IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received October 10, 2017, accepted November 22, 2017, date of publication December 4, 2017, date of current version February 28, 2018.

Digital Object Identifier 10.1109/ACCESS.2017.2779823

Fuzzy Based Approach for Restoration of Distribution System During Post Natural Disasters

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ABSTRACT Distribution systems are inevitably vulnerable to natural disasters, which causes multiple damages within or outside the system. The disruption of supply demands microgrid formation, where the objective is to maximize the restoration of critical loads. The complete restoration requires repair of damaged regions which brings the need for an efficient crew selection, repair time estimation, and crew dispatch. Ranking of load points and location are important considerations for strategic placement of distributed generation units. Prioritization of damaged regions is required for efficient crew dispatch. These ranking depends on multiple criteria based on subjective opinions of the experts. However, the existing methods fail to take account of the same. This paper presents fuzzy approaches which fill the gap present in the existing methods by explaining the theoretical solutions to ranking of load points, locations, crew selection, estimation of repair times, and prioritization of the damaged regions.

INDEX TERMS Critical load, fuzzy logic, fuzzy theory, microgrid, natural disaster, repair crew.

I. INTRODUCTION

The power outages caused by natural disasters (floods, hurricanes/cyclones, tsunamis and earthquakes) have raised the importance of robustness and islanding capability of distribution systems. Weather related power outages accounts almost 44% of total power system outages and leads to severe power blackouts [1] which has been observed to increase [2] in recent times.

The restoration of critical loads and minimization of outage duration are major objectives of the system operators after a natural disaster. Due to the multiple damages, main grid may not be available for restoration of loads which enables the need of microgrid formation. The necessity and a method of microgrid formation is explained in [3] to increase the distribution system resilience. The benefits of the microgrids are explained in [4] with cost analysis from the view of natural disasters.

The microgrids are achieved by integrating the distributed generation (DG) into the conventional distribution system. Integration of DGs introduces various operational complexities in the distribution system. Despite of the operational complexities, improper DG location degrades the system performance instead of improving. Extensive research has been carried out to solve the optimal DG placement (ODGP) problem considering different objectives of distribution system, voltage stability margin improvement [5], minimization of power loss and voltage deviation [6] and improvement of reliability [7], [8]. Georgilakis and Hatziargyriou [9] mentioned the state-of-art of ODGP problem, different objective functions and optimization techniques. From the literature, it is found that researchers have considered the normal operating conditions and operational constraints (voltage limits, power balance and thermal limit) to solve ODGP problem.

An outage management system is essential during multiple outages in the system. Hierarchical outage management scheme is discussed in [10] considering multiple microgrids. The outage management system in [11] is aimed to identify the faulted section using information from smart meters. The outage management methods in the literature are not considered the quick restoration of critical load points. The repair crew ability to repair multiple faults in a single location is very important in case of natural disasters and researchers have ignored this.

The consideration of natural disaster scenario for ODGP enables the need of new constraints and objectives. The objective of the system operators is to maximize the critical load pickup and reduce the restoration time. The objective of maximizing the critical load pick up after the natural disaster needs the ranking/prioritization of loads. In the literature, selection of DG location is done by checking the operational constraints of a system. However, it also depends on many other factors which necessitates the consideration of a location constraint. The early restoration of critical loads needs prioritization of damaged regions. Also, the crew repair abilities and repair time for different damaged regions are required to be assessed before the crew dispatch.

The ranking of critical load points, finding location constraint and prioritizing damaged regions usually depends on multiple criteria and each criterion gives a linguistic opinion. In this paper, Fuzzy Multi Criteria Decision Making (FMCDM) is used to solve the ranking problem. The application of FMCDM in different fields can be found in [12]–[14]. Repair time depends on the severity of damage and number of damages in a damaged region. A fuzzy rule based system is developed for the estimation of repair time considering linguistic information available about damage severity of the system. The crew ability to repair a damage is determined by considering crew repair skills, required resources and crew resource handling capability. Fuzzy damage severity in a damaged region is evaluated considering the damage severity information. Fuzzy max-dot composition is applied to get a fuzzy relational matrix between crew and damaged region which gives the crew ability to repair a particular damaged region.

II. ISSUES WITH DISTRIBUTION SYSTEM RESTORATION

The distribution system restoration is done in two stages i.e. 1). Formation of microgrids for a quick restoration of critical loads. 2). Restoration of loads after the repair/replacement of damaged components.

A. MICRO GRID FORMATION

The objective of microgrid formation after natural disasters is quick restoration of critical loads i.e. critical loads are restored first. The objective is achieved by proper identification of critical loads in the system and placing DGs at strategic location in such a way that location is less/not affected with disasters.

1) LOAD POINT WEIGHTS

The typical loads in an urban distribution system are hospitals, government offices, public utilities, grocery, domestic and commercial consumers, etc. The preference of a load type over other load types can not be simply decided by a binary opinion of yes or no, instead it is a range of subjective opinions (strongly not, weakly not, equal, weakly and strongly) and it differs from consumer to consumer and situation to situation.

TABLE 1. Linguistic opinions and fuzzy numbers (example).

Linguistic term	Fuzzy number
Not applicable (NA)	(0,0,0)
Very less (VL)	(0,0,1)
Less (L)	(0,3,5)
Medium (M)	(4,6,8)
High (H)	(6,8,10)
Very high (VH)	(8,10,10)

In a distribution system, each load point is a mix of different load types, so each load type is a criterion for ranking the load points. The opinions are collected for each load point with regards to the importance of the load point from the point of view of each load type. The linguistic opinions and their associated triangular fuzzy numbers are given in the Table 1. The fuzzy numbers illustrated in Table 1 are taken as example. System operators are free to choose their own number of opinions and associated fuzzy numbers. However, all fuzzy numbers are taken in a fixed standard scale and each fuzzy number must overlap with other numbers. The evaluation of load type weights and load point ranking are explained in section III-A.

2) DG LOCATION

The selection of strategic location for DG placement will depend on many factors and their necessity is as follows:

- The availability of feeder section and vulnerability to weather conditions: It shows the impact on DG availability during natural disasters.
- Space availability: It includes rooftops and ground space which is required for the installation of DGs along with microgrid control facilities and fuel storage.
- Accessibility of location: It helps in the early restoration of DG damages and fuel supply.
- Public willingness: It handles the acceptance level of households surrounded by the DG location.
- Critical loads: Consideration of critical loads near to or around DG will help in maximizing the restoration of critical loads.

The experts' opinions are also collected to find the weight of each factor. The opinions are also collected for each location on how much that particular location is favourable for DG placement from the point of view of each factor. Based on these opinions, weights of factors and weights of locations (fuzzy ranking of locations) are evaluated.

B. REPAIR AND RESTORATION

The objectives considered during the repair and restoration process are minimization of repair time and maximization of early restoration of critical loads. The problem becomes critical because damaged regions may have multiple damage types (ex. pole damage, line damage, transformer damage and DG damages etc.) with different level of severity. Due to the limitation of crew skills and available resources, it is very important to prioritize the damaged regions and crew selection for repair of a damaged region. The demand to determine the repair time for damaged region increases due to multiple damages and severity levels.

1) CREW SELECTION

The repair crew selection for a damaged region is subjected to the crew skills and resource handling capacity. The crew selection process is simple if damaged region has a single damaged component, but it is not a realistic consideration during the natural disasters because multiple damages may occur in a single area/region. The repair crew have expertise in repairing particular types of damages and at the same time they have some ability to repair other types of damages at certain level. The crew selection for a particular damaged region is needed to be done by coordinating the crew abilities to repair damages, type and severity of damages along with consideration of resource handling capability.

2) REPAIR TIME

In the literature, repair time of a failed component is assumed as a constant value for particular damage. However, this assumption will fail during the natural disasters because single component damage is not a reasonable assumption at these situations. During natural disaster, a damaged region includes several component damages with a varying degree of severity, which initiates the need of an effective methodology to determine the repair time of a damaged region.

3) CREW DISPATCH

The crew dispatch to a damaged region is done in such a manner that it satisfies the objectives of minimum restoration time and an early restoration of critical loads. This requires the prioritization of the damaged regions after which the repair crew is dispatched based on the priority. The prioritization of the damaged regions depends on several factors, which are noted below:

- Minimum repair time
- More critical loads
- Less resources requirement
- Easy restoration of loads after repair
- Damaged regions containing DGs or near to substation/DGs
- Substation and DG damages
- Restoration of more number of consumers
- Interconnection of two microgrids or substation
- Accessibility of location

III. PROPOSED FUZZY BASED APPROACH

A. FUZZY RANKING BY MULTI CRETERIA DECISION MAKING

A distribution system comprises several load points and each load point can have different load types e.g. hospitals, public utilities, etc. The decision of assigning one load point as critical over the other load points should be made on the basis of various load types present on that load point. Now, a load type (say hospital) should be given more weight over the other load types. The problem of assigning weights to the load types is solved using fuzzy reciprocal matrix $B = [a_{jk}]$ [15], where a_{jk} is a positive number given to assign priority of j^{th} load type over k^{th} load type. The a_{jk} values are determined based on the subjective decision of experts and Table 2 shows the positive number assigned for each subjective decision. The subjective decision and positive numbers given in Table 2 will vary according to the system operators wish, but, the value '1' is always associated with equal preference and remaining value are taken more or less than '1' based on its preference.

TABLE 2. Subjective decision and assigned number(example).

Subjective decision	Assigned number
Strongly preferred	4
Weakly preferred	2
Equally preferred	1
Weakly not preferred	0.5
Strongly not preferred	0.25

The weights of each load type is obtained by using a geometric mean method to define the fuzzy mean number corresponding to a row e_j of B matrix and determination of weights are as follows:

$$e_j = (a_{j1}(.)a_{j2}(.)...(.)a_{jm})^{1/m} \tag{1}$$
$$w_j = e_j/(e_1(+)e_2(+)...(+)e_m) \tag{2}$$

Now, the ranking of load points considering different load types is evaluated using FMCDM [12]. A load point is rated with respect to the load types by a set of K experts based on the linguistic opinions given as an example in Table 1. Let $L = \{L_1, L_2, ..., L_l\}$ be the set of possible load points considered for rating in the distribution system and $C = \{C_1, C_2, ...C_m\}$ be the set of load types. Based on the linguistic opinions on the load points given by the experts, a rating $\tilde{x}_{ij}$ of i^{th} load point on j^{th} load type is calculated as follows:

$$\tilde{x}_{ij} = \frac{1}{K}\sum_{t=1}^{K}\tilde{x}_{ij}^{t} \tag{3}$$

The ratings thus found out can be summarized in the form of a matrix D given as

$$\tilde{D} = [\tilde{x}_{ij}]_{l\times m} \tag{4}$$

here, l is the total number of load points and m is the total number of load types.

The $\tilde{D}$ matrix is termed as the decision matrix which is used to obtain Fuzzy Grey Relational Coefficient (FGRC) of each load point which, as described in [12], is obtained as follows:

1. The $\tilde{D}$ matrix is normalized into $\tilde{R}$ matrix by a linear scale transformation so as to have a comparable scale.

$$\tilde{r}_{ij} = \left(\frac{x_{ij}^{l}}{c_j^{*}}, \frac{x_{ij}^{m}}{c_j^{*}}, \frac{x_{ij}^{r}}{c_j^{*}}\right);\, c_j^{*} = max(x_{ij}^{r}) \tag{5}$$

where, $\tilde{x}_{ij} = (x_{ij}^{l}, x_{ij}^{m}, x_{ij}^{l})$

2. After normalisation, hamming distance matrix $\tilde{H} = [\tilde{d}_{ij}]_{l\times m}$ is constructed by evaluating the hamming distance between the possible load points L_i and the referential sequence L^* is as follows:

$$\tilde{d}_{ij} = (\tilde{r}^*_{0j} - \tilde{r}_{ij}) \tag{6}$$

The referential sequence L^* is a set of ideal solution written as:

$L^* = [\tilde{r}^*_{0j}]$ where $\tilde{r}^*_{0j} = (0, 1, 0)$ for $j = 1, 2, ..., m$. and $\tilde{r}_{ij}$ is an element of $\tilde{R}$ matrix.

3. The FGRC is thus obtained by the following equation:

$$\tilde{\tau}_{0,i} = \sum_{j=1}^{m} \tilde{w}_j(.)\gamma(\tilde{r}^*_{0j}, \tilde{r}_{ij}) \tag{7}$$

where, $\gamma(\tilde{r}^*_{0j}, \tilde{r}_{ij}) = \frac{min_i min_j \tilde{d}_{ij} + \zeta max_i max_j \tilde{d}_{ij}}{(\tilde{d}_{ij} + \zeta max_i max_j \tilde{d}_{ij})}$

Thereupon, the preference relationships between the load points are obtained by fuzzy difference between $\tau_{0,i}$ and $\tau_{0,j}$ and is given as:

$$\tilde{Z}_{ij} = \tau_{0,i}(-)\tau_{0,j} \tag{8}$$

$\tilde{Z}_{ij}$ is also a fuzzy number as the complete analysis is dealt with fuzzy numbers of expert linguistic opinions and thus for an α cut it can be written as: $Z^{\alpha}_{ij} = [Z^{\alpha}_{ijl}, Z^{\alpha}_{ijr}]$.

If $Z^{\alpha}_{ijr} > 0$ and $Z^{\alpha}_{ijl} < 0$ with some α values, then e_{ij} is obtained to evaluate fuzzy preference relation of the load points which is given as

$$e_{ij} = \frac{S_1}{S}; S > 0 \tag{9}$$

where $S = S_1 + S_2$,

$S_1 = \int_{x>0} \mu_{Z_{ij}}(x)dx$, and $S_2 = \int_{x<0} \mu_{Z_{ij}}(x)dx$.

Thus fuzzy preference relation matrix is given as

$$E = [e_{ij}]_{l\times l} \tag{10}$$

And the fuzzy strict preference relation matrix, for strict comparison of load points, is written as

$$E^s = [e^s_{ij}]_{l\times l} \tag{11}$$

where,

$$e^s_{ij} = \begin{cases} e_{ij} - e_{ji}; & \text{when } e_{ij} \geq e_{ji} \\ 0; & \text{otherwise} \end{cases}$$

To obtain a rank of load points without comparison with other load points, a non dominated degree is needed and is written as

$$\mu^{ND}(L_i) = min[1 - e^s_{ji}] \;\; for\; j\epsilon\; \Omega \; and\; j \neq i \tag{12}$$

The non dominated degree thus obtained is used for the purpose of ranking each load points. Although, the method mentioned above is illustrated by taking the example of load points for the purpose of ranking, the same is used to obtain DG location ranking/location constraint and prioritizing the damaged regions for crew dispatch.

B. FUZZY RULE BASE SYSTEM FOR REPAIR TIME

The repair time estimation of a damaged region is a key factor for crew dispatch. As mentioned earlier, a damaged region contains several damages with different degree of severity. In general, the information regarding damage severity is received in linguistic terms such as: very low severity (VLS), low severity (LS), medium severity (MS), high severity (HS) and very high severity (VHS). A triangular fuzzy number is allotted for each linguistic term. The severity matrix $\tilde{SR}$ is constructed using these linguistic opinions.

$$\tilde{SR} = [S^{\beta}_{i,j}]_{n\times N} \tag{13}$$

here, $S^{\beta}_{i,j}$ is the severity of damage d_i in damaged region DR_j. β is the severity index. n and N are the number of damage types and damaged regions respectively.

Repair time for a damaged component varies based on the severity of damage. Based on the expert knowledge, a fuzzy rule base system is developed to determine the repair time of a damaged region. The inputs are severity of damages in a damaged region, given in linguistic terms and output is also considered in linguistic terms (very less time, less time, medium time, high time and very high time). These linguistic terms are associated with a fuzzy number and repair time is derived from this fuzzy number. Pictorial representation of the fuzzy rule base system is shown in Fig.1

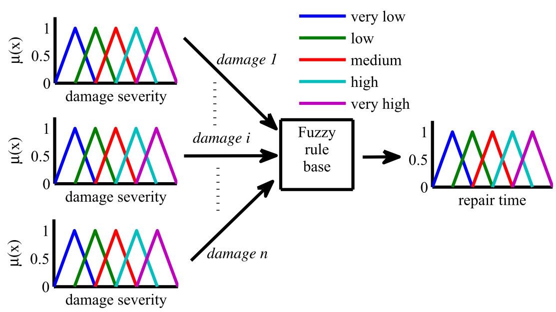

FIGURE 1. Fuzzy rule base system for evaluation of repair time.

C. CREW SELECTION BY FUZZY RELATIONS

The crew selection depends on the crew ability to repair a particular damage and total damages and their severity in a damaged region. The crew ability to repair a particular damage depends on the crew skills and resource handling capacity of the crew. The fuzzy membership value for a relation between the crew and a damage type is determined using the following membership function:

$$\mu_R(CR_i, d_j) = \begin{cases} 1; & M_{(CR_i,d_j)} \geq M_{d_j} \text{ and } Cap_i \geq Cap_{d_j} \\ 0; & M_{(CR_i,d_j)} \leq M^{min}_{d_j} \text{ or } Cap_i \leq Cap^{min}_{d_j} \\ b; & \text{otherwise} \end{cases} \tag{14}$$

where, $b = min\left\{\frac{M_{(CR_i,d_j)} - M^{min}_{d_j}}{M_{d_j} - M^{min}_{d_j}}, \frac{Cap_i - Cap^{min}_{d_j}}{Cap_{d_j} - Cap^{min}_{d_j}}\right\}$, Cap_{d_j} is the resources required to repair damage d_j, $Cap^{min}_{d_j}$ is the minimum required resources to repair damage d_j, Cap_i is the resource capacity of crew i, M_{d_j} is the required skilled persons to repair damage d_j, $M_{d_j}^{min}$ is the minimum required skilled persons to repair damage d_j and $M_{(CR_i,d_j)}$ is the skilled persons in crew i to repair damage d_j.

The fuzzy relational matrix which is formed between crew and damages is as follows:

$$P = [\mu(CR_i, d_j)]_{c\times n} \tag{15}$$

here, c is the total number of crew.

The more membership value means a crew has more ability to repair that damage and vice versa.

The severity of damage is a linguistic decision obtained from local people or inspection team and each linguistic information is associated with a triangular fuzzy number(example $A(a_1, a_2, a_3)$). The linguistic terms in matrix $\tilde{SR}$ are replaced with these fuzzy numbers. These fuzzy numbers are used to evaluate the yager's indices [16] using α-cut approach. The α-cut of fuzzy number $\tilde{A}$ having a crisp interval is represented as $A_\alpha = [A_\alpha^L, A_\alpha^U]$ and $\alpha \in [0, 1]$. The calculation of yager's indices are as follows:

$$Y(A) = \int_{\alpha^{min}}^{\alpha^{max}} V.(A_\alpha^L + A_\alpha^U)d\alpha \tag{16}$$

here, $V = \frac{\alpha^{min}+\alpha^{max}}{2}$,
$A_\alpha^L = (a_2 - a_1)\alpha + a_1$ and $A_\alpha^U = -(a_3 - a_2)\alpha + a_3$

The yager's indices arranged in a matrix form is as follows:

$$Y = [Y_{i,j}(A)]_{n\times N} \tag{17}$$

here, $Y_{i,j}(A)$ is the yager's indice for damage d_i in a damaged region DR_j. The elements of the matrix Y is normalized and elements are in the range of [0, 1] and these values represents the severity of a damage for a particular damaged region in a scale of 0 to 1 and it's called as membership value for damaged severity. The fuzzy damage severity relation matrix (S) is given below:

$$S = [\mu(d_i, DR_j)]_{n\times N} \tag{18}$$

here, $\mu(d_i, DR_j) = \frac{Y_{i,j}(A_{i,j})}{max(Y)}$

The membership value represents the severity of a damage d_i in damaged region DR_j.

Fuzzy max-product composition [17] is applied between fuzzy relational matrices P and S to get the fuzzy relation between a crew and a damaged regions, and it is as follows:

$$T(CR_i, DR_j) = \max_{k\in n} \{\mu(CR_i, d_k) \bullet (1 - \mu(d_k, DR_j))\} \tag{19}$$

The fuzzy relational matrix T is written as:

$$T = [\mu(CR_i, DR_j)]_{c\times N} \tag{20}$$

The membership value shows the crew ability to repair a damaged region.

D. DG PLACEMENT AND MICROGRID FORMATION

The optimal placement and size of DGs are determined using Particle swarm optimization techinque by taking critical load pick up as an objective function [18]. Different natural disaster scenarios are simulated while the DGs placement to make sure the avaialbility of DGs during any type of disaster scenario. The objective function is formulated using weigths of load points and is given by [18]:

$$Obj(critical\ load) = \max \left\{ \sum_{i=1}^{N} \sum_{j=1}^{M} W_j^i \right\} \tag{21}$$

here, W_j^i is the weight of j^{th} load point restored after i^{th} natural disaster scenario. N is the disaster scenarios considered. M is the total number of loads pick up by DGs for each scenario.

The ODGP problem is done by considering many constraints in the system. A location constraint is used to assure the DG availability during post disaster scenario [18]. It is formulated based on the weights of feeder sections and added to objective function as penalty factor. The location constraint (LC) is given by

$$LC = \sum_{k=1}^{N_{DG}} W_{FS,k} \tag{22}$$

N_{DG} is the number of DGs and $W_{FS,k}$ is the weight of the feeder section in which the k^{th} DG is connected. For secure operation of the system, operational constraints like voltage and thermal limits are considered and given by

$$V^{min} \le V_j \le V^{max} \tag{23}$$
$$I_i \le I_i^{max} \tag{24}$$

Microgrid formation is required during post disaster, but, operational constraints are not enough for secure microgrid formation. Hence, DG capacity limits and power flow constraints are taken in consideration for secure operation of microgrid and these are given by

$$P_{DG_i}^{min} \le P_{DG_i} \le P_{DG_i}^{max} \tag{25}$$
$$Q_{DG_i}^{min} \le Q_{DG_i} \le Q_{DG_i}^{max} \tag{26}$$
$$P_i = V_i \sum_{j\in n} V_j(g_{ij}Cos(\theta_{ij}) + b_{ij}Sin(\theta_{ij})) \tag{27}$$
$$Q_i = V_i \sum_{j\in n} V_j(g_{ij}Sin(\theta_{ij}) - b_{ij}Cos(\theta_{ij})) \tag{28}$$

IV. NUMERICAL EXAMPLE

In this section, a reliability test system RBTS bus 2 [19] is considered to validate the proposed methods. The test system is shown in Fig. 2. The necessary data for validation purpose is hypothetically assumed for the test system. Sectionalizing switches are available to isolated the feeder sections and disconnect switches are used to connect/disconnect the load points to the supply during the restoration process. The distribution system is represented as a graph and used during clustering and restoration process. Five damaged regions

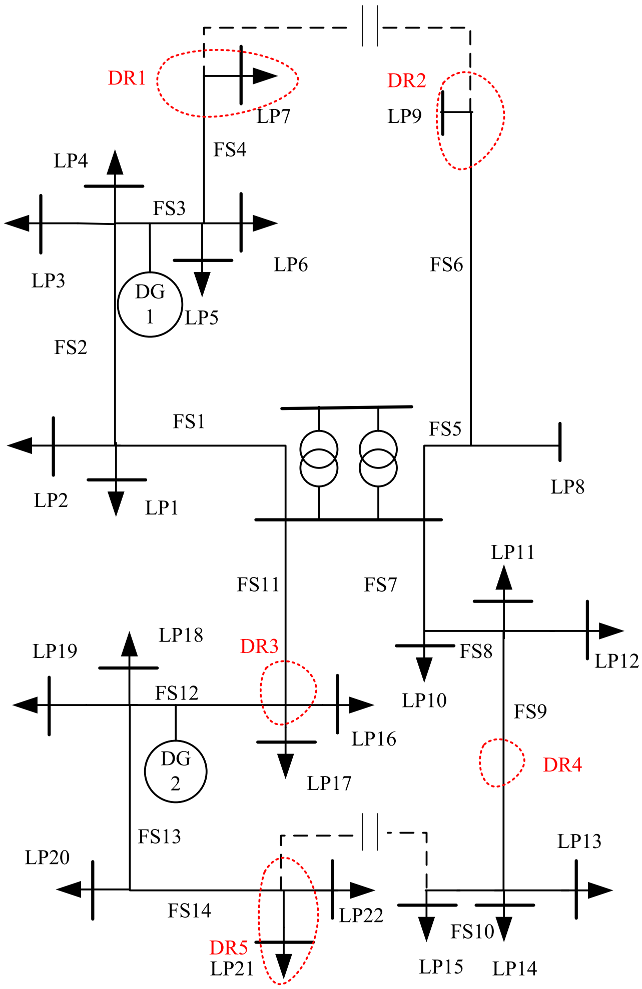

FIGURE 2. RBTS bus 2 test system with damaged regions and DGs

are aribitorily taken for the study and locations are shown in Fig. 2. The DG locations and size are taken from [18], and locations are mentioned in Fig. 2. The capacity of DGs are 4.5 MW and 3.2 MW for DG 1 and DG 2 respectively. DGs are placed during the system planning by simulating different natural disaster situations.

TABLE 3. Requirements for different damages and crew abilities.

	Requirements		Crew capacity(Crew 1, Crew 2)	
	Resources	Skilled persons	Resource	Skilled persons
d_1	1 - 4	2-4	(4,3)	(3,3)
d_2	1 - 5	2-5	(5,4)	(5,3)
d_3	1 - 4	2-5	(4,3)	(3,5)
d_4	1 - 4	1-3	(2,4)	(2,3)

The requirement of resources and skilled persons to repair a damage is given in Table 3, the minimum and maximum values represents the requirement from low severity to high severity respectively. Table 3 also contains the crew resource handling capacity and total number of skilled personals to repair a damage.

TABLE 4. fuzzy rules.

	Damages				Repair time
Rule	d_1	d_2	.....	d_n	out put
1	VLS	VLS	.....	VLS	VLT
....					
l	VHS	VHS	.....	VHS	VHT

A. ESTIMATION OF REPAIR TIME

As explained in the previous section III-B, a fuzzy rule base system is developed for estimation repair time of a damaged region. The generalized fuzzy rules are shown in Table 4, the output is a repair time in hours and it is decided by repair history of the damages. In this work, damage severities are classified into five different severity levels and repair time is also divided into five groups, each group is a triangular fuzzy number. Based on the damage severity in a damaged region, the respective fuzzy rule is fired and the respective output fuzzy number is defuzzified to get repair time of a damaged region.

In this demonstration, as mentioned earlier, each damaged region has different damaged types with different damage severity. The damage severity data is assumed and given in Table 5. The estimated repair times for damaged regions DR1, DR2, DR3, DR4 and DR5 are 15, 17, 17, 20 and 20 hours respectively.

TABLE 5. Damage severity in different damaged regions.

	d_1	d_2	d_3	d_4
DR1	MS	MS	MS	HS
DR2	HS	HS	LS	NA
DR3	VHS	HS	MS	NA
DR4	VHS	VHS	NA	NA
DR5	HS	MS	VHS	NA

B. FUZZY RANKING

The ranking problem is solved using FMCDM, which will be done in two stages. In first stage, the weights of the each criteria is determined and fuzzy weights for each alternative is evaluated in second stage. Here, the ranking of damaged regions is taken to demonstrate the proposed ranking approach. The ranking is done for two different cases i.e. with and with out main grid availability for restoration. The hierarchical structure of the ranking problem is shown in Fig. 3.

The experts subjective opinions are collected for each factor influencing the ranking of damaged region over another factor. The fuzzy reciprocal matrix B is evaluated using experts opinions and values given in Table 2. The fuzzy

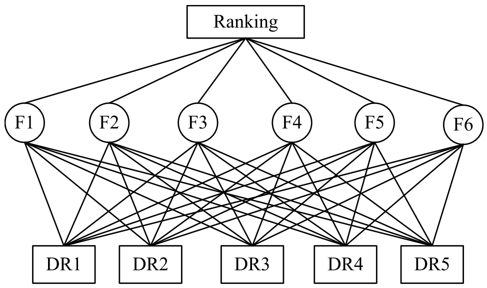

FIGURE 3. Hierarchical structure for ranking of damaged regions.

TABLE 6. Factors and weights for ranking of damaged regions.

Factor	Weight	Fuzzy number
Repair time	0.2019	(0.1817 0.2019 0.2221)
Critical loads	0.3142	(0.2828 0.3142 0.3456)
Resources requirement	0.1247	(0.1122 0.1247 0.1372)
Easy restoration	0.1373	(0.1235 0.1373 0.1510)
Number of consumers	0.1099	(0.0989 0.1099 0.1209)
Accessibility	0.1121	(0.1009 0.1121 0.1233)

reciprocal matrix is given below:

$$B = \begin{bmatrix} 1 & 0.75 & 2 & 0.75 & 3 & 1.5 \\ 1.33 & 1 & 3 & 3 & 3 & 2 \\ 0.5 & 0.33 & 1 & 1.5 & 1.5 & 0.75 \\ 1.33 & 0.33 & 0.67 & 1 & 2.25 & 0.75 \\ 0.33 & 0.33 & 0.67 & 0.44 & 1 & 4 \\ 0.67 & 0.5 & 1.33 & 1.33 & 0.25 & 1 \end{bmatrix}$$

By using the eq. (2), the weights of each factor is determined. The weights of each factor is given in Table 6. The weights of factors influencing the ranking of load points and location are evaluated using same process and are also represented by triangular fuzzy numbers, as given in Table 7 and Table 8 respectively.

TABLE 7. Factors and weights for ranking of load points.

Factor	Weight	Fuzzy number
Hospital	0.2775	(0.2498 0.2775 0.3053)
Govt. office	0.1599	(0.1439 0.1599 0.1759)
Public utilities	0.157	(0.1413 0.1570 0.1727)
Grocery	0.2001	(0.1801 0.2001 0.2201)
Domestic	0.1394	(0.1255 0.1394 0.1533)
Commercial	0.0661	(0.0595 0.0661 0.0727)

From Table 6, critical loads secure highest weight as objective of the DR ranking is early restoration of critical loads. Repair time plays a key role to repair a damaged region, so, it appears next to the critical loads. After repairing a damaged region, it must help to restore some of the load points. Hence, easy restoration secure third place. The resource requirement, accessibility and number of customers appears in descending order.

During a post disaster scenario, medical facilities and food availability are the primary concern and this is reflected in Table 7 and got highest weight values. The govt. offices and public utilities are very important to restore the normal life of people and these loads together got next priority. The commercial loads are not a concern during disaster scenarios and it's clearly reflected.

TABLE 8. Factors and weights for ranking of location.

Factor	Weight	Fuzzy number
Availability of feeder	0.2235	(0.2011 0.2235 0.2458)
Vulnerability to weather conditions	0.185	(0.1665 0.1850 0.2035)
Space availability	0.3244	(0.2920 0.3244 0.3568)
Public willingness	0.1229	(0.1106 0.1229 0.1352)
Critical loads	0.1442	(0.1298 0.1442 0.1586)

The weight values in Table 8 are supported with the following explanation. Space availability has got highest weight because without any space/land, it's impossible to place a DG at that location. The availability of feeder section (both technical feasibility and failure history) is required to make sure the location feasibility to place a DG. The aim of the DG placement is to restore the critical loads after a disaster situation. So, it's very important to consider vulnerability of location to extreme weather conditions. The critical load is a very important factor but without satisfying the space availability, availability of feeder and vulnerability to weather conditions, placing a DG cannot guarantee it's availability to pick the loads, so, it is placed in fourth position. If all other factors are satisfied then public willingness is not taken in a serious manner.

The linguistic ratings of each damaged region versus each factor is collected and these opinions are used to construct the fuzzy decision matrix $\tilde{D}$ by using fuzzy numbers in Table 1 and equation (3), the matrix is given in Table 9.

TABLE 9. Fuzzy decision matrix.

F1	F2	F3	F4	F5	F6
(4,6,8)	(8,10,10)	(8,10,10)	(8,10,10)	(8,10,10)	(0,3,5)
(8,10,10)	(0,0,1)	(4,6,8)	(4,6,8)	(0,0,1)	(4,6,8)
(0,0,1)	(4,6,8)	(4,6,8)	(0,0,1)	(0,0,1)	(8,10,10)
(4,6,8)	(8,10,10)	(0,3,5)	(8,10,10)	(8,10,10)	(4,6,8)
(6,8,10)	(6,8,10)	(0,3,5)	(6,8,10)	(0,3,5)	(0,3,5)

The decision matrix is normalized using eq. (5) and hamming distance matrix is calculated using eq. (6). The hamming distance matrix is given in Table 10.

The FGRC matrix is evaluated using eq. (7) and eq. (8), the result is shown in Table 11.

The fuzzy preference matrix is constructed using eq. (9) and eq. (10). The fuzzy strict preference matrix is evaluated

TABLE 10. Hamming distance matrix.

(0.2,0.4,0.6)	(0,0,0.2)	(0,0,0.2)	(0,0,0.2)	(0,0,0.2)	(0.5,0.7,1)
(0,0,0.2)	(0.9,1,1)	(0.2,0.4,0.6)	(0.2,0.4,0.6)	(0.9,1,1)	(0.2,0.4,0.6)
(0.9,1,1)	(0.2,0.4,0.6)	(0.2,0.4,0.6)	(0.9,1,1)	(0.9,1,1)	(0,0,0.2)
(0.2,0.4,0.6)	(0,0,0.2)	(0.5,0.7,1)	(0,0,0.2)	(0,0,0.2)	(0.2,0.4,0.6)
(0,0.2,0.4)	(0,0.2,0.4)	(0.5,0.7,1)	(0,0.2,0.4)	(0.5,0.7,1)	(0.5,0.7,1)

TABLE 11. Fuzzy grey relation coefficients.

(0.5,0.7,1.1)	(0.7,1,1.3)	(0.7,1,1.3)	(0.7,1,1.3)	(0.7,1,1.3)	(0.4,0.5,0.8)
(0.7,1,1.3)	(0.4,0.5,0.6)	(0.5,0.7,1.1)	(0.5,0.7,1.1]	(0.4,0.5,0.6)	(0.5,0.7,1.1)
(0.4,0.5,0.6)	(0.5,0.7,1.1)	(0.5,0.7,1.1)	(0.4,0.5,0.6)	(0.4,0.5,0.6)	(0.7,1,1.3)
(0.5,0.7,1.1)	(0.7,1,1.3)	(0.4,0.5,0.8)	(0.7,1,1.3)	(0.7,1,1.3)	(0.5,0.7,1.1)
(0.6,0.8,1.3)	(0.6,0.8,1.3)	(0.4,0.5,0.8)	(0.6,0.8,1.3)	(0.4,0.5,0.8)	(0.4,0.5,0.8)

TABLE 12. Ranking of damaged regions.

Damaged region	Case 1		Case 2	
	Weight	Rank	Weight	Rank
DR1	0.8436	3	1	1
DR2	0.6858	4	0.371	5
DR3	0.6069	5	0.5619	4
DR4	0.9362	2	0.7326	3
DR5	1	1	0.8658	2

TABLE 13. Load point weigths and ranking.

LP	Weight	Rank	LP	Weight	Rank
LP1	0.9966	2	LP12	0.5471	15
LP2	0.9004	6	LP13	0.5735	14
LP3	0.6207	12	LP14	0.9474	4
LP4	1	1	LP15	0.3816	20
LP5	0.9261	5	LP16	0.4938	19
LP6	0.8325	7	LP17	0.5424	16
LP7	0.7084	9	LP18	0.5949	13
LP8	0.6299	11	LP19	0.5424	16
LP9	0.3595	21	LP20	0.9699	3
LP10	0.5027	18	LP21	0.8062	8
LP11	0.5326	17	LP22	0.6806	10

using eq. (11) and the results are shown in matrix E^s.

$$E^s = \begin{bmatrix} 0 & 0.5389 & 0.6014 & 0.0880 & 0.2674 \\ 0 & 0 & 0.1017 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0.4740 & 0.5414 & 0 & 0.1961 \\ 0 & 0.2790 & 0.3578 & 0 & 0 \end{bmatrix}$$

The non-dominated (ND) weights are evaluated for each DR using eq. (12) and higher weighted DR gets the top priority and results are shown in Table 12. The same process is used to determine the ranking of load point and locations. The Table 13 and Table 14 are the weights and ranking of LPs and feeder sections respectively.

The effectiveness of proposed ranking method for prioritization of damaged regions are explained with the help of weight values given in Table 12 and Table 13. Firstly, case 1 is taken, the loads are isolated due to DR5 and DR4 are more critical and are easily restored with the help of DG 2 and main grid by closing tie switch after repair of these damaged regions. Both DR5 and DR4 are equally important, but DR5 stores more load point than DR4, hence, DR5 gets higher priority than DR4. The load points isolated by DR3 are less critical than DR1 and DR2. So, DR3 has given low priority than others. In case 2, main grid is not available and changes the complete restoration scenario. The loads isolated by DR1 are easily restored with DG 1 after DR1 repair. Due to the capacity limitation of DG 2, the loads isolated by DR4 and DR5 are may not be restored. However, DR1 repair time is comparatively less, so, DR1 has given high priority and DR5 and DR4 has ranked after the DR1. DR3 gives the easy restoration of loads compare to DR5 and DR4 but the loads are less important.

TABLE 14. Feeder section/location weights and rankings.

Feeder section	Weight	Rank	Feeder section	Weight	Rank
FS1	0.6853	7	FS8	0.7018	6
FS2	0.5998	11	FS9	0.6415	9
FS3	0.6563	8	FS10	0.8865	2
FS4	1	1	FS11	0.5792	12
FS5	0.5428	13	FS12	0.6853	7
FS6	0.7465	5	FS13	0.7785	4
FS7	0.6046	10	FS14	0.8121	3

However, the weights and rankings in Table 12, Table 13 and Table 14 are for illustration purpose. The weight values depends on the subjective ratings of experts and changes from person to person and situation to situation. The subjective rating must reflect the system operators policies on system priority load types and DG placement etc.

C. CREW SELECTION

The crew dispatch to damaged regions for repair needs the ranking of damaged regions and crew ability to repair a damaged region. This section demonstrates the evaluation of crew ability to repair each damaged region. In this example, two repair crews and four types of damages are considered for evaluation purpose. The fuzzy relation matrix P is evaluated using eq. (14) and data given in Table 3. This matrix gives the fuzzy relation between crew and damage type, more the membership value represents, more is the ability of the crew to repair that damage.

$$P = \begin{bmatrix} 0.5 & 1 & 0.3 & 0.3 \\ 0.3 & 0.5 & 0.7 & 1 \end{bmatrix}$$

The fuzzy severity relation matrix SR is obtained by using the data given in Table 5. The linguistic information in Table 5 is replaced by triangular fuzzy numbers given in Table 1.

The yager's indices are determined for severity matrix SR using eq. (16), the severity matrix and its yager's indices are

TABLE 15. Fuzzy severity matrix.

	DR1	DR2	DR3	DR4	DR5
d_1	(4,6,8)	(6,8,10)	(8,10,10)	(8,10,10)	(6,8,10)
d_2	(4,6,8)	(6,8,10)	(6,8,10)	(8,10,10)	(4,6,8)
d_3	(4,6,8)	(0,3,5)	(4,6,8)	(0,0,0)	(8,10,10)
d_4	(6,8,10)	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)

given below:

$$SR = \begin{bmatrix} 6 & 8 & 9.5 & 9.5 & 8 \\ 6 & 8 & 8 & 9.5 & 6 \\ 6 & 2.75 & 6 & 0 & 9.5 \\ 8 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The yager's indices are normalized to get the fuzzy damage severity relation matrix S, the element $S_{i,j}$ represents the membership value of damage d_i in damaged region DR_j, higher values represents more severity in that region. The fuzzy relational matrix is given below:

$$S = \begin{bmatrix} 0.6 & 0.8 & 1 & 1 & 0.8 \\ 0.6 & 0.8 & 0.8 & 1 & 0.6 \\ 0.6 & 0.3 & 0.6 & 0 & 1 \\ 0.8 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The fuzzy max-product composition is applied on fuzzy relation matrices P and S to get the fuzzy relation matrix T between repair crew and damaged regions using eq. (19) and eq. (20). The membership values indicates the crew ability to repair a damaged region.

$$T = \begin{bmatrix} 0.6 & 0.8 & 0.8 & 1 & 0.6 \\ 0.8 & 0.4 & 0.5 & 0.5 & 0.7 \end{bmatrix}$$

D. REPAIR OF DAMAGED REGIONS

The repair of damaged regions needs the prioritizing/ranking of damaged regions, so that optimal repair sequence is determined to achieve the objectives. The ranking of damaged regions are done for two cases as mentioned in previous section IV-E and the ranking details are given in Table 12. The crew ability to repair a damaged region is demonstrated by T matrix. According to the priority of the damaged regions, the crew having a higher value of membership function in the T matrix for a particular damaged region is being dispatched for the repair purpose. As an example, in case 1, the $DR5$ has the highest priority to get repaired, and the crew 1 and crew 2 for that damaged region have a value of 0.6 and 0.7 respectively. As higher value of membership value represents better ability to repair, crew 2 is, thus, selected as the dispatch crew to repair the damaged region $DR5$. At the same time, crew 1 dispatched to repair the damaged region $DR4$.

E. MICRO GRID FORMATION

The objective of the proposed fuzzy theory approach is to maximize the critical load pick up after natural disasters. This objective is achieved by proper ranking of load points, available locations and placement of a DG at a strategic location, so that DG is available after the natural disaster. The ranking of load points and feeder section for DG placement is given in Tables 13 and 14. Two DGs are placed in the test system by considering the ranking values given in Tables 13 and 14. Two DG are optimally placed at test system by considering the location constraint along with the operational constraints and DG locations are shown in Fig. 2. Two different cases are considered for microgrid formation after a natural disaster.

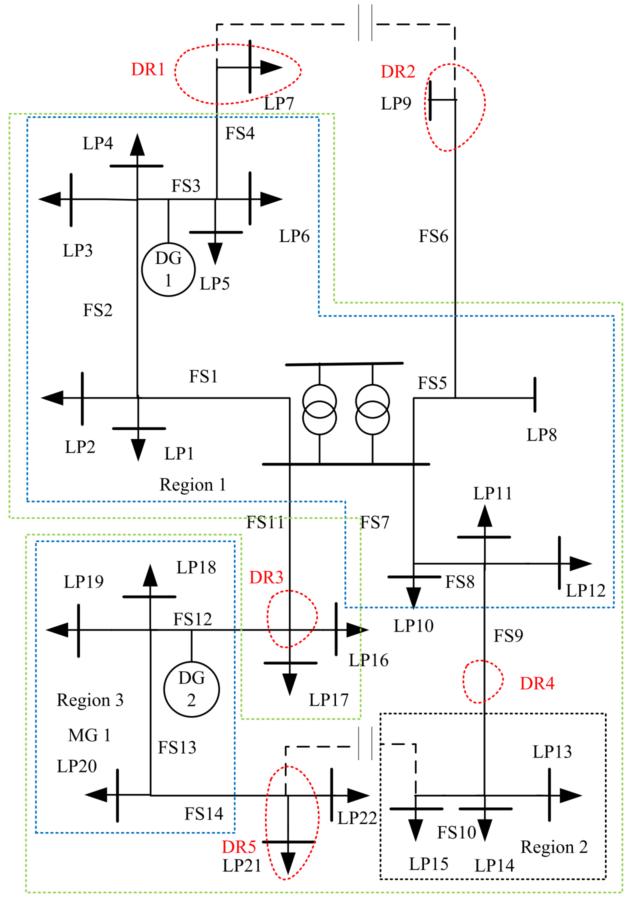

FIGURE 4. Microgrid formation for case 1

1) CASE 1

In this case, main grid is available for restoration purpose. Firstly, healthy system components are divided into three clusters and named as region 1, region 2 and region 3 and are shown in Fig. 4. As main grid is available in this case, region 1 is restored using main grid after the isolation of damaged regions. The region 3 has a DG and microgrid (MG 1) is formed in region 3 using the available DG. The MG 1 serves all three load points (LP18, LP19 and LP20) in the region 3 as the DG2 capacity is sufficient to serve. The load point restored immediately after isolation of damaged regions are covered with blue dotted lines in the Fig. 4. As region 2 doesn't have any possibility of restoration, the load points in that region are in waiting for repair of any of damaged regions i.e. DR5 and DR4 or DR5 and DR3. In the damaged region prioritization, DR5 and DR4 are in highest priority, repair crew are dispatched simultaneously. As the repair time of both regions are same and are repaired at the same time. The repair of DR5 and DR4 restores the service to region 2 along with load points LP21 and LP22. At this situation MG 1 is merges with main grid and total restored load points are shown under the green dotted lines in the Fig. 4. DR1 and DR2 are repaired with repair crew 2 and crew 1 respectively and restores the supply to LP7 and LP9 respectively. Finally, DR3 is repaired by crew 1 and restores the load points LP16 and LP17.

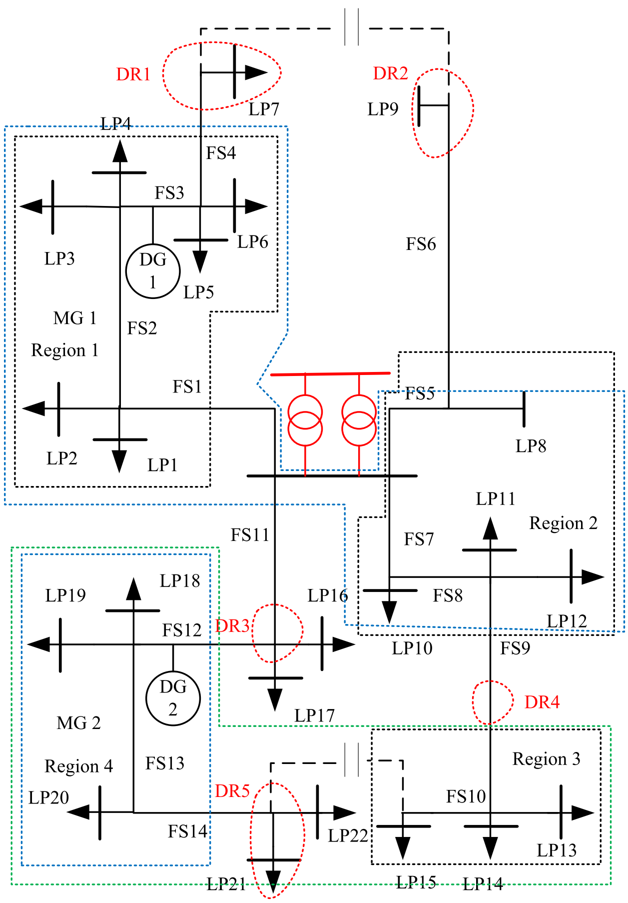

FIGURE 5. Microgrid formation for case 2.

2) CASE 2

In this case, main grid is not available for restoration purpose. The healthy system components are divided into four clusters named as region 1, region 2, region 3 and region 4. The different regions are shown in Fig. 5. Region 1 and Region 4 are having DGs and have a chance of microgrids formation. The region 2 joins with region 1 to form the microgrid MG 1 by DG1 (blue dotted line), but due to the generation limit of DG1, it's not possible to restore all load points in the MG 1. Hence, based on load point ranking, highest ranked load points are restored first and remaining kept isolated. Microgrid MG 2 is formed in region 4 (blue dotted line) by using DG2. Damaged region DR1 is repaired first because the load point (LP7) isolated by DR1 is easily restored with the help of DG1. The repair of DR5 merges the region 3 with MG 2 and repair of DR4 merges the region 3 with MG 1. But, MG 1 is too big as compared to MG 2 and there is a long way for power flow. So, DR5 repaired first and MG 2 is extended to region 3 (shown in green dotted line). Again, DG 2 capacity is not sufficient to restore all load points in the MG 3 and only high priority loads are served with a priority basis.

Based on the system operators restoration policy, whether, load shedding and/or curtailment is allowed during the micro-grid operation or not. If the shedding is allowed, highly critical load points are served continuously, on the other hand, less critical load are shedding in timely manner to satisfy the all loads in the microgrids. If the load curtailment is allowed, all load points are restored with reduced demand and no shedding of load points. The possibility of shedding of loads within a load point is a way for load curtailment of a load point.

Load flow analysis is done during the microgrid formation after connecting each load point to verify the techincal feasibility of microgrid formation.

V. CONCLUSION

The paper has presented different fuzzy based approaches to solve the distribution system restoration issues after natural disasters. The fuzzy multi criteria decision making is used for ranking of load points, feeder sections/location and damaged regions. The rankings have been found effective in choosing preferable DG placement and micro-grid formation. During a natural disaster, prioritization of damaged regions become necessary. Our proposed method effectively ranks the DRs for an optimal repair sequence and their rankings are justified, as discussed in the result section, on RBTS bus 2 with necessary data assumptions under two cases i.e with and without main grid supply. Ranking of a DR is a precursory to its repair as crew selection and dispatch becomes the next most important issue. Our proposed method on fuzzy max-product composition and rule base system has been found to efficiently tackle this issue with simple and feasible computations. The proposed methods are validated on small test system. However, the methods are having the ability to give the optimal solution for large systems consisting of thousands of load points and more number of DGs.

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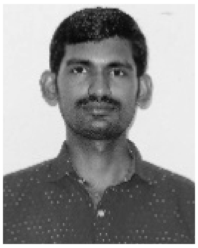

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