}{\lambda_j} \quad (9)$$

where

λ_i = failure rate of component i
λ_j = failure rate of load point j
M = number of components which affect load point j
U_j = annual outage time of load point j
T_{ji} = restoration time of load point j after the failure of component i
r_j = average outage time of load point j

B. *Customer-Oriented Indices*

System average interruption frequency index, SAIFI:

$$SAIFI = \frac{\sum \lambda_j N_j}{\sum N_j} \quad (10)$$

System average interruption duration index, SAIDI:

$$SAIDI = \frac{\sum \lambda_j U_j}{\sum U_j} \quad (11)$$

Average service availability index, ASAI:

$$ASAI = \frac{\sum N_j \times 8760 - \sum U_j \times N_j}{\sum N_j \times 8760} \quad (12)$$

Expected energy not supplied, EENS:

$$EENS = \sum L_j U_j \quad (13)$$

where

N_j = number of customer of load point j

5. INTERRUPTION COST CALCULATION

One approach to assess reliability worth is to relate it to the costs or losses incurred by utility customers due to electric supply interruption [5]. A common way to analyze reliability worth is to determine customer costs due to electric power supply interruptions. One convenient way is an interpretation of customer interruption costs in terms of customer damage functions (CDF).

The CDF can be determined for given customer types and aggregated to make sector customer damage functions (SCDF), which reflect economic consequences of supply interruption as a function of cost in different groups of customers. The SCDF is normally obtained from customer surveys, the data of which are complied according to major sectors or industrial categories. With the SCDF, outage duration and average disconnected load, customer interruption cost can be evaluated.

The sector customer damage function (SCDF) of each group of customers is used to calculate customer interruption cost at each load point. The expected interruption cost used to identify the priority of restoration calculated from Eq. (7).

$$ECOST = \sum_{j \in U} L_j \times CDF_j(d_j) \quad (14)$$

where

L_j = average load connected to load point j
$CDF_j(d_j)$ = interruption cost of load point j for outage duration d_j

6. DETERMINATION OF OPTIMAL RESTORATION TIME

Three main schemes of restoration are considered in this paper:

Scheme 1 : Subareas that can be restored only by automated switched (classes B and D). These areas will have the first priority for parallel operation.

Scheme 2 : Subareas that can be restored by automated and manual switches (classes C and E), the interruption costs for each area will be first calculated. The subarea with the highest interruption cost is given the first priority, followed by those with lower interruption costs.

Scheme 3 : Subareas in class F have the last priority for restoration, although the customers in these subareas may have the highest interruption cost.

From the system shown in Figure 1, subarea V is first restored because it belongs to class B. The restoration is achieved by opening switch S1 and breaker B2 is reclosed. Let us suppose that the interruption cost of subarea IV is highest, followed by subareas II and III, therefore, the optimal restoration sequence is V→IV→II→III→I [2].

The techniques used to determine the optimal restoration time and evaluate load points and distribution system reliability indices are as follows:

Step 1: Input network and component data.

Step 2: Consider failure of component i .

Step 3: Determine the affected area and load points using the parent search and offspring search techniques.

Step 4: Determine the sub-areas and the concerned switches using parent search, breadth-first search and off-spring search techniques.

Step 5: Calculate the expected interruption cost using Eq. (14).

Step 6: Determine the optimal switching sequence for the service restoration.

Step 7: Calculate the restoration times for load points in each subarea using the multi-state models.

Step 8: Calculate load point index $U_{ji} = \lambda_i T_{ji}$.

Step 9: Go to step 10 if all components have been considered; otherwise, go to step 2.

Step 10: Calculate outage time r_j for each load point j

Step 11: Calculate customer-oriented reliability indices using Eqs. (10)-(13).

7. TEST SYSTEM AND RESULT

The test system is modified from an existing Phatthanakarn radial distribution system of MEA. The distribution system with 4 feeders, designated as PTN411, PTN412, PTN421, PTN422, and 35 load points is analyzed to determine the impact of restoration on reliability indices. There are 28 manual switches, 12 manual tie-switches and 2 auto tie-switches. The system configuration is shown in Figure A1 in Appendix. The data of the system are provided in Table A1. According to MEA customer database, the classes of customer presented in this paper are categorized as large users, medium users, and small users. Table 1 shows the sector customer damage function as of the year 1996 [6] for the calculation of ECOST. The interruption cost per kW in the table is adjusted with an average annual inflation rate of 4%.

Two cases are of interest. The first case is simulated with parallel switching operation or in other words, no crew constraint is imposed in this case. Therefore, only parallel switching time is modeled in case 1. The second case takes into account sequential switching sequence.

Table 1. Sector Interruption Cost

User Class	*Interruption Cost (Baht/kW)/min*					
	5	10	30	60	120	240
Small User	0.58	1.78	6.58	23.54	74.20	217.89
Medium User	20.06	25.34	75.76	99.54	142.43	213.15
Large User	22.43	25.31	47.14	64.06	77.68	105.33

Figures 7 and 8 show the EENS and ECOST of cases 1 and 2. It is seen that the EENS and ECOST have a similar trend. That is to say, load points with high average MW consumption and constrained by steps of restoration will have high EENS and ECOST. Both figures suggest that it is quite optimistic for reliability point of view when sequential restoration as a result of the crew constraint is ignored. A difference of almost 4 million baht is introduced in case 2. Load point 14 in both cases sees the highest EENS mainly because the largest average load, 16,872.5 kW, is connected to this load point.

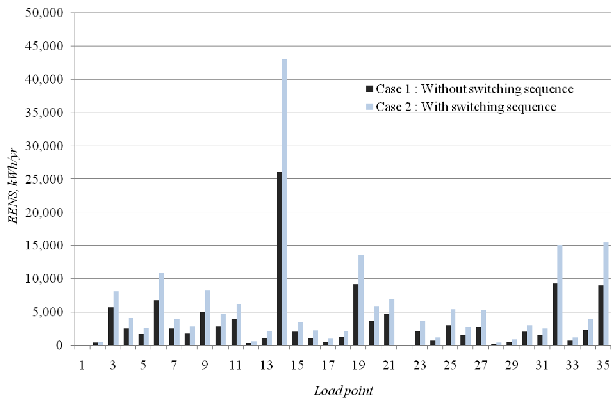

Fig.7. EENS the Load Points for Cases 1 and 2

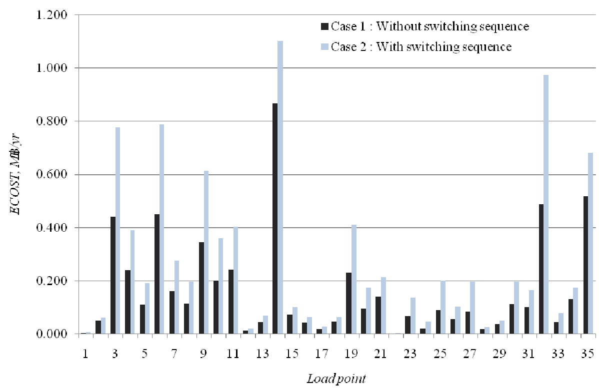

Fig.8. ECOST of Load Points for Cases 1 and 2

Table 2. Feeder and System Reliability Indices of Case 1

Feeder	SAIFI (f/yr)	SAIDI (h/yr)	ASAI	EENS (MWh/yr)	ECOST (B/yr)
PTN411	0.587	0.900	0.99990	33.23	2,356,736.2
PTN412	1.510	1.736	0.99980	49.99	1,570,672.6
PTN421	1.240	2.225	0.99975	10.09	319,121.8
PTN422	0.771	1.042	0.99988	25.67	1,450,166.8
PTN	0.946	1.254	0.99986	118.98	5,696,697.4

Table 3. Feeder and System Reliability Indices of Case 2

Feeder	SAIFI (f/yr)	SAIDI (h/yr)	ASAI	EENS (MWh/yr)	ECOST (B/yr)
PTN411	0.587	1.419	0.99984	52.39	4,056,500.38
PTN412	1.510	2.824	0.99968	81.31	2,236,118.51
PTN421	1.240	4.080	0.99953	18.50	678,805.57
PTN422	0.771	1.730	0.99980	42.61	2,335,923.15
PTN	0.946	2.054	0.99977	194.82	9,307,347.61

Table 4. Feeder and System Reliability Indices for Case 2.1 (Adding an Manual Switch between Buses 18 and 20)

Feeder	SAIFI (f/yr)	SAIDI (h/yr)	ASAI	EENS (MWh/yr)	ECOST (B/yr)
PTN411	0.587	1.419	0.99984	52.39	4,056,500.38
PTN412	1.510	2.559	0.99971	73.69	2,123,012.09
PTN421	1.240	4.080	0.99953	18.50	678,805.57
PTN422	0.771	1.730	0.99980	42.61	2,335,923.15
PTN	0.946	1.973	0.99977	187.19	9,194,241.19

Table 5. Feeder and System Reliability Indices for Case 2.2 (Adding an Automated Switch between Buses 18 and 20)

Feeder	SAIFI (f/yr)	SAIDI (h/yr)	ASAI	EENS (MWh/yr)	ECOST (B/yr)
PTN411	0.587	1.419	0.99984	52.39	4,056,500.38
PTN412	1.510	1.892	0.99978	54.48	1,752,688.90
PTN421	1.240	4.080	0.99953	18.50	678,805.57
PTN422	0.771	1.730	0.99980	42.61	2,335,923.15
PTN	0.946	1.771	0.99980	167.98	8,823,918.00

Tables 2 and 3 give feeder and system reliability indices for the individual feeders. As far as the interruption cost of each feeder is concerned, feeder PTN411 is ranked on top of PTN412, PTN422, and PTN421, suggesting that to minimize the total customer outage cost, the feeders should be restored in this order. However, for the current practice in MEA, feeder PTN 412 has been given priority on switching action for the reason that there are special customers whose interruption costs are not able to be quantified using the cost data in Table 1, such as embassies, hospital. For this reason, the optimal sequence may not be implemented in actual systems.

The reliability of feeder PTN 412 (see Figure A1) is poor because, as expected, whenever a fault occurs between buses 17 and 18, or buses 18 and 20, the system operators have to isolate the fault by 4 switching actions. Fault locations between these buses are most vulnerable to a single failure in this feeder. After it has been cleared, these three load points are classified as class F and therefore remain disconnected until the failed component has been repaired. The total time to recover the load points located between these buses is about 6 hours, 2 hours of which are switching time and 4 hours repair time The reliability of these load points can be improved by adding a manually operated disconnecting switch between buses 18 and 20 (case 2.1), or adding an automated disconnecting switch between buses 18 and 20 (case 2.2), or replacing the disconnecting switch at location PTN412SG427-1H (tie-switch) by an automatic load break switch (case 2.3).

The extension of case 2 for the alternative network reinforcements and their effects on customer reliability are shown in Tables 4, 5 and 6 respectively. The table shows how the customer interruption costs response with the modifications in the system, compared with those of case 2. Among the three alternatives, the customers on this feeder would prefer the improvement obtained from case 2.2 since the feeder can be quickly recovered by the added automated switch. About 500,000 baht could be saved from the interruption cost. From economic point of view, this cost is financially justified if the investment cost for the switch is in a region of, say, 200,000 baht; hence the payback period is within 3 years. Note that the switch replacement policy in case 2.3 is able to help only load points 16 and 17, which are nearest to normally open transfer point, while the other load points, particularly load point 14, on this feeder do not enjoy any benefit from the load transfer. To be precise, whether the switch is manually or automatically operated, load lost cannot be recovered for any failure between the busbar and bus 20.

To optimize the utility's expenditure and use of resources while supplying customers with reasonable reliability criteria, optimal placement of manual and automated sectionalizing switches should be judiciously determined to provide the balance between the utility's cost and the customers' outage cost [7].

Table 6. Feeder and System Reliability Indices for Case 2.3 (Replacing the Disconnecting Switch with an Automated Switch at PTN412SG427-1H)

Feeder	SAIFI (f/yr)	SAIDI (h/yr)	ASAI	EENS (MWh/yr)	ECOST (B/yr)
PTN411	0.587	1.419	0.99984	52.39	4,056,500.38
PTN412	1.510	2.756	0.99969	79.36	2,192,684.78
PTN421	1.240	4.080	0.99953	18.50	678,805.57
PTN422	0.771	1.730	0.99980	42.61	2,335,923.15
PTN	0.946	2.040	0.99977	192.87	9,263,913.88

8. CONCLUSION

This paper presents a reliability assessment of distribution system with optimal restoration time. Fault traversal technique has been applied to classify the area of the system into healthy subareas and affected subareas. Restoration time for each of the affected subareas is determined from multi-state models. The methodology is tested with a distribution system of MEA taking into account constraints of available man power, distance to the faulted component and customer interruption cost. The study results indicate that restoration sequences have a significant impact on the customer interruption cost.

MEA should prioritize areas to be restored in order to minimize the impact of the total customer outage cost for any failure events. However, it is not straightforward to implement the presented restoration procedure mainly because the outage cost of each of the areas was not available and its importance might have been overlooked. If the restoration procedure were to be implemented, it could be served as a practical guideline in decision making for operation and planning for reliability improvement in MEA.

The presented model can also include other practical constraints, for example, voltage drop, feeder capacity rating, and important load points. On the basis of the result from the case study, the system reliability can be improved by manual or automated switches. The reliability worth gaining from the improvement needs to be considered in conjunction with the additional investment cost for optimum balance between the utility and customers.

ACKNOWLEDGMENT

The authors would like to express their sincere thanks Power Control Department, Metropolitan Electricity Authority for the technical data used in the case study.

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APPENDIX

Table A1. Data of Modified Phatthanakarn Distribution System

Feeder Section	*From Bus*	*To Bus*	*Length (m)*	*Feeder Section*	*From Bus*	*To Bus*	*Length (m)*	*Load point*	*Average load (kW)*	*Customer No.*	*Load point*	*Average load (kW)*	*Customer No.*	*Component*	*Failure rate*	*Repair/ Replace Time (h)*	*Switching time*
1	0	1	30	24	24	25	3,600	1	95.625	29	19	3434	1,041	Feeder	0.1 f/km/yr	5	-
2	1	2	150	25	25	26	3,150	2	1275	386	20	1466.25	444	Transformer	0.01 f/yr	3	-
3	2	3	150	26	0	27	100	3	6158.25	1,866	21	1211.25	367	Fuse	-	1	-
4	3	4	1,500	27	27	28	100	4	2465	747	22	38.25	12	Switch			
5	4	5	1,700	28	28	29	450	5	1797.75	545	23	1032.75	313	- Manually	-	-	0.05 h/km
6	6	7	1,500	29	29	30	300	6	7450.25	2,258	24	297.5	90	- Automated	-	-	0 h
7	6	8	1,500	30	30	31	300	7	2669	809	25	1317.5	399	- Decision time	-	-	0.5 h
8	6	9	1,800	31	31	32	3,150	8	1891.25	573	26	573.75	174				
9	6	10	1,700	32	32	33	1,400	9	5690.75	1,724	27	1275	386				
10	6	11	1,300	33	33	34	2,200	10	3357.5	1,017	28	350.625	106				
11	6	12	1,200	34	34	35	1,000	11	4058.75	1,230	29	726.75	220				
12	6	13	2,200	35	34	36	3,300	12	325.125	99	30	1700	515				
13	0	14	50	36	0	37	30	13	1275	386	31	1712.75	519				
14	14	15	50	37	37	38	220	14	16872.5	5113	32	7012.5	2,125				
15	15	16	550	38	38	39	600	15	1678.75	509	33	850	258				
16	15	17	150	39	39	40	700	16	1041.25	316	34	2486.25	753				
17	17	18	400	40	40	41	1,100	17	446.25	135	35	9796.25	2,969				
18	18	19	700	41	38	42	100	18	1041.25	316							
19	18	20	600	42	42	43	1,150										
20	20	21	650	43	43	44	2,100										
21	21	22	700	44	44	45	900										
22	20	23	4,200	45	45	46	1,500										
23	23	24	200	46	45	47	1,400										

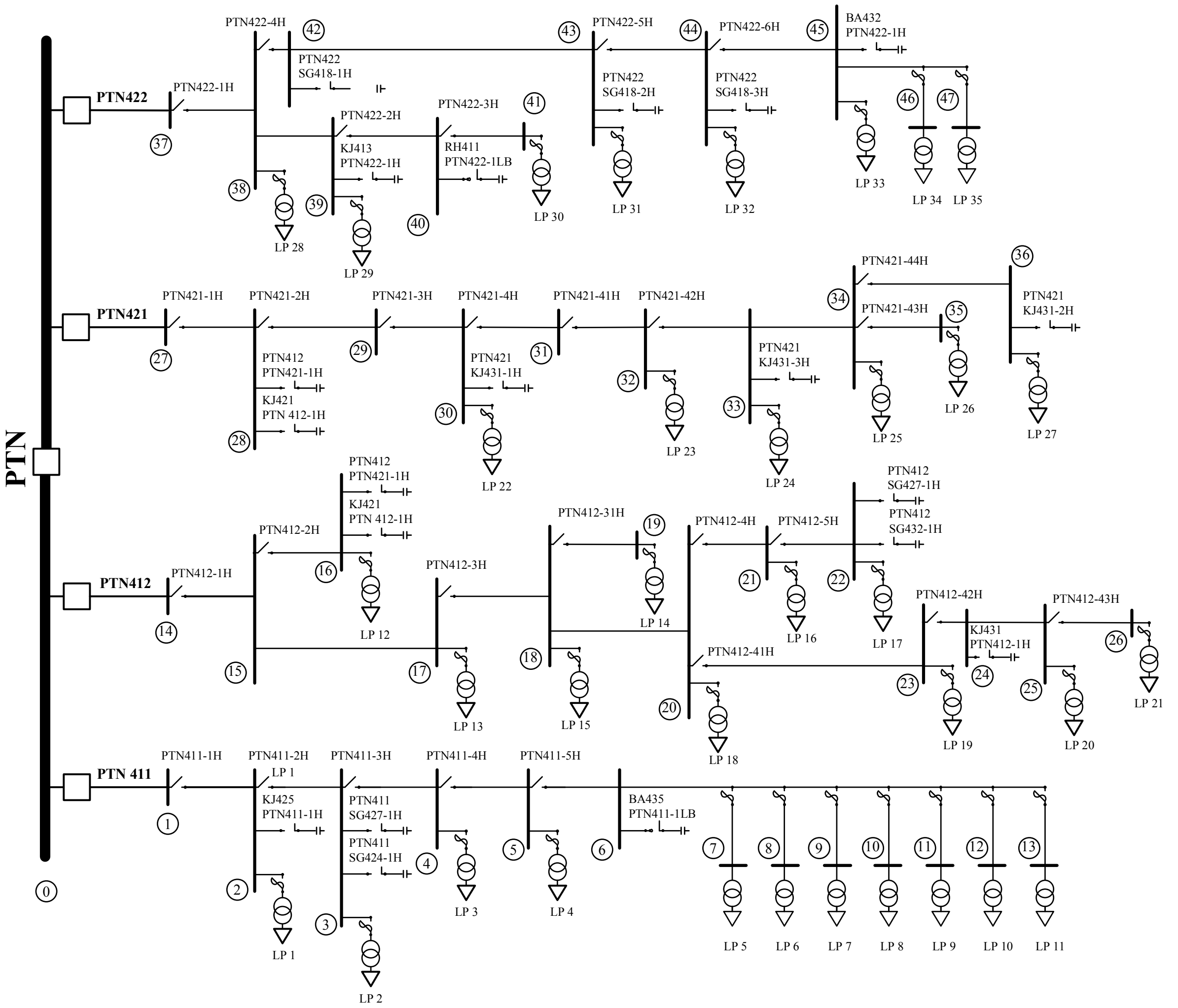

Fig. A1. Modified Phatthanakarn Distribution System