

A Fuzzy-Rule Based Power Restoration Approach for a Distribution System with Renewable Energies

Hong-Tzer Yang, Jian-Tang Liao, and Xiang-He Su

Department of Electrical Engineering
National Cheng Kung University
Tainan, TAIWAN
htyang@mail.ncku.edu.tw

Abstract—Based on heuristic fuzzy rules, a new power restoration approach is presented in this paper. The restoration approach developed can be used to deal with different fault cases in a distribution system (DS) with sources of renewable energies. This paper introduces “Load Path” as the main framework for restoration. The proposed strategy can achieve the advantages of simple decision criterions, balance of backup feeders, fast execution time, and applicability for different fault cases. Depending on fault situations, the number of load paths is different. With more than two load paths existing, the proposed fuzzy rules infer the best main load path with one of its switches operated as the restoration strategy (RS) for the specific case. To consider the distributed generations (DGs) of renewable energies, the proposed approach has been validated in a test system adapted from Taipower distribution system for different scenario studies.

Keywords—Restoration Strategies, Fuzzy Rules, Renewable Energies, Distribution System

I. INTRODUCTION

Due to rapid increases in demand and consumption of electrical energy, safe and reliable power supplies in an electrical system are drawing much more important than before. However, the growing size of power systems increases the complexity of its supervision, control, and energy demand supply management, especially as the DGs of renewable energies are taken into account.

Effective service RSs are very important when there is a fault occurring in the power system. The primary task of restoration is to find appropriate backup feeders to restore the outage zones (loads) as much as possible. For a large system, as a fault happens, the outage zones would be large and restoration of the outage zones appears relatively complicated.

There have been many studies focused on the RSs for the power systems. Heuristics based search methods [1-3] collect the operators' practical manipulation experiences to derive the restoration scheme. Expert system approaches [4-7] build a rule-based data system composed of operators' empirical rules and documents. Under occurrence of a fault, RSs would be automatically generated via the inference engine. Fuzzy theory [8-12] translates the problem's variables and objective functions into membership functions. By using the fuzzy inference value, feasible RSs are obtained. Petri-net algorithm

[13, 14] constructs into a net the feeders of a distribution system and the switches' states and the locations. With combination of empirical rules and evaluation function, the searching process infers a restoration plan. These methods above can be roughly regarded as heuristic-based restoration strategies. They can find appropriate RSs fast; however it needs a large data base to handle different fault cases, and it can't ensure if the obtained RS is the best one for the fault case.

On the other hand, the RSs are derived on the basis of optimization algorithms. Genetic algorithm [15-18] has been employed to generate optimal restoration plan through imitating the evolution process. Particle-swarm optimization [19-21] and ant-colony optimization [22] are alternative optimization approaches. They are all inspired from the swarm or colony of creatures, such as fish, birds, and ants. Though these methods can deal with multi-objective optimization problem and achieve a near-optimal solution, the results are influenced by different parameters given. Besides, far more computational time is needed to generate an optimal restoration plan. Plus, in the optimization process, most of the switches considered as variables to determine may be unrelated to the restoration of the outage zones, a fact which wastes the searching time a lot.

In this paper, a fuzzy-rule based power restoration approach is proposed. For different types of faults occurring, a corresponding inference procedure is performed to create the restoration strategies. By using the “Load Path” notion, the developed RS transfers appropriate amount of outage loads to backup feeders based on backup feeders' capacity and their loads at the instance of restoration. Balanced loads of the backup feeders are expected with overloads avoided as much as possible. As more than one load paths are considered, a fuzzy-rule based inference process is used to achieve an appropriate restoration scheme. Load transferring or shedding would be used, as there is no enough margin of capacity on the backup feeders. With DGs of renewable energies existing in the distribution system, the developed RS can also take the influences of DGs into consideration.

II. PROPOSED FUZZY RULE BASED RESTORATION APPROACH

The proposed restoration approach to be detailed in this section is based on simple decision fuzzy rules. The algorithm developed is described in the flowchart of Figure 1. The

following assumption is made before the restoration algorithm proceeds:

- The fault and the outage zones have been identified and isolated from the grid.
- The loads of each zone and the available output of DGs of renewable energy are well known enough at the instance of restoration in a smart-grid system.

In the proposed approach described below, the load transferring process will be used to make the backup feeder have more capacity to supply the loads. The load transferring process is to choose the secondary backup feeder with the largest capacity margin to supply appropriate amount of loads originally belonging to some backup feeder. The secondary backup feeders with smaller capacity margin are then considered. If capacity margin of the secondary backup feeder is smaller than the amount of loads needed to transfer, the transferring load process would not be performed.

A. Proposed Restoration Approach

The proposed restoration algorithm is described step by step as follows.

Step 1) Detect the fault, and open the isolation switch(es) to isolate the fault. The outage zones are recognized.

Step 2) Find out the set of available tie switches for restoring the outage zones.

Step 3) Based on the number of available tie switches, the sub-steps next are followed:

Step 3-1) For number of available tie switches, $n_{TSW}=1$.

Step 3-1-1) Check if the backup feeder has enough capacity margin. If it is, then go to **Step 3-1-5**; otherwise go to **Step 3-1-2**.

Step 3-1-2) Execute the load transferring process of the backup feeder.

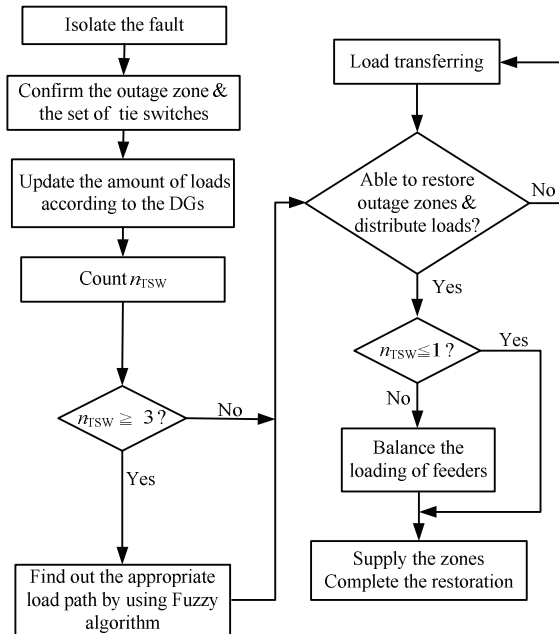


Figure 1. Flowchart of the proposed RS

Step 3-1-3) Check again whether the backup feeder has enough capacity margin. If it is, then go to **Step 3-1-5**; otherwise go to **Step 3-1-4**.

Step 3-1-4) Supply the loads in the outage zones by the backup feeder as much as possible; shed the loads still not restored in the remaining outage zones.

Step 3-1-5) Restore the outage zones by the backup feeder and finish the restoration process.

Step 3-2) For number of available tie switches, $n_{TSW}=2$

Step 3-2-1) Construct the only one load path between the two tie switches (for example, the load path is Z_5 - Z_6 - Z_7 - Z_8 - Z_9 in Figure 5).

Step 3-2-2) Identify and integrate the outage zones which would be integrated into a load path (for example, Z_4 in Figure 5).

Step 3-2-3) Check if the total capacity margin of the two backup feeders is enough to supply the outage loads. If it is, then go to **Step 3-2-6**; otherwise go to **Step 3-2-4**.

Step 3-2-4) Perform the load transferring process.

Step 3-2-4-1) Perform load transferring of the backup feeder with less capacity margin until the total capacity margin of the two backup feeders can meet the outage loads. If it cannot meet, then go to Step 3-2-5; otherwise go to Step 3-2-6.

Step 3-2-4-2) Perform load transferring of the backup feeder which cannot supply its corresponding loads. After the load transferring, if the backup feeder still doesn't have enough capacity margin, then go to **Step 3-2-5**; otherwise go to **Step 3-2-6**.

Step 3-2-5) Supply the outage zones as much as possible by the backup feeders individually; shed the remaining outage loads in the zones, if there still are.

Step 3-2-6) According to backup feeders' loading ratios of capacity margin, as shown in (1), divide appropriately the loads into two parts by opening a switch on the load path to be supplied by individual backup feeders.

$$\text{Min}\left(\left|\frac{LS_1}{MC_1} - \frac{LS_2}{MC_2}\right|\right) \quad (1)$$

where LS_i is the load supplied by backup feeder i , and MC_i is the capacity margin of backup feeder i . If both backup feeders can supply the corresponding loads individually, finish the restoration process; otherwise go to **Step 3-2-4-2**.

Step 3-3) For number of available tie switches, $n_{TSW} \geq 3$

Step 3-3-1) Determine and integrate the outage zones into load paths.

Step 3-3-2) Determine the main load path based on the

proposed fuzzy inference rules, to be illustrated further below.

Step 3-3-3) Integrate the remaining outage zones other than those on the main load path into the main load path.

Step 3-3-4) Check whether the total capacity margin of the two backup feeders on the main load path is enough to supply all the outage loads. If it is, then go to **Step 3-3-9**; otherwise go to **Step 3-3-5**.

Step 3-3-5) Have the integrated outage zones (not belonging to the original main load path) be supplied by the other backup feeder as much as possible.

Step 3-3-6) Check again whether the total capacity margin of the two backup feeders on the main load path is enough to supply the outage loads. If it is, then go to **Step 3-3-9**; otherwise go to **Step 3-3-7**.

Step 3-3-7) Perform the load transferring process.

Step 3-3-7-1) Perform load transferring of the backup feeder with less capacity margin until the total capacity margin of backup feeders can supply the outage loads. If it cannot, go to **Step 3-3-8**; otherwise go to **Step 3-3-9**.

Step 3-3-7-2) Perform load transferring of the backup feeder which cannot supply its corresponding loads. After the load transferring, if the backup feeder still doesn't have enough capacity margin, go to **Step 3-3-8**; otherwise go to **Step 3-3-9**.

Step 3-3-8) Supply the outage zones as much as possible individually by two backup feeders; shed the remaining outage loads of the zones, if there are.

Step 3-3-9) According to backup feeders' loading ratios of capacity margin as shown in Eq. (1), allocate appropriate amounts of loads into two parts to open a switch on the load path. If both backup feeders can supply the corresponding loads individually, finish the restoration process; otherwise **Step 3-3-7-2**.

B. Update of Loads and DGs in Outage Zones

DGs of renewable energies may have discontinuous output due to weather conditions, such as PV, wind-turbine (WT), combined heat and power (CHP), and fuel cell (FC) generation systems in the DS. To restore the loads in the outage zones, the loads of the still energized area and the available power output of the DGs can be updated before the restoration process under the assumption of an established smart-grid system. At the same time, information on number of available tie switches n_{TSW} in the outage zone is needed.

C. Restoration Process

Figure 2 shows the example DS diagram used for illustration of the restoration process. In description of the proposed restoration approach below, cases of different numbers of available tie switches that can be used in restoration are discussed.

1) Case 1: Number of available tie switch = 1

In Figure 3, suppose there was a fault occurring at Z7, switches S_9 and S_{10} , therefore, were opened to isolate the fault. Then, the load path of Z_8-Z_9 is defined. This is the simplest case where to close S_{12} is the strategy to restore the outage zones. If the backup feeder, Feeder4, doesn't have enough capacity to supply the outage zones, the backup feeder transfers load to the other feeder (secondary backup feeder) to obtain more capacity.

However, if it still fails to restore outage zones after the load transferring process, the restoration process will start to shed the loads. As many loads as possible are supplied by the backup feeder (Feeder4) with the remaining loads in the outage zones being shed.

2) Case 2: Number of available tie switches = 2

a) Type 1: No outage zones to be integrated

Suppose there was a fault occurring in Z_4 as shown in Figure 4. Switches S_5 and S_6 were opened to isolate the fault. Load path of $Z_5-Z_6-Z_7-Z_8-Z_9$ is defined. It is clear to see that the outage zones have two backup feeders: Feeder2 and Feeder4. The RS will choose one switch of S_8 , S_9 , S_{10} , and S_{11} to separate the load path into two parts. Appropriate amount of loads is allocated to the two backup feeders according to the loading ratios of capacity margin of the individual backup feeder as shown in Eq. (1).

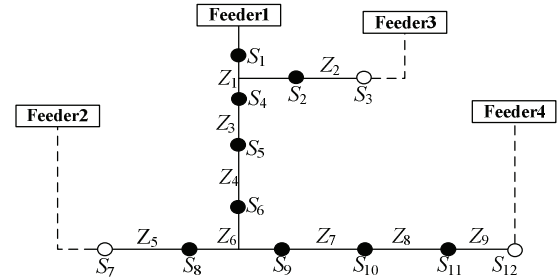


Figure 2. An example DS diagram

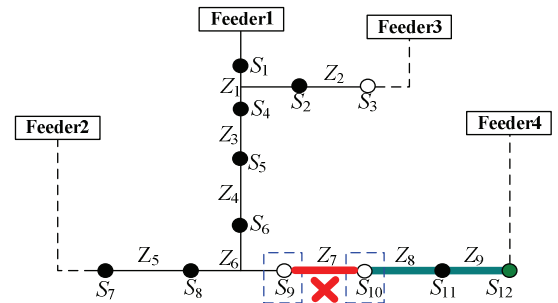


Figure 3. The DS diagram with one tie switch

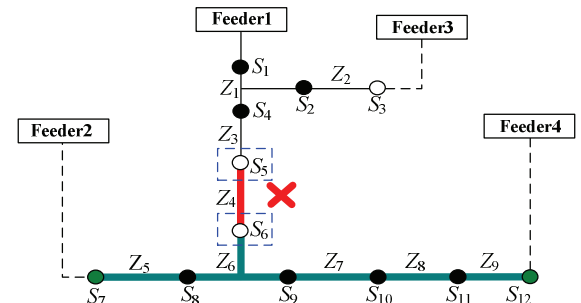


Figure 4. The DS diagram with two tie switches & no outage zones be integrated

The purpose is to make the loads of backup feeders balanced to avoid overloading for either of the backup feeders.

If the backup feeders, Feeder2 or Feeder4, don't have enough capacity margin to supply the outage zones, the backup feeders will proceed to the load transferring process trying to obtain more capacity. If it still fails to restore outage zones after their own load transferring process, the strategy will start to shed the loads to have as most loads supplied.

b) *Type 2: Outage zones to be integrated*

If the fault occurred at Z_3 as shown in Figure 5, S_4 and S_5 were opened to isolate the fault. The load path of Z_5 - Z_6 - Z_7 - Z_8 - Z_9 is defined. However, it is noted that Z_4 should be integrated into the load path, otherwise it cannot be restored. In this case, the outage zones also have two backup feeders: Feeder2 and Feeder4. The same steps are followed as in Type 1 above to restore the outage zones.

3) *Case 3: Number of available tie switches ≥ 3*

Suppose a fault occurred at Feeder1 as shown in Figure 6, S_1 was opened to isolate the fault. Based on the proposed algorithm, three tie switches of S_3 , S_7 , and S_{12} are available for the restoration in this case. Accordingly, three load paths in Figure 6 are defined below:

- Load Path 1 (S_3 to S_7): Z_2 - Z_1 - Z_3 - Z_4 - Z_6 - Z_5
- Load Path 2 (S_3 to S_{12}): Z_2 - Z_1 - Z_3 - Z_4 - Z_6 - Z_7 - Z_8 - Z_9
- Load Path 3 (S_7 to S_{12}): Z_5 - Z_6 - Z_7 - Z_8 - Z_9

The RS will find out the main load path by using the following fuzzy inference process. Two membership functions of the following fuzzy variables are used as illustrated in Figure 7 for the fuzzy inference rules.

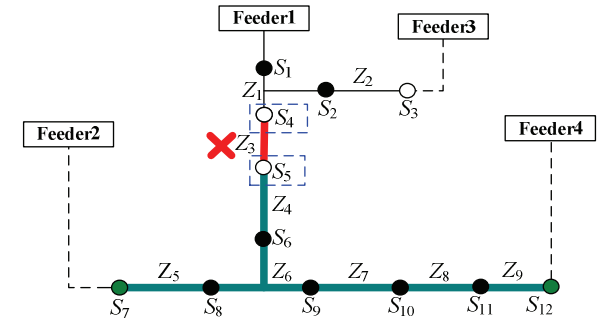


Figure 5. The DS diagram with two tie switches & outage zones to be integrated

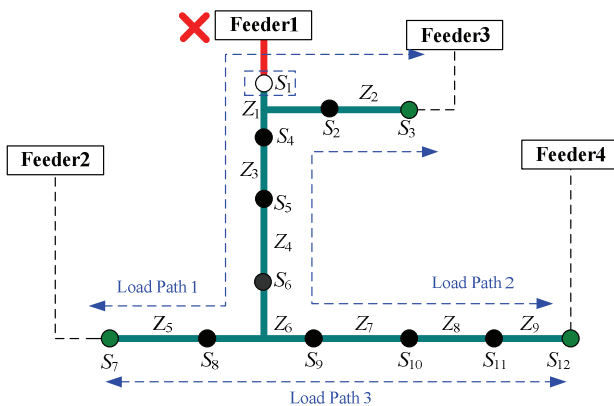


Figure 6. The DS diagram with more than three tie switches

- The total capacity margin of two backup feeders on the load path
- The total outage loads of the load path

The fuzzy rules are showed in Table. I. Take "Load Path 1" in Figure 6 for example, the inputs of the fuzzy inference engine are defined as the total capacity margin of Feeder3 and Feeder2 and the total outage loads of "Load Path 1." Based on the fuzzy inference and defuzzification process, the main load path with highest output value will be determined, whose outage zones will be restored with priority.

With the main load path determined, loads of the rest outage zones are integrated into the zone of the main load path. For example, if the "Load Path 2" is the determined main load path, the restoration process will integrate Z_5 into Z_6 , and the outage zones will be restored by Feeder3 and Feeder4. Then, the restoration process will choose one switch among S_2 , S_4 , S_5 , S_6 , S_9 , S_{10} , S_{11} , or S_{12} to separate the load path into two parts. The objective is to allocate appropriate amount of loads to different backup feeders.

If the backup feeders have no enough capacity margin, the proposed algorithm will check whether the integrated outage zones (e.g. Z_5) can be supplies by its connecting backup feeder (e.g. Feeder2) or not. In case the margin for restoration of the outage loads is still not enough, the load transferring process will proceed. However, if the load transferring process fails restoration of all the outage zones, the algorithm will start to shed the loads of the remaining outage zones, as the backup feeders (Feeder3 & 4) supply as many loads as they can.

III. SIMULATION RESULTS

The proposed algorithm is implemented in MATLAB 7.1 on a windows-XP based PC with Intel Core 2, Duo E7200, 2.53-GHz CPU and 2GB of RAM. The proposed restoration approach was applied to a practical 6-feeder DS of Taipower Company (TPC) [23].

A. Scenario 1: Large Outage Zone Situation

Suppose that there was a fault occurring at Feeder5 as in Figure 8. The system opened S_{59} (CB_5) first to isolate the fault. Because the number of corresponding available tie switches is three, including S_{38} , S_{41} and S_{44} , with three load paths existing.

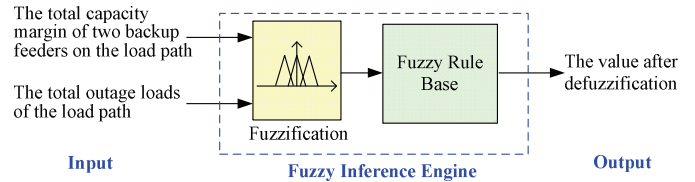


Figure 7. The fuzzy inference process in determining the main load path

TABLE I. THE FUZZY RULES USED IN THE INFERENCE ENGINE

A \ B	Low	Medium	High
Low	Medium	Low	Medium
Medium	Medium	Medium	High
High	Low	Medium	High

Note: A: total capacity margin of the backup feeders on the load path
B: the total outage loads on load path

The proposed algorithm determined the main load path based on the fuzzy inference rules described. Then the process proceeded to restore the outage zones to have balanced loading of feeders. The final result is showed in TABLE II. Through this scenario, it shows that the proposed restoration can deal with serious fault cases with large outage zones and achieve load balancing as much as possible.

B. Scenario 2: Comparison with the Method in [23]

In this scenario, the proposed approach was compared with the method in [23]. It was assumed that there was a fault occurring at Z_{43} as shown in Figure 9. The restoration algorithm opened S_{47} and S_{48} first to isolate the fault. The corresponding two available tie switches are S_4 and S_{41} for only one load path existing.

The proposed restoration approach determined whether outage zones were needed to be integrated or not. In this scenario, Z_{44} and Z_{45} must be integrated into Z_{46} for restoration. Then the process proceeded to restore the outage zones and balance the loading of feeders as much as possible simultaneously. The final result is showed in TABLE III, the proposed approach can achieve a solution with all outage zones restored with balanced loads of the backup feeders.

In comparison, the solution obtained by the expert system proposed in [23] still has the outage zones of Z_{49} and Z_{50} un-restored, and all the restored zones are supplied by single feeder instead of balancing the loads via two backup feeders as in the proposed method.

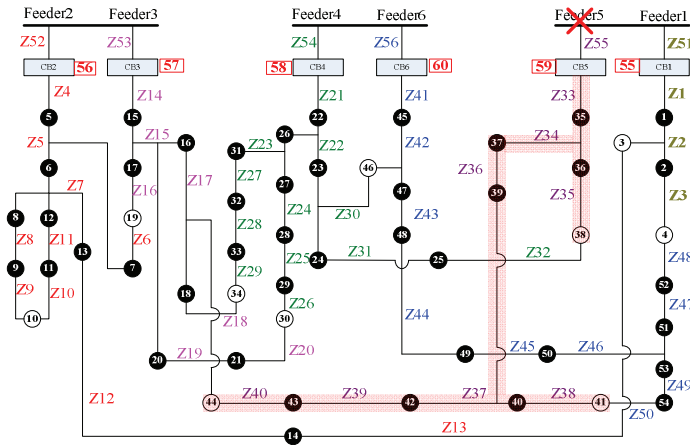


Figure 8. TPC 6-feeder system with fault at Feeder5

TABLE II. THE FINAL RESULTS FOR SCENARIO 1 AFTER RESTORATION

Items	Scenario 1
Fault Location	Feeder5
Isolation Switch	CB5 (S_{59})
Total Outage Zones Before Restoration	$Z_{33}, Z_{34}, Z_{35}, Z_{36}, Z_{37}, Z_{38}, Z_{39}, Z_{40}$
Backup Feeder (FD)	Feeder3 Feeder4
Supplied Zones	$Z_{37}, Z_{38}, Z_{39}, Z_{40}$ $Z_{33}, Z_{34}, Z_{35}, Z_{36}$
Switch Operation	Close: S_{44}, S_{38} ; Open: S_{39}
Outage Zones After Restoration	None
Execution Time (s)	1.367136

C. Scenario 3: Comparison with/without DGs Considered

In this scenario, the purpose is to find out influence of DGs considered on restoration strategies. The DS without DGs considered was compared with that with DGs. To consider the DGs, the fault situation is assumed the same as Scenario 1 as shown in Figure 8, but having some zones installed generators of renewable energies.

TABLE IV summarizes the zone conditions with DGs considered for Scenario 3. Accordingly, capacities of all feeders were also adjusted to lower values to make the restoration more difficult in recovering the loads.

TABLE V show the results obtained with and without DGs considered. It was supposed in a smart-grid system the loading conditions are updated periodically. Different switching operations for the two cases are shown in TABLE V. The case without DGs considered needs more switching operations to transfer the loads for the system restoration.

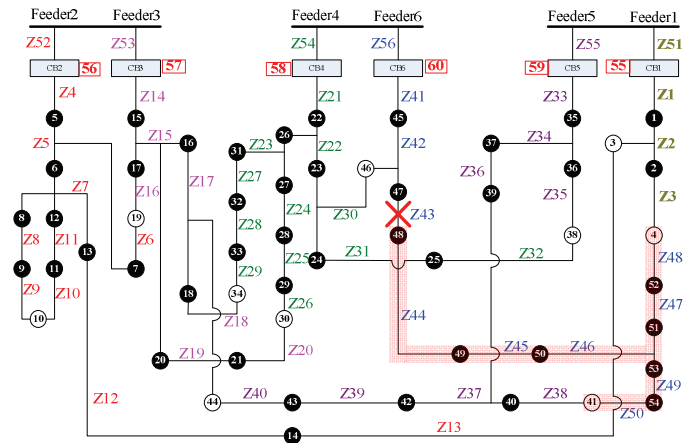


Figure 9. TPC 6-feeder system with fault at Z_{43}

TABLE III. THE FINAL RESULTS FOR SCENARIO 2 AFTER RESTORATION

Method	Proposed strategy	Expert system [23]
Items		
Fault Location	Z_{43}	
Isolation Switch	S_{48}	
Total Outage Zones Before Restoration	$Z_{44}, Z_{45}, Z_{46}, Z_{47}, Z_{48}, Z_{49}, Z_{50}$	
Backup Feeder	Feeder1 Feeder5	Feeder1
Supplied Zones	Z_{47}, Z_{48} $Z_{44}, Z_{45}, Z_{46}, Z_{49}, Z_{50}$	$Z_{44}, Z_{45}, Z_{46}, Z_{47}, Z_{48}$
Switch Operation	Close: S_4, S_{41} , Open: S_{51}	Close: S_4 Open: S_{53}
Outage Zones After Restoration	None	Z_{49}, Z_{50}
Execution Time (s)	1.005192	N/A

TABLE IV. THE ZONE CONDITIONS FOR DGs IN SCENARIO 3

Zone	Type of DG	Capacity
33	PV+WT	60kW (5kW×8+2kW×10)
34	PV	40kW (5kW×8)
35	PV+FC	50kW (5kW×2+20kW×2)
36	WT	40kW (2kW×20)

TABLE V. THE RESULTS FOR SCENARIO 3 AFTER RESTORATION

Case	With DGs	Without DGs
Fault Location	Feeder5	
Isolation Switch	S_{59}	
Total Outage Zones Before Restoration	$Z_{33}, Z_{34}, Z_{35}, Z_{36}, Z_{37}, Z_{38}, Z_{39}, Z_{40}$	
Backup Feeder	Feeder3	Feeder4
Supplied Zones	$Z_{37}, Z_{38}, Z_{39}, Z_{40}$	$Z_{33}, Z_{34}, Z_{35}, Z_{36}$
Switch Operation	Close: S_{44}, S_{38} Open: S_{39}	Close: S_{44}, S_{38}, S_{41} Open: S_{37}, S_{40}
Outage Zones After Restoration	None	None
Execution Time (s)	1.374077	1.359812
Remark	None	Z_{38} is transferred to Feeder6

IV. CONCLUSIONS

In this paper, a heuristic fuzzy-rule based system was proposed for restoration of a DS with/without existing DGs of renewable energies. Based on the concept of load path, loads in the outage zones are supplied as much as possible by backup feeders. Through the proposed process, balanced feeders' loading can thus be achieved. For large outage zones, the main load path is determined for more than two load paths via the proposed fuzzy inference rules. With different types of DGs and fault conditions existing in the DS, the proposed algorithm can also deal with the corresponding restoration problem easily based on the simple fuzzy decision rules.

The test results by using a practical Taipower distribution system showed different faulty situations can be well dealt with by using the proposed approach. Further, the proposed approach can have better restoration results (without loads un-restored in the outage zones) as compared with the expert system tested on the same system. The influence of DGs of renewable energies on restoration of a DS was also evaluated through the proposed approach.

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