Optimal Placement of Sectionalizing Switches in Radial Distribution Systems by a Genetic Algorithm

K. Klinieam and S. Sirisumrannukul

Abstract— *Proper installation of sectionalizing switches in a distribution system can improve system reliability. Subjective placement of sectionalizing switches could lead to underinvestment which, although less reliable, can produce unacceptable load point failures or to overinvestment which, although more reliable, is uneconomic. Therefore, placement of sectionalizing switches should be judiciously determined to provide the balance between the utility's cost and the customers' outage cost. This problem falls into a class of combinatorial optimization which can be efficiently solved by a genetic algorithm. The genetic algorithm is used to search for the number of switches and their locations. Reliability cost/worth analysis is then performed to calculate the customer's outage cost. The methodology is illustrated by a subdistribution network of Provincial Electricity Authority (PEA) of Thailand, which consists of 2 primary feeders and 26 load points.*

Keywords— **Distribution system reliability, Genetic algorithm, Sectionalizing switches, Service restoration.**

1. INTRODUCTION

Reliability in a distribution system, which transfers electrical energy from transmission systems to end-user customers, can be improved by the installation of sectionalizing switches. A sectionalizing switch is a device that isolates a faulted part from the system so that the healthy part can still be electrically supplied and the interruption duration is minimized. Switch placement plays an important role in automated distribution network, where the sectionalizing switches can be remotely activated.

Utilities normally employ past experience, customer data, and other consideration for the appropriate number of switches and their locations. Subjective placement of sectionalizing switches would, however, lead to underinvestment and therefore low reliability for the customers. On the other hand, although high reliability, it would lead to uneconomic owing to the utility's increased investment for the installation costs of the switches, which are quite significant as indicated by [1]. Therefore, the evaluation of the costs associated with different placements and the corresponding reliability worth associated with the differences should be judiciously determined.

The solution to the problem presented in this paper is based on a genetic algorithm and reliability cost/worth analysis. Genetic algorithms are stochastic optimization techniques that have a large number of applications, including power system areas, for example optimal reconfiguration distribution networks, optimal capacitor placement in distribution system and optimal power flow. With the genetic algorithm and reliability cost/worth analysis, the optimal placement of sectionalizing devices can be obtained providing the lowest total cost that is the sum of investment cost, maintenance cost and customer outage cost. The methodology is illustrated by a subdistribution network of Provincial Electricity Authority (PEA), which consists of 2 primary feeders and 26 load points.

2. GENETIC ALGORITHM

The genetic algorithm (GA) is a stochastic search technique based on the principles of genetics and natural selection [2]. The GA operates on populations that consist of a number of individuals. The initial population is randomly generated. Each individual is then evaluated to obtain a measure of its fitness in terms of the objective function to be optimized. The algorithm allows a population composed of many individuals to evolve by two basic operators crossover and mutation. The crossover operator creates new individual by combining substrings from the parent individuals. The mutation operator creates a new individual by changing randomly selected bits in its coding. The genetic algorithm employed in this paper is based on the following ten steps [3].

Step 1: Generate population 1 and population 2 which satisfy the constraints of a problem.

Step 2: Evaluate the fitness of each individual in population 2 to find the best fitness of population 2. The fitness is calculated from the objective function.

Step 3: Create a new population 3 from the crossover operator between population 1 and the best fitness individual of population 2. If it turns out that the fitness of an individual in population 3 is better than the best fitness individual in population 2, then that individual in population

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3 replaces the best fitness individual. Otherwise, the individual replaces its parent in population 1 with a probability of replacement.

Step 4: Select and keep the best fitness from population 2.

Step 5: Bring population 1 to the crossover and mutation process.

Step 6: This is the same as step 3 except that instead of using the best fitness individual in population 2, a randomly selected individual from population 2 is brought to crossover with some probability.

Step 7: Select and keep the best fitness from population 2.

Step 8: Compare the best fitness individual from step 4 with that of step 7.

Step 9: Update the best fitness individual of population 2 in step 3 with the one obtained from step 8.

Step 10: Repeat step 3 through step 7 until the maximum generation has been reached.

3. RELIABILITY COST/WORTH IN DISTRIBUTION SYSTEMS

A distribution circuit normally uses primary or main feeders and lateral distributions. A primary feeder originates from a substation and passes through major load centers. The lateral distributors connect the individual load points to the main feeder with distribution transformers at their ends. Many distribution systems used in practice have a single-circuit main feeder and defined as radial distribution system. Radial distribution systems are widely used because of their simple design and generally low cost.

A radial distribution system consists of series components (e.g., lines, cables, transformers) to load points. This configuration requires that all components between a load point and the supply point operate and therefore poor reliability can be expected because the failure of any single component causes the load points disconnected. However, many distribution systems have normally open points that can be switched to meshed systems in the event of a system failure [4]. In addition, load point reliability can be improved by installing sectionalizing switches that can remove the faulted part from the remaining healthy system.

Reliability cost is quantified in forms of investment incurred by installation of sectionalizing switches, whereas reliability worth is quantified in forms of customer outage costs served as input data for cost implications and worth assessments of system planning and operational decisions. The customer outage costs are calculated from reliability indices of the load points and customer damage functions. The customer damage function utilized in this paper is shown in Figure 1 [5].

The basic distribution system reliability indices are average failure rate l , average outage duration r , and annual outage duration U. With the three load point indices and load model at load points, system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), expected energy not supplied (ENS), and expected outage cost (ECOST) can be calculated. These four reliability indices are calculated from

$$SAIFI = \sum_{j=1}^{nj}\sum_{k=1}^{nk}\lambda_j P_k \Big/ \sum_{l=1}^{nl} P_l \tag{1}$$

$$SAIDI = \sum_{j=1}^{nj}\sum_{k=1}^{nk}\lambda_j r_j P_k \Big/ \sum_{l=1}^{nl} P_l \tag{2}$$

$$ENS = \sum_{i=1}^{ni}\sum_{j=1}^{nj}\sum_{k=1}^{nk} L_{ik} r_j \lambda_j \tag{3}$$

$$ECOST = \sum_{i=1}^{ni}\sum_{j=1}^{nj}\sum_{k=1}^{nk} L_{ik} C_{jk}(r_j)\lambda_j \tag{4}$$

where

ni = number of load steps

nk = number of load points that are isolated due to a contingency j

nj = number of outage events

nl = total number of load points

L_{ik} = load at load point k for the i th step of load duration curve at load point k

r_j = average outage time of contingency j

λ_j = failure rate of contingency j

P_k = number of customers connected to a load point k

$C_{jk}(r_j)$ = outage cost ($/kW) of customer class k due to outage j with an outage duration of r_j

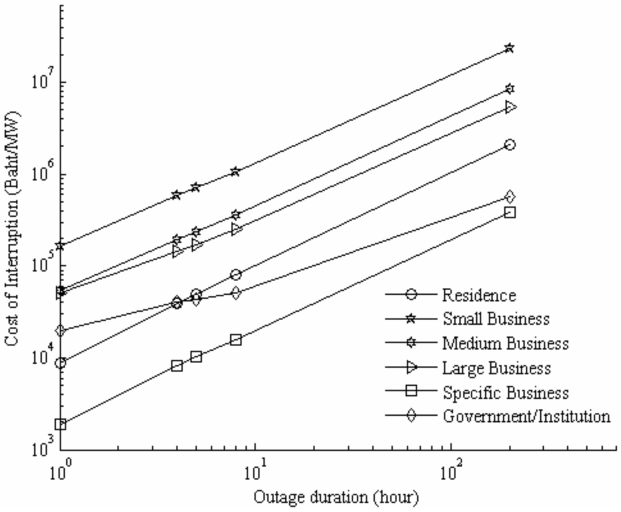

Fig. 1. Customer Damage Function.

4. PROBLEM FORMULATION

The objective function of the problem of sectionalizing switch placement is to select the number of switches and their locations such that the sum of the installation cost maintenance cost and ECOST is minimized subject to system constraints. The system constraints are voltage and line current limits. The objective function is mathematically expressed by (5). The first two costs of (5) depend on the number of sectionalizing switches whereas the last cost is calculated from (4).

$$\text{Minimize} \sum_{n=1}^{ns} \text{Installation cost} + \sum_{n=1}^{ns} \text{Maintenace cost} + ECOST \qquad (5)$$

subject to

$$V_i^{\min} \le V_i \le V_i^{\max}$$

$$I_l \le I_l^{\max}$$

where

ns = number of sectionalizing switches

V_i = voltage at i th node

I_l = current of feeder section l

V_i^{min} = minimun voltage at i th node

V_i^{max} = maximun voltage at i th node

I_l^{max} = rated current of feeder section l

5. DISTRIBUTION POWER IN RADIAL SYSTEM

Load flow solution in a radically operated distribution network can be efficiently solved by the formation of a constant spare upper triangle matrix to determine the bus voltages. This method requires initial voltages, system configuration, and a branch-to-node matrix. The voltages at all nodes are calculated by iterative process without matrix inversion. This method is efficient in terms of speed, convergence and computer storage requirement. The algorithm is described as follows [7].

Step 1: Consider the network topology description, network data, and load data.

Step 2: Form matrix $[C]$ from branch-to-node of the branch currents from topology description of the given system.

Step 3: Assume voltages at all nodes are equal to the source node or initialize all nodes with previously calculate voltage

Step 4: Determine the load current at all nodes by

$$J_i = \frac{P_i - jQ_i}{V_i^*} + \frac{V_i}{Z_i} + Y_i V_i + I_{Li} \qquad i = 1,2,\ldots,nb$$

where

nb = number of node (including source node)

n = $nb - 1$

b = number of branches

V_o = source node voltage

J_i = load current at i th node

V_i = voltage at i th node

P_i, Q_i = real and reactive loads at i th node, respectively

Z_i = load at i th node modeled by a constant impedance

Y_i = load at i th node modeled by a constant admittance

I_{Li} = load at i th node modeled by a constant current

$[i_b]$ = vector of branch currents of order (b´ 1)

$[v_b]$ = vector of branch voltage of order (b´ 1)

$[J_L]$ = vector of load current at all nodes of order (n´ 1)

$[C]$ = branch-to-node matrix of order (b´ n)

$[z]$ = primitive impedance matrix of order (b´ b)

Step 5: Determine the branch currents of all branches by $[i_b] = [C][J_L]$

Step 6: Determine the branch voltages of all branches by $[v_b] = [z][i_b]$

Step 7: Determine all the new node voltages from

$$V_i = V_0 - \sum_{j=1}^{b} C_{ij} v_j \, , \; i = 1, 2, \ldots, n$$

Step 8: Check for convergence based on node voltage differences between consecutive iterations and repeat step 4 to step 7 until the solution converges to a prespecified tolerance of 0.00001 per unit.

6. SOLUTION ALGORITHM

The following steps present the solution algorithm for the optimal placement of sectionalizing switches in radial distribution systems based on the genetic algorithm and reliability cost/worth analysis.

Step 1: Input length of feeder in each section, load level per load point, failure rate, repair time, switch time, replacement time, transfer time, outage cost to customer due to supply outage, switch locations and failure probability of fuses.

Step 2: Input population size and maximum generation.

Step 3: Generate populations 1 and 2 as described in step 1 of Section 2. Each individual in the populations is represented by a string of binary numbers. Binary values of 0 and 1 indicate switch installation and uninstallation, respectively.

Step 4: For each individual, consider a contingency j at load point k (e.g., outage of a line or a transformer) in the network for a load step i . Determine all the affected customers (nk) due to the contingency and the interruption duration r_j . The value of r_j is repair time, replacement time or switching time. Repair time and replacement time are used for the customers who are subjected to long interruptions.

Switching time is used for those to whom the service is restored through alternate supply.

Step 5: Calculate the current in each feeder section and the voltage at each load point using the distribution load flow algorithm presented in Section 5, taking into account load transfer if an alternative supply is available.

Step 6: Obtain the load point interruption cost $C_{jk}(r_j)$ with the customer damage function shown in Figure 1.

Step 7: Calculate the contribution of the contingency to system ECOST using $\sum_{k=1}^{nk} L_{ik} C_{jk}(r_j)\lambda_j$.

Step 8: If $k = nk$, go to step 9. Otherwise, repeat step 5 to step 7 for a next load step.

Step 9: If $j = nj$ (all the contingencies on the primary and the lateral sections at all loads have been considered), go to step 10. Otherwise, repeat step 5 for next contingency.

Step 10: If $i = ni$, go to step 11. Otherwise, repeat step 5 for next load level.

Step 11: Calculate the objective function from the summation of the investment cost, maintenance cost, ECOST and a penalty term. The penalty term is used if the population being considered violates the constraints of line current and bus voltage limits.

Step 12: Do step 4 to step 11 until every individual in populations 1 and 2 are considered.

Step 13: Perform step 3 to step 10 in Section 2.

7. CASE STUDY

The test system in this case study consists of two feeders of PEA designated as KWA01 (stand for Klongkwang01) and KWA06 (stand for Klongkwang06) [8]. These two feeders have 2 feeders and 26 load points shown in Figure 2 and connected with residential customers, small users, medium users, large users, special users and government. Fuses are installed at the tee-point in each lateral. The network data is provided in appendix. Three phase pad mounted sectionalizing switches are considered for the test system. The investment cost of a pad mounted sectionalizing switch is taken as 200,000 Baht. The annual maintenance cost is 2% of the annual investment cost. The life period of the switch is considered to be 20 years and the interest rate as 8%.

Five cases are investigated.

Case 1: Sectionalizing switches are installed along the main feeders at the positions numbered in Figure 2. The fuses at the lateral distributors are assumed to be 100% reliable.

Case 2: This is the same as case 1 except that no sectionalizing switches are installed at the locations numbered in Figure 2.

Case 3: This is the same as case 1 except that the number and locations of sectionalizing switches are determined by the genetic algorithm with 100 generations and 70 populations.

Case 4: The same as case 3 except that the fuses are 90% reliable.

Case 5: This is the same as case 3 except that a seven step load duration curve shown in Figure 3 instead of the average load is applied to each load point with a load increment of 10%. The corresponding step probabilities are 0.0132, 0.1114, 0.1651, 0.2328, 0.2147, 0.2263, 0.0365 [5].

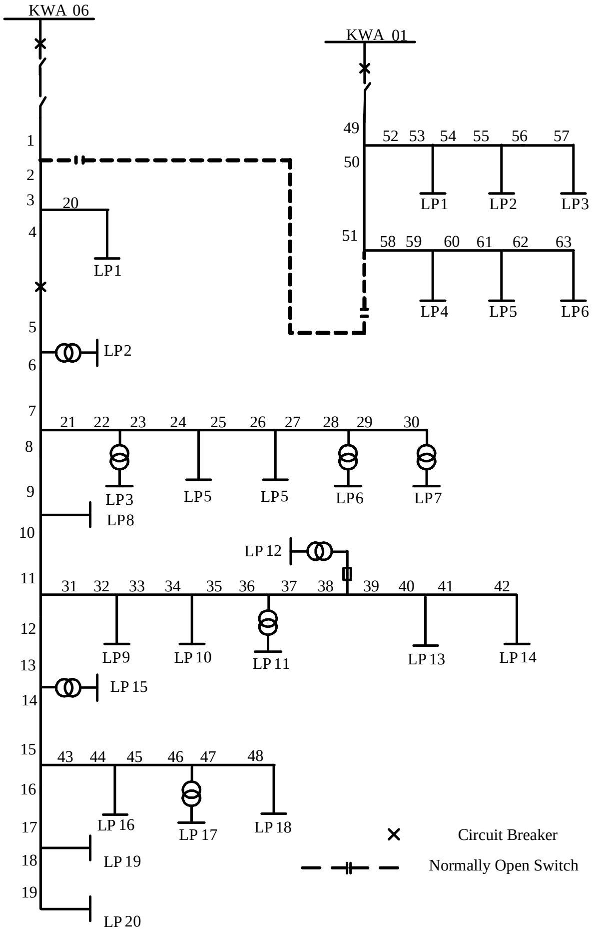

Fig. 2. Feeder KWA01 and KWA06.

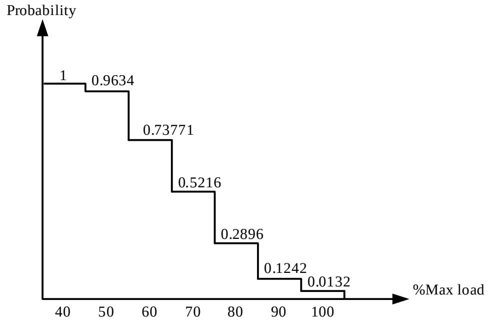

Fig. 3. Seven Step Load Duration Curve.

Table 1. Results of Five Cases

Case	SAIFI	SAIDI	ENS	ECOST	Total Cost	No. of Switches	Locations
1	7.506	17.416	35,554.40	1,696,498	3,005,474	63	1-63
2	7.506	26.651	72,295.92	2,940,815	2,940,815	0	-
3	7.506	19.421	37,526.77	1,759,361	1,925,580	8	1,4,12,16,21,49,50,51
4	7.531	19.446	37,632.06	1,764,575	1,930,794	8	1,4,12,16,21,49,50,51
5	7.506	19.284	48,050.84	2,303,629	2,469,848	9	1,4,12,16,21,31,49,50,51
6	7.506	15.990	27,543.02	1,625,078	1,791,297	8	1,4,12,15,21,49,50,51
7	7.506	18.936	41,185.17	2,160,063	2,472,774	8	1,4 (automated),12,16,21,49,50,51

Units: SAIFI – interruptions/customer.year SAIDI – hour/customer.year Total Cost – Baht/year

ENS – kWh/year Expected Outage Cost – Baht/year

The simulation results for the five cases are shown in Table 1. In case 1, the system requires 63 sectionalizing (63 positions) with a total cost of 3,005,474 Baht. Without any sectionalizing switches in case 2, the total cost is 2,940, 815 Baht. We can see that the total costs of the two cases are not much different. The investment cost is higher in case 1 but lower in case 2. The expected outage cost is lower in case 1 but higher in case 2. These two cases represent two extremes from the utility's and customers' point of view; to be precise, the customers are served with a very good electric supply in case 1 whereas case 2 would be favored by the utility. Nevertheless, there exists the optimum balance between the two cases. Such a balance can be found in case 3, where 8 sectionalizing switches at locations 1, 4, 12, 16, 21, 49, 50, 51 (see Fig. 4.) are required with a total cost of 1,925,580 Baht. Note that the first three cases have the same SAIFI because sectionalizing switches have nothing to do with system failure frequency but they do affect SAIDI and ENS.

If the fuses in the lateral are considered 90 % reliable as in case 4, its SAIFI, SAIDI, ENS, ECOST and total cost are increased, compared with those of case 3. The number and locations of sectionalizing switches remain, however, unchanged. If the seven step load model are applied to each load point for case 5, 9 sectionalizing switches in total should be installed, namely one additional switch is needed at location 31.

8. IMPACT OF AUTOMATED DEVICES

It is seen from the case study that supply restoration becomes crucial for reliability improvement. In the other words, the sooner the restoration time, the better the system reliability. Fast restoration can be achieved by automated devices, which can be remotely activated (minute or less) after a fault has occurred. The impact of automated devices will be demonstrated by two more cases, case 6 and case 7, that are an extension from case 3 of the case study in section 7.

Case 6 is the same as case 3 except that the normally open switch, by which the load can be transferred from KWA01 to KWA06 and vice versa, has a switching time of 1 minute (0.0167 hour). The simulation result is shown in Table 1. The difference between the results of the two cases is that the switch at location 16 in case 3 is moved to location 15 in case 6. Although the optimal patterns of sectionalizing switches for both cases are similar, the total cost of case 6 is significantly reduced, mainly because of a decrease in the ECOST.

In the case study, sectionalizing switches considered so far are manually operated. In fact, system reliability can be further improved by automated sectionalizing switches. Most distribution systems either have only manually operated devices (no automated devices) or are partially automated with a combination of manual and automated devices. A system with partial automation can be two-stage upstream and downstream restorations as shown in Figs. 4 and 5, respectively [9].

In Fig. 4, the breaker will clear the fault. The automated switch is opened allowing section A to be quickly restored and the manual sectionalizing switch will later be opened to restore the customers on section B. In case of downstream restoration in Fig. 5, after the fault is cleared, the automated switch in the downstream path immediately prior to section A will be opened, allowing section A to be supplied from a normally open point (n.o.1). Section B remains without power until the first manual sectionalizing switch is opened and the normally open point in the downstream path (n.o.2) is closed.

If automated sectionalizing switches become a candidate in case 3 of the case study with a switching time of 1 minute and an investment cost of 400,000 Baht (i.e., twice the cost of the manually operated switch), no sectionalizing switch is required. However, if we suppose that the load at LP1 were increased from 3.13075 MW to 4 MW, 8 sectionalizing switches would be required as indicated in case 7 of Table 1. It can be observed from the results that the system should replace the switch of manual type in case 3 at location 4 with that of automation type in case 7. This replacement is reasonable because the load at LP1 is so high enough that fast service restoration can help it reduce the customer interruption cost. Therefore, it is worth investing the automated sectionalizing switch.

Note from the results of cases 3 to 7 that many of the switches are installed at common locations. To be precise, a sectionalizing switch is installed at or near a main feeder. This is logical because the switch can cover several sections of the feeder and laterals downstream to the switch, and therefore it can isolate any faults that may occur on those sections.

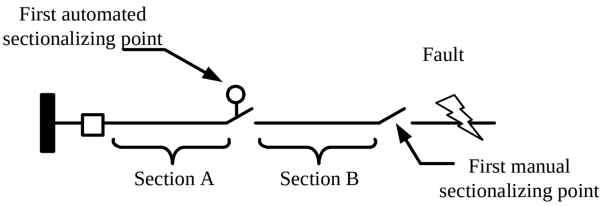

Fig. 4. Two-Stage Upstream Restoration.

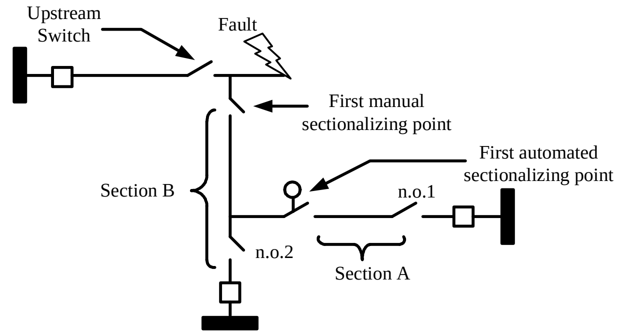

Fig. 5. Two-Stage Downstream Restoration.

9. CONCLUSION

The optimal placement of sectionalizing switches in a radial distribution system has been presented. The objective function is to minimize the sum of investment cost, maintenance cost and customer outage cost, subject to line current and bus voltage limits. The first two costs depend directly upon the number of installed sectionalizing switches that are determined from algorithm. The last cost is obtained from reliability cost and worth analysis. A distribution load flow algorithm is developed based on a constant sparse upper triangle matrix to calculate line current and load-point voltages used to penalize populations that violate the constraints of line current and bus voltage limits in the optimization problem. A case study on a distribution network of the PEA system reveals that methodology provides an optimum decision between economic and reliability consideration. The impact of fast service restoration from the automated normally open switch and the automated sectionalizing switch is also investigated.

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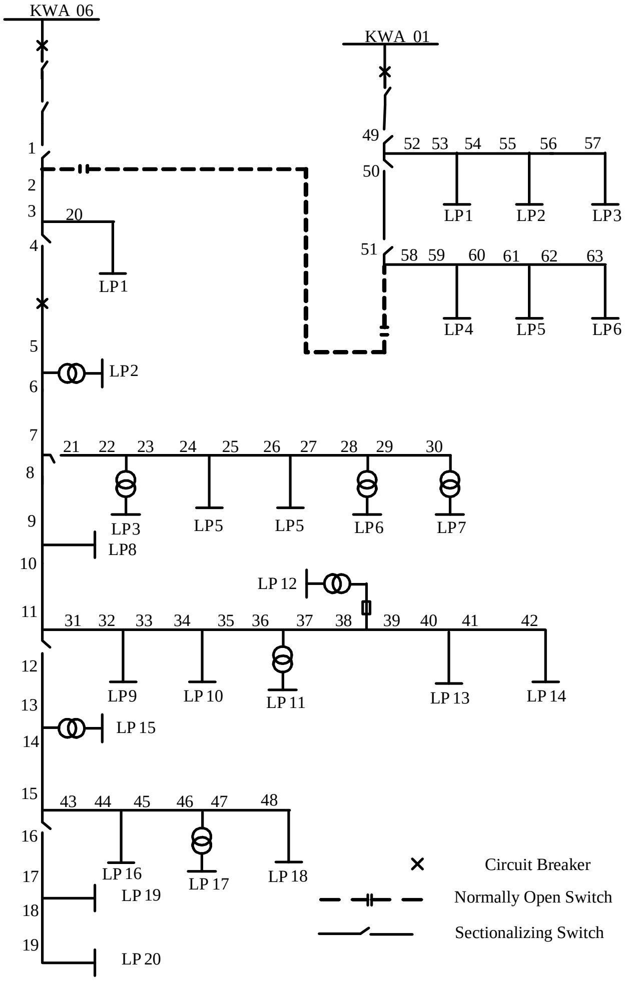

Fig. 6. Optimal Placement of Sectionalizing Switches in Test System.

APPENDIX

Table A1. Customer Data of Feeder KWA01

Load Point	**Number of Customer**	**Type**	**Demand (MW)**	
			Average	
LP1	1	Large Business	0.7000	LP1
LP2	1	Large Business	0.7000	LP2
LP3	1	Medium Business	0.2205	LP3
LP4	1	Medium Business	0.0350	LP4
LP5	1	Medium Business	0.1050	LP5
LP6	1	Medium Business	0.1050	LP6

Table A2. Customer Data of Feeder KWA01

Load Point	**Number of Customer**	**Type**	**Demand (MW)**	
			Average	**Maximum**
LP1	1	Large Business	3.13075	LP1
LP2	105	Residence	0.0325	LP2
LP3	31	Residence	0.00975	LP3
LP4	1	Medium Business	0.11025	LP4
LP5	31	Residence	0.00975	LP5
LP6	31	Residence	0.00975	LP6
LP7	21	Residence	0.00650	LP7
LP8	1	Government	0.04550	LP8
LP9	21	Residence	0.00650	LP9
LP10	1	Small Business	0.01050	LP10
LP11	1	Medium Business	0.17500	LP11
LP12	31	Residence	0.00975	LP12
LP13	84	Residence	0.02600	LP13
LP14	1	Medium Business	0.05600	LP14
LP15	1	Medium Business	0.17500	LP15
LP16	1	Government	0.02275	LP16
LP17	1	Government	0.01750	LP17
LP18	1	Government	0.03500	LP18
LP19	21	Residence	0.00650	LP19
LP20	1	Government	0.00975	LP20

Table A3. Reliability Data of Feeder KWA01 and KWA06

Component	*l*	*r*	*s*
Transformers	0.0150	200	-
Lines	0.37	5	1.06

where *l* = failure rate

r = repair time (hour)

s = switching time (hour)

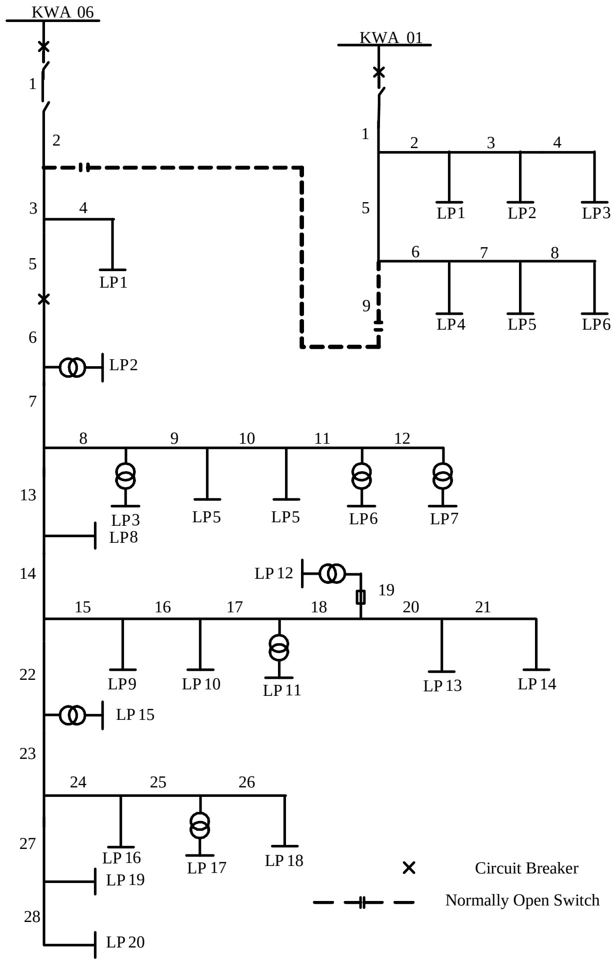

Fig. A1. Feeder KWA01 and KWA06.

Table A4. Type and Length of Feeder KWA01

Section	Length (km)	Type
1	1.0760	SAC 185
2	0.9740	SAC 185
3	0.0066	SAC 185
4	0.1960	SAC 185
5	2.1750	SAC 185
6	0.4150	SAC 185
7	0.0610	SAC 185
8	0.0130	SAC 185
9	0.9800	SAC 185

Table A5. Type and Length of Feeder KWA06

Section	Length (km)	Type
1	8.7400	SAC 185
2	0.3830	SAC 185
3	0.4290	SAC 185
4	0.2890	SAC 185
5	3.0060	SAC 185
6	0.1900	ACSR 50
7	1.0690	ACSR 50
8	0.8540	ACSR 50
9	0.0170	ACSR 50
10	0.2220	ACSR 50
11	0.5180	ACSR 50
12	0.0810	ACSR 50
13	0.5080	ACSR 50
14	0.0640	ACSR 50
15	0.3120	ACSR 50
16	0.0510	ACSR 50
17	0.4660	ACSR 50
18	0.0910	ACSR 50
19	0.4100	ACSR 50
20	0.1660	ACSR 50
21	0.3190	ACSR 50
22	0.5050	ACSR 50
23	0.1300	ACSR 50
24	0.3940	ACSR 50
25	0.6930	ACSR 50
26	0.4300	ACSR 50
27	0.2910	ACSR 50
28	0.0910	ACSR 50