Application of Fuzzy Reasoning Algorithm for Service Restoration Plan to Metropolitan Electricity Authority's Distribution System

J. Kaewmanee* and S. Sirisumrannukul

Abstract— *Service restoration in a distribution system plays an important role for a high level of reliability of electric power supply to the customers. In general, after a fault location has been identified, the faulted area has to be isolated as soon as possible. The system operators then, with information from their customer; use their experience expressed in terms of heuristic rules for service restoration. In addition, a number of objectives for service restoration should be, in many cases, satisfied at the same time such as minimal number of switching operations, no interrupted customers, no overloaded components, as much load as possible restored in the unserved energy area. Therefore, compromise need to be achieved in order to arrive at a plan which meets the operators' practical multi-objective requirements. In this paper, the concept of fuzzy set is employed to deal with these imprecise linguistic objectives and constraints. Fuzzy reasoning procedures, where the constraints and objective are treated equallly important, are developed to solve the multiple-objective optimization problem. The developed heuristic search algorithm is tested with a Metropolitan Electricity Authority (MEA)'s distribution system. The test results of the case study reveal the effectiveness of the fuzzy models in compromising the benefits obtained from the conflicting objectives and offer a system operator flexibility to incorporate his/her own judgement in the model.*

Keywords— **Service restoration planning, heuristic search method, distribution system, fuzzy reasoning, fuzzy set.**

1. INTRODUCTION

Restoration is an important routine task for electric power utilities as it directly affects the system reliability indices that involve outage duration and the number of unserved customers [1]. When a fault occur somewhere in a distribution system, the system operators at the associated control center will try to locate the fault location, isolate the faulted zone from the healthy areas and restore the areas outside the faulted zone [2-4]. These actions need to be performed as soon as possible to reduce any possible impact on the affected customers. In general, the purposes of a service restoration plan in most utilities are: I) the restoration plan must be reached in a very short time, II) the loss of load should be minimized within the faulted area [5], III) the required number of switching operations should be kept at minimum, IV) the configuration of the restored system should be as close to the original configuration as possible, V) the radial system structure must be retained after the reconfiguration, and VI) no components are overloaded [3], [6-7].

Metropolitan Electricity Authority (MEA) is an electricty distribution utility in Thailand that serves its customers in the capital of the country, Bangkok, and two nabouring provices, Samutprakran and Nonthaburi. The services areas cover 3,192 km^2 and its electricity consumption accounts for 37% of the whole country. There are two medium voltage levels currently being utilized: 12 kV and 24 kV. The reliability of MEA is evaluated by a number of well-known indices such as system average interruption duration index (SAIDI), energy not supplied (ENS) and average system availability index (ASAI). The main contribution to values of these indices is the interruption duration. In otherwords, the longer the interruption duration, the greater the indices and therefore higher customer outage cost.

A service restoration plan in MEA's distribution system after an outage event is normally performed in the following sequential steps. First, a system operator at the associated control center informs a system operator at the dispatching center located in the faulted area. Second, the system operator at the dispatching center (also known as district control center) tries to identify the fault location with the help from the customers in the faulted area. Field staff is then dispatched to isolate the faulted zone from the out-of-service areas by opening appropriate disconnecting switches on the faulted feeder and closing tie switches on supporting feeders and laterals. Note that at present there are 5 control centers and 18 dispatching centers in MEA. As most of the distribution systems in MEA's service area have many laterals and many tie switches, it may be time-consuming to determine feasible or proper service restoration plans. Therefore, the system operators of MEA must rely on their past experience to reach a good restoration plan in a short period of time.

This paper presents a fuzzy reasoning algorithm [2], in which the system operator is able to use linguistic expression, to identify proper switching orders with the information of feeder loads, feeder lengths, capacity margins of supporting feeders and average traveling

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time. Although several objectives and constraints can be implemented for service restoration in MEA's distribution systems, of interest in this paper is the minimum number of switching operations as the objective and capability limits on feeder and lateral loading capacity as the constraints. The methodology is demonstrated by a 9-lateral distribution feeder with 8 supporting feeders and tested with a 31-lateral distribution feeder of Metropolitan Electricity Authority (MEA) with 8 supporting feeders.

2. SERVICE RESTORATION

To illustrate the main idea of service restoration employed in this work, consider a sample distribution system as shown in Figure 1 [2].

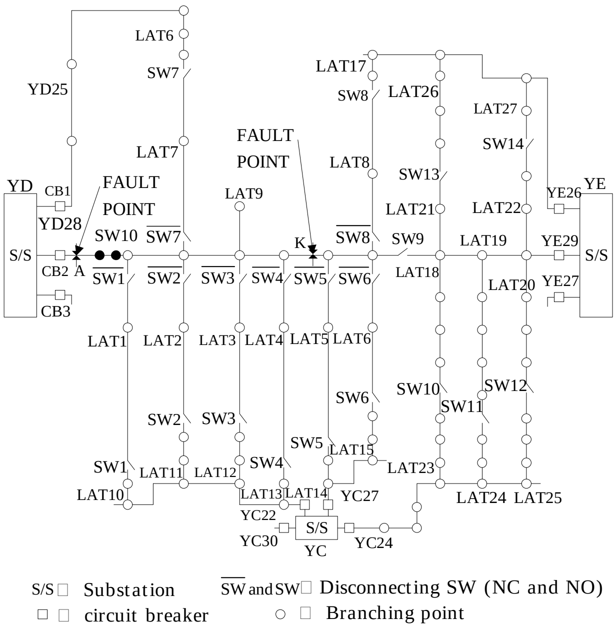

Fig. 1. Sample distribution system.

Figure 1 shows the main feeder with 9 laterals supplying electrical energy from feeder YD28. From the figure, we can see that feeder YD28 is connected to feeder YE29 through a disconnecting switch (normally open) SW9. Each lateral has a spare capacity from supporting laterals except for LAT9. For example, lateral LAT1 can be supported from lateral LAT10 through a disconnecting switch SW1 (normally open) and $\overline{\text{SW1}}$ (normally close).

Service restoration is fault location-specific; namely, an after-the-fault recovery process varies location by location. As an illustration, if a fault occurs at point A on feeder YD28 of Figure 1. Circuit breaker CB2 is tripped, leaving 9 laterals LAT1, LAT2, LAT3, LAT4, LAT5, LAT6, LAT7, LAT8 and LAT9 out-of-service. Isolating the fault requires opening switch SW10 at branching point 10. These 9 laterals is then restored by supporting feeder YE29 and 8 supporting laterals LAT10, LAT11, LAT12, LAT13, LAT14, LAT15, LAT16 and LAT17.

When a short circuit occurs at point K (between $\overline{\text{SW4}}$ and $\overline{\text{SW5}}$) in the Figure, circuit breaker CB2 is tripped, causing every load point in feeder YD28 to be disconnected. Isolating the fault from this system is to open the switch in the main feeder between $\overline{\text{SW4}}$ and $\overline{\text{SW5}}$ After that, the circuit breaker can be closed to pick-up some load points; that is, those located on laterals LAT1, LAT2, LAT3, LAT4, LAT7 and LAT9. However, LAT5, LAT6, LAT8, which stay outside the faulted zone, have not been yet restored. How to restore these load points within this unfaulted zone is a major concern in this work. The three unserved load points on LAT5, LAT6 and LAT8 can be supported form feeder YE29 and another three supporting laterals LAT14, LAT15 and LAT17. In general, the service restoration plan must satisfy the following requirements [3], [5].

1. The restoration plan must be reached in a very short time.
2. Load loss should be minimized within the faulted area.
3. The required number of switching operations should be kept at minimum.
4. The configuration of the restored system should be as close to the original configuration as possible.
5. Radial system structure must be retained after the reconfiguration.
6. No components are overloaded.

From above requirements, the problem is formulated as.

1. Objective function

   The switching operation must be minimized.
2. Constraints

   All component should not be overloaded (conductor feeder and conductor lateral)

3. FUZZY SET CONCEPT

The application of fuzzy set has been well documented for the representation of uncertainty inherent in natural language and human thinking [1]. The development of fuzzy set has provided an effective way of reasoning with uncertain environment. The fuzzy set is a grading concept in which everything can be described as a degree in representing the certain forms of uncertainty. It appears to be a useful approach and can offer suitable models to integrate uncertain parameters for the wider range of operating conditions.

A fuzzy set is the generalisation of the classical set or crisp set in which any object is logically defined as either a member of the set or not at all. Contrary to crisp sets, fuzzy sets do not have a sharp boundary, i.e. there is a room for gradual transitions. A fuzzy set allows an object to be a member of a set to some degree but not only zero or one as defined in the conventional set. The degree of membership to a set is indicated by a number between 0 and 1 that is the number in the closed inteval [0,1]. A fuzzy set $\tilde{A}$ is a set of pairs of numbers. The membership function can be mathematically expressed as [8]:

$$\tilde{A} = \{(x,\mu_{\tilde{A}}(x))|x\in X, \text{ and } 0 \leq x \leq 1\} \quad (1)$$

where $\mu(x)$ = the membership function of x in $\tilde{A}$.

This function indicates the membership grade of these elements in the set. The larger the membership values, the higher degrees of set membership. Figures 2 and 3 show the membership function defined by a crisp set and fuzzy set.

The shapes of membership function can be modeled in a number of various forms. Normally, the assignment of the membership functions are subjectively chosen and constructed based on decision makers' judgment and experience. The most commonly-used shapes are triangle, trapezoidal, piecewise linear and Gaussian. The well-defined basic operations in classical crisp sets such as union and intersection are also defined in fuzzy sets.

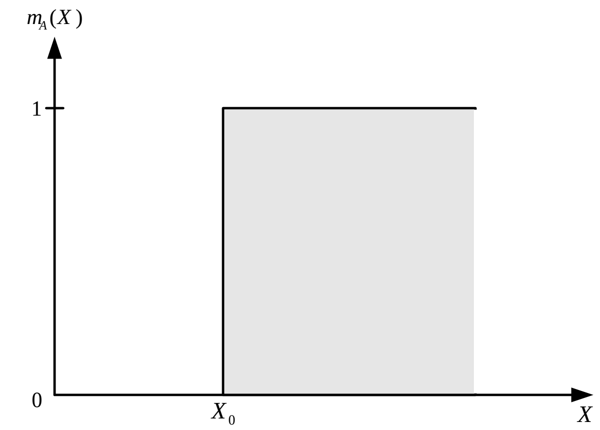

Fig. 2. Membership function of crisp set A.

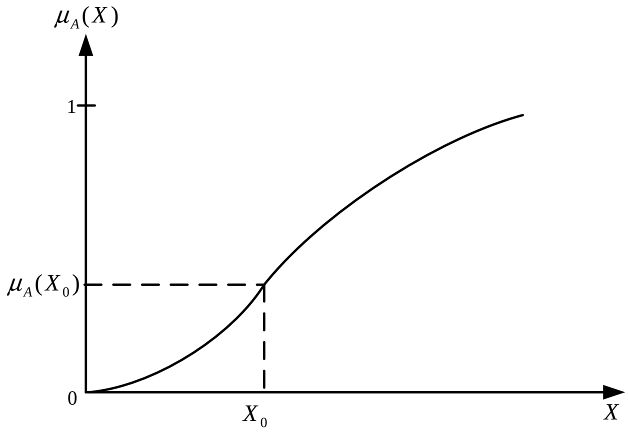

Fig. 3. Membership function of fuzzy set A.

4. FUZZY DECISION MAKING

The symmetric model was initially proposed by Bellman and Zadeh [9] for decision making in a fuzzy environment based on three basic components: fuzzy goals (or fuzzy objectives), fuzzy constraints and fuzzy decisions. It is assumed in this model that the objective and constraints in an imprecise situation could be represented by fuzzy sets. In a fuzzy environment, the fuzzy goal and the fuzzy constraints are characterised by their corresponding membership functions and desired to be satisfied simultaneously. The fuzzy decision set is defined as the intersection of all of membership functions of the fuzzy constraints and fuzzy objective function(s). It is clearly seen that their concept forms the symmetry between constraints and objective function(s), that is, there is no longer a difference between the former and the latter.

Let a fuzzy goal G be a fuzzy set on X characterized by its membership function.

$$\mu_G: X \rightarrow [0,1] \quad (2)$$

Let a fuzzy constraint C be fuzzy set on X characterised by its membership function.

$$\mu_C: X \rightarrow [0,1] \quad (3)$$

Based on Bellman and Zadeh's concept, the fuzzy decision D is defined by the intersection of fuzzy goal G and fuzzy constraint C .

$$D = G \cap C \quad (4)$$

and is characterized by its membership function

$$\mu_D(x) = \min(\mu_G(x),\mu_C(x)) \quad (5)$$

$$\max_{x\in X} \mu_D(x) = \max_{x\in X}\left(\min(\mu_G(x),\mu_C(x))\right) \quad (6)$$

The decision variables corresponding to the solution with the highest membership which can be calculated from the by Max-Min operator in the fuzzy decision set can then be taken as the optimal decision.

More generally, if there are equation fuzzy goals $G_1, G_2, \ldots, G_k$ and m fuzzy constraints $C_1, C_2, \ldots, C_m$, the fuzzy decision is defined as follows:

$$D = G_1 \cap G_2 \ldots \cap G_k \cap C_1 \cap C_2 \ldots \cap C_m \quad (7)$$

and the corresponding maximizing decision is given as:

$$\max_{x\in X} \mu_D(x) = \max_{x\in X}\left(\min(H)\right) \quad (8)$$

where $H = \mu_{G1}(x),\mu_{G2}(x),\ldots,\mu_{Gk}(x), \mu_{C1}(x), \mu_{C2}(x),\ldots, \mu_{Cm}(x)$

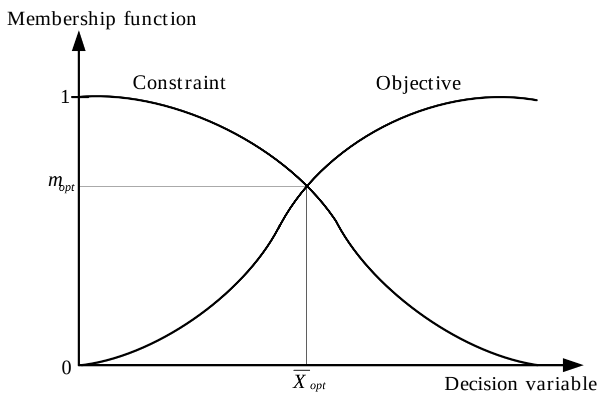

Fig. 4. Membership function of objective and constraint.

The concept of fuzzy decision making described above is graphically illustrated in Figure 4 [10].

5. FUZZY REPRESENTATION FOR SERVICE RESTORATION

The fuzzy objective function is to minimize the number of switching operations subject to the fuzzy constrains in the capacity limit of feeders and of laterals. In these fuzzy constraints, our goal is to keep the load currents on supporting feeders and laterals as small as possible. However, under peak load conditions, we allow a certain degree of overloads for a short period of time in order to be able to reach a restoration plan.

5.1 Fuzzy Objective: Number of Switching Operations

Since our goal is to reduce the number of switching as much as possible. Let $m(\tilde{N})$ be the membership function of the objective function. The membership function of the number of switching operations can be assigned to be a trapezoidal fuzzy number demonstrated in Figure 5. It is fully satisfied if $\tilde{N}$ is smaller than $N_{\min}$. Between $N_{\min}$ and $N_{\max}$, the satisfaction level declines as the number of swithcing operations becomes wider and unacceptable if exceeding $N_{\max}$, thus the zero membership value given for this point. The membership function for this objective is mathematically written as

$$\mu(\tilde{N}) = \begin{cases} 1 & \tilde{N} < N_{\min} \\ \dfrac{N_{\max} - \tilde{N}}{N_{\max} - N_{\min}} & N_{\min} < \tilde{N} < N_{\max} \\ 0 & \tilde{N} > N_{\max} \end{cases} \tag{9}$$

where $\tilde{N}$ = fuzzy variable representing the number of switching operations
$N_{\min}$ = minimum number of switching operations
$N_{\max}$ = maximum number of switching operations
$\mu(\tilde{N})$ = membership function of number of switching operations

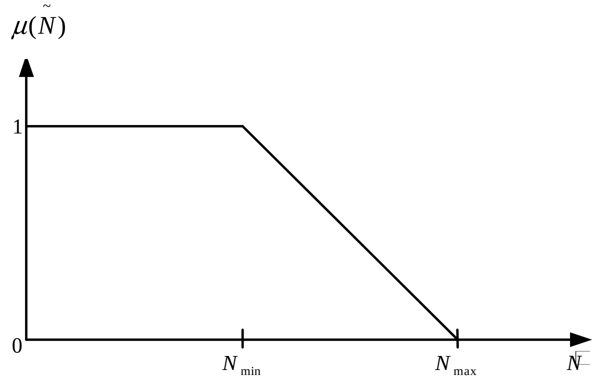

Fig. 5. Membership function of the number of switching operations.

5.2 Fuzzy Constraint: Feeder Loading

The membership function of feeder loading can be represented by a trapezoidal fuzzy number as in Figure 6 and mathematically defined in Equation (10). As can be seen from Figure 6, the system operator would be more happy for a smaller feeder current than a larger one. The allowable range of feeder loading capability varies from 0 to $I_{FD}^{\max}$.

$$\mu(\tilde{I}_{FD}) = \begin{cases} 1 & \tilde{I}_{FD} < I_{FD}^{\min} \\ \dfrac{I_{FD}^{\max} - \tilde{I}_{FD}}{I_{FD}^{\max} - I_{FD}^{\min}} & I_{FD}^{\min} < \tilde{I}_{FD} < I_{FD}^{\max} \\ 0 & \tilde{I}_{FD} > I_{FD}^{\max} \end{cases} \tag{10}$$

where $\tilde{I}_{FD}$ = fuzzy variable representing the feeder loading
$I_{FD}^{\min}$ = minimum loading capacity of feeder
$I_{FD}^{\max}$ = maximum loading capacity of feeder
$\mu(\tilde{I}_{FD})$ = membership function of feeder loading

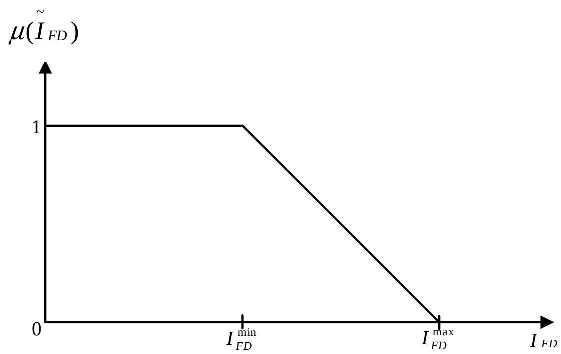

Fig. 6. Membership function of Feeder Loading.

5.3 Fuzzy Constraint: Lateral Loading

Like that of feeder loading capability, the membership function of laterals is also represented by a trapezoidal fuzzy number as shown in Figure 7, indicating that if high current flows in a lateral, its value of membership function is low. The amount of $\tilde{I}_{LAT}$ is expected to be less than $I_{LAT}^{\min}$ and not grater than $I_{LAT}^{\max}$. The mathematical representation is shown in Equation (11).

$$\mu(\tilde{I}_{LAT}) = \begin{cases} 1 & \tilde{I}_{LAT} < I_{LAT}^{\min} \\ \dfrac{I_{LAT}^{\max} - \tilde{I}_{LAT}}{I_{LAT}^{\max} - I_{LAT}^{\min}} & I_{LAT}^{\min} < \tilde{I}_{LAT} < I_{LAT}^{\max} \\ 0 & \tilde{I}_{LAT} > I_{LAT}^{\max} \end{cases} \tag{11}$$

where $\tilde{I}_{LAT}$ = fuzzy variable representing the lateral loading

$I_{LAT}^{\min}$ = minimum loading capacity of lateral

$I_{LAT}^{\max}$ = maximum loading capacity of lateral

$\mu(\tilde{I}_{LAT})$ = membership function of lateral loading

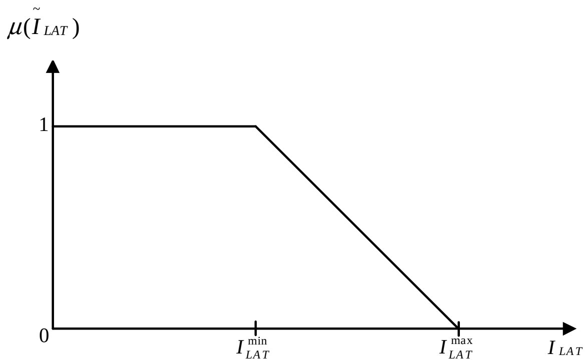

Fig. 7. Membership function of lateral loading.

6. FUZZY REASONING APPROACH FOR SERVICE RESTORATION

The fuzzy reasoning approach requires statuses of tie switches (normally open) located at the end of laterals to be formulated in the optimization problem. The statuses of the tie switches indicate whether the laterals need alternative supply from other feeders or laterals to fulfill the service restoration plan. The statuses can be represented by a vector. Based on Figure 1, there are 8 laterals to be considered and therefore:

$$X = [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8]^T \tag{12}$$

where x_i = status of tie switch i

If $x_i = 0$, the status of tie switch i is "open" and if $x_i = 1$, the status of tie switch i is "closed." As an illustration, if

$$X = [1, 0, 0, 0, 0, 0, 0, 0]^T$$

In this case, $x_1 = 1$ indicates that LAT1 requires a support from LAT10 by closing tie switch SW1 and opening lateral switch $\overline{\text{SW1}}$. For this particular sample distribution system, because there are 8 tie switches, the overall service restoration plan equals 2^8=256 combinations to be considered.

The methodology for service restoration by the fuzzy reasoning algorithm is described step by step as follows.

Step 1: Compute the fuzzy objective function and determine its membership function $\mu(\tilde{N})$ from $\tilde{N}$.

Step 2: Compute the load current on supporting laterals after restoration and determine their membership function $\mu(\tilde{I}_{LAT})$ from $\tilde{I}_{LAT}$.

Step 3: Compute the load current on supporting feeders and other feeder after restoration and determine membership function $\mu(\tilde{I}_{FD})$ from $\tilde{I}_{FD}$ (overall load in feeders in not exceed maximum capacity current of each feeder is the fuzzy objective function).

Step 4: Calculate all membership function obtained from steps 1-3 and find the minimum value of them. To be specific,

$$\mu_x = \min(\mu(\tilde{N}), \mu(\tilde{I}_{LATi}), \mu(\tilde{I}_{LATj}))$$
$$i \in \{\text{lateral number}\} \text{ amd } j \in \{\text{feeder number}\} \tag{13}$$

Step 5: For all possible service restoration plans, find the highest membership value $\mu_{x\max}$ using

$$\mu_{x\max} = \max[\mu_x] \tag{14}$$

7. CASE STUDY

The developed fuzzy reasoning algorithm is tested with an MEA's distribution system in the 69/24kV Eakkamai (EM) substation. The substation is located in Sukumvit Rd., Bangkok and supplies 2 power transformers. One of the 24 kV feeders of the second transformer is chosen to demonstrate the performance of the restoration algorithm. The 7.7 circuit-km feeder, designated as EM422, serves 31 laterals with a total demand of 11.66 MW. This system is of interest because it features many laterals, tie and disconnecting switches. The single line diagram of the system is shown in Figure 7. The main feeder has 21 normally close switches and 13 normally open switches. To see the effect of line overload due to power flow from other feeders through a tie switch during restoration, the system is simulated with three different loading conditions described in Tables 2 and 3.

The fuzzy parameters for the membership function associated with the objective and the two constraints are listed in Table 1.

Table 1: Fuzzy Parameters for Objective and Constraints

Membership function	min	max
$\mu(\tilde{N})$	5	19
$\mu(\tilde{I}_{FD})$	333 A	407 A
$\mu(\tilde{I}_{LAT})$	225 A	250 A

For the distribution system of MEA, Equation (15) is the fuzzy objective function. Equations (16)-(24) is the fuzzy capacity constraint of supporting laterals and Equations (25)-(30) is the fuzzy capacity constraint of supporting feeders.

$$\tilde{N} = 2\sum_{i=1}^{9} x_i + 1 \tag{15}$$

$$\tilde{I}_{LAT32} = I_{LAT32} + x_1 I_{LAT1} \tilde{\leq} I_{LAT}^{rated} \tag{16}$$

$$\tilde{I}_{LAT33} = I_{LAT33} + x_2 I_{LAT2} \tilde{\leq} I_{LAT}^{rated} \tag{17}$$

$$\tilde{I}_{LAT34} = I_{LAT34} + x_3 I_{LAT3} \tilde{\leq} I_{LAT}^{rated} \tag{18}$$

$$\tilde{I}_{LAT35} = I_{LAT35} + x_4 I_{LAT4} \tilde{\leq} I_{LAT}^{rated} \tag{19}$$

$$\tilde{I}_{LAT36} = I_{LAT36} + x_5 I_{LAT5} \tilde{\leq} I_{LAT}^{rated} \tag{20}$$

$$\tilde{I}_{LAT37} = I_{LAT37} + x_6 I_{LAT6} \tilde{\leq} I_{LAT}^{rated} \tag{21}$$

$$\tilde{I}_{LAT38} = I_{LAT38} + x_7 I_{LAT7} \tilde{\leq} I_{LAT}^{rated} \quad (22)$$

$$\tilde{I}_{LAT39} = I_{LAT39} + x_8 I_{LAT8} \tilde{\leq} I_{LAT}^{rated} \quad (23)$$

$$\tilde{I}_{LAT40} = I_{LAT40} + x_9 I_{LAT9} \tilde{\leq} I_{LAT}^{rated} \quad (24)$$

$$\tilde{I}_{FD3} = x_1 I_{LAT1} + x_5 I_{LAT5} + I_{FD3} \tilde{\leq} I_{FD}^{rated} \quad (25)$$

$$\tilde{I}_{FD4} = x_2 I_{LAT2} + I_{FD4} \tilde{\leq} I_{FD}^{rated} \quad (26)$$

$$\tilde{I}_{FD5} = x_4 I_{LAT4} + x_7 I_{LAT7} + x_8 I_{LAT8} + I_{FD5} \tilde{\leq} I_{FD}^{rated} \quad (27)$$

$$\tilde{I}_{FD6} = x_3 I_{LAT3} + x_6 I_{LAT6} + I_{FD6} \tilde{\leq} I_{FD}^{rated} \quad (28)$$

$$\tilde{I}_{FD7} = x_9 I_{LAT9} + I_{FD7} \tilde{\leq} I_{FD}^{rated} \quad (29)$$

$$\tilde{I}_{FD8} = \sum_{i=1}^{9} (1 - x_i) I_{LATi} + \sum_{i=10}^{31} I_{LATi} + I_{FD8} \tilde{\leq} I_{FD}^{rated} \quad (30)$$

$$\mu_j = \min\left\{\mu(\tilde{N}), \mu(\tilde{I}_{LAT32}), \ldots, \mu(\tilde{I}_{LAT40}), \mu(I_{FD3}), \ldots, \mu(I_{FD8})\right\} \quad (31)$$

$$\mu_{\max} = \max(\mu_j); \quad j \in \{1, 2, 3, \ldots, 512\} \quad (32)$$

where I_{LATi} = current at lateral i before switching operation

$\tilde{I}_{LATi}$ = current at lateral i after switching operation

I_{FDj} = current at feeder j before switching operation

$\tilde{I}_{FDj}$ = current at feeder j after switching operation

I_{LAT}^{rated} = rated current of laterals

I_{FD}^{rated} = rated current of feeder

$\tilde{\leq}$ = fuzzy inequality relation "essentially less than or equal to

Note that case 1 represents the yearly average capacity load in 2009 whereas that of case 2 is assumed. If there is a short circuit near the substation (Point A in Figure 7), the simulation results for the two cases are shown in Tables 4, 5 and 6. The discussion for each case is given as follows.

Case 1: The restoration plan requires opening lateral switches SW2, SW6, SW8, SW9 and close tie switches SW14, SW18, SW20, SW22 so that the load in Lateral No.2, No.6, No.8 and No.9 can be supplied from SV427, EM412, SV418 and PA418, respectively. Tie switch SW10 can now be closed to complete the service restoration plan of case 1. Tables 4 and 5 show the restoration plans obtained the fuzzy reasoning method and heuristic method [3]. In this case, the number of switching operations of the fuzzy reasoning algorithm is greater because the feeder loading on SV422 (356.68A) and SV418 (357.18 A) is allowed to exceed the preferred limit (333 A) with less membership values, although these current flows satisfy the short term thermal limit constraint (407 A).

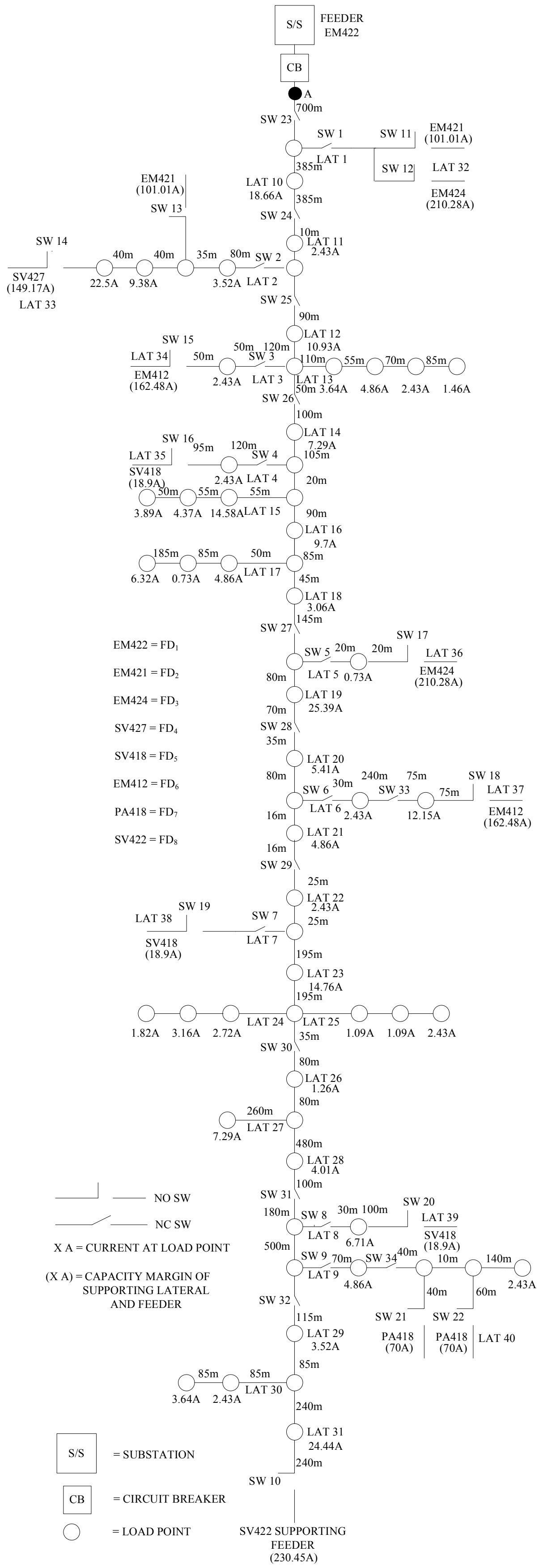

Fig. 7. MEA's distribution system.

Case 2: This case represents a peak demand scenario. The heuristic method has 4 more switching operations than the fuzzy reasoning method. The fuzzy method requires 5 lateral switches to be opened and 6 tie switches to be closed. However, because the number of switching operations and loading capability are considered as the soft constraint, the number of switching operations is decreased at the expense of degree of violation for feeder overload. Although the feeder conductors deteriorates for such short-term overload, it would be practically worth doing so because that restoration action, in turn, lengthens the expected life time of disconnecting switches in the system and shortens interruption duration and therefore the system reliability will be improved.

Table 2. Prefault loading condition for interrupted laterals and supporting laterals

Lateral No.	Load Lateral (A) (Case1/Case2)	Supporting Lateral No.	Load supporting Lateral (A) (Case1/Case2)
1	0.00/0	32	11.91/7
2	35.4/25	33	14.75/9
3	2.43/5	34	25.30/15
4	2.43/25	35	10.43/25
5	0.73/1	36	4.01/7
6	14.58/22	37	9.54/20
7	0.00/0	38	6.71/26
8	6.71/13	39	20.28/29
9	7.29/9	40	7.29/10
10	18.66/22	-	-
11	2.43/4	-	-
12	10.93/9	-	-
13	12.39/10	-	-
14	7.29/10	-	-
15	22.84/19	-	-
16	9.70/12	-	-
17	11.91/15	-	-
18	3.06/4	-	-
19	25.39/23	-	-
20	5.41/8	-	-
21	4.86/7	-	-
22	2.43/4	-	-
23	14.76/10	-	-
24	7.70/9	-	-
25	4.61/4	-	-
26	1.26/9	-	-
27	7.29/5	-	-
28	4.01/7	-	-
29	3.52/6	-	-
30	6.07/9	-	-
31	24.44/1	-	-

Table 6 shows the loading of feeders, supporting feeder and supporting laterals for the two cases. We can see that no overload is observed for each restoration plan except that supporting feeder SV422 is 5 A overload. However, this amount of overload is acceptable in practice and does not seriously harm the system. The overload may have been avoided if 4 more switching operations are allowed, as obtained in the heuristic method.

Table 3. Prefault feeder currents (A)

Feeder	Case1	Case2
EM422	280.53	321
EM421	268.99	220
EM424	159.72	180
SV427	220.83	270
SV418	351.10	300
EM412	207.52	270
PA418	300.00	300
SV422	139.55	148

Table 4. Restoration plan reached by fuzzy reasoning approach

Case	Switching Action	Number of Switching Operations
1	SW10, SW2, SW6, SW8, SW9, SW14, SW18, SW20, SW22	9
2	SW10, SW2, SW4, SW6, SW8, SW9, SW14, SW16, SW18, SW20, SW22	11

Table 5. Restoration plan for reached by heuristic search approach [3]

Case	Switching Action	Number of Switching Operations
1	SW10, SW2, SW6, SW9, SW14, SW18, SW22	7
2	SW10, SW2, SW3, SW4, SW5, SW6, SW8, SW9, SW14, SW15, SW16, SW17, SW18, SW20, SW22	15

8. DISCUSSION

The main contribution of this paper is a comprehensive treatment of network restoration based on heuristic and fuzzy reasoning methods using a real distribution system of MEA. The heuristic method is attractive for its computational efficiency but considers only the thermal limit of feeders (370 A). The fuzzy method is employed to compromise the number of switching operations and the overload constraint on main feeders and laterals. Since in the past, MEA has been using system operators' experience to restore its distribution systems after sustained interruptions. Although in many cases the solutions obtained were feasible, an optimal or near optimal solution was usually not guaranteed. More importantly, for a complex distribution system with a number of tie and sectionalizing switches, the system operator may fails to identify a feasible solution within a short period of time and therefore, short-term overload (400 A) was sometimes observed during switching actions, particularly during peak load periods. Such erroneous procedures would be eliminated if a rigorous restoration program were in use.

Table 6. Load Current (A) on Supporting Laterals and Supporting Feeder after Restoration of 2 Cases

FD&LAT	Case 1.1	Case 1.2	Case 2.1	Case 2.2
LAT32	11.91	11.91	7	7
LAT33	50.15*	50.15*	34*	34*
LAT34	25.30	25.30	15	20*
LAT35	10.43	10.43	50*	50*
LAT36	4.61	4.61	7	8*
LAT37	24.12*	24.12*	42*	42*
LAT38	6.17	6.17	26	26
LAT39	26.99*	20.28	42*	42*
LAT40	14.58*	14.58*	19*	19*
EM422	-	-	-	-
EM421	268.99	268.99	220	220
EM424	159.72	159.72	180	181*
SV427	256.23*	256.23*	295*	295*
SV418	357.81*	351.10	338*	338*
EM412	222.10*	222.10*	292*	297*
PA418	307.29*	307.29*	309*	309*
SV422	356.68*	363.39*	375*	369*

Note : Case 1.1 and 2.1 = restoration plan obtained from fuzzy reasoning approach.

: Case 1.2 and 2.2= restoration plan obtained from heuristic search approach.

* = there is a change in feeder or lateral current

Our results are always better and offer more flexibility than those obtained from an experience-based system restoration in terms of the number of switching operations and line overloads. Without fuzzy consideration (i.e., only crisp sets), both methods might arrive at the same solution. At present, switching schedules obtained from an experience-based system restoration procedure do not normally violate the thermal limits of feeders in MEA's distribution systems primarily because of a large capacity margin of supporting feeders and laterals. In fact, feeders and laterals are quite over-designed for almost all of the distribution systems in MEA; namely, their conductor sizes are the same (185 mm^2). For this reason, handling current flow is not difficult. However, as far as network congestion is concerned during peak load periods or due to load growth in the future, restoration by operators' judgment tends to be error-prone and hence the introduction of a restoration program becomes necessary in MEA's systems for efficient use of its capacity resource.

9. CONCLUSION

This paper presents the proposed methodology for service restoration in an uncertain environment based on fuzzy framework. The number of switching operations and loading capability of feeders and laterals are fuzzified using trapezoidal membership functions to indicate their membership values and are integrated into a fuzzy decision value. The service restoration is illustrated by a distribution system of MEA is presented. The searching process is performed by the complete enumeration algorithm to find an optimal solution. On the basis of these results, it is found that the number of switching operations can be decreased at the expense of degree of feeder and lateral loading for a short period of time. Although such an action degrades the useful lifetime of the conductors, it would be worth doing so owing to the customer's benefit in forms system reliability improvement. Therefore, the fuzzy models can offer flexibility and the means for including subjective judgement of the system operators for service restoration.

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