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A Decentralized Technique for Autonomous Service Restoration in Active Radial Distribution Networks

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***Abstract*—This paper proposes a fully decentralized Multi-Agent System (MAS) based technique for service restoration of radial distribution networks. The technique utilizes expert system rules and considers the customers' priority and the presence of distributed generators (DGs). It also considers the operational constraints in both healthy and restored sections of the feeder. The technique relies on one type of agents only, hence, simplifying its implementation. Moreover, it allows for assigning a back-up decision making agent to improve the reliability of the restoration process. The effectiveness of the technique is validated through several case studies simulated on an 11 kV distribution feeder. The agents are implemented in Java Agent Developing Framework (JADE) environment for communications and decisions making. Power flow calculations are performed in MATLAB environment to validate the correctness of the agents' decisions.**

***Index Terms*—service restoration, DGs, Multi-agent, decentralized, active distribution system.**

I. Introduction

SERVICE restoration aims to find an appropriate healthy path to restore the maximum possible out of service loads of a faulted feeder [1]. Restoration techniques can be based on optimization methods [2][3], heuristic algorithms [4] or expert system rules [5]. Optimization based techniques require a centralized coordination strategy to find an optimal restoration path. Thus, they require extensive computations which might limit the fast restoration process, especially in large networks [6]. Moreover, the centralized coordination strategy has low reliability due to its dependence on one central unit for the decision making. Restoration techniques that are based on heuristic algorithms and expert system rules can utilize decentralized coordination strategy which leads to fast restoration [6]. However, the restoration path obtained by these techniques is dependent on the implemented rules, and thus, requires careful design.

The MAS usually utilizes expert system rules to achieve a decentralized coordination strategy. It consists of a number of agents distributed along the network where they communicate together to make the necessary decisions. Several studies utilized different MAS frameworks to solve the restoration problem. For example, the method in [6] uses one agent at each bus and one facilitator agent. Thus, the method requires a large number of agents, which makes it impractical for large networks. Moreover, the method relies on one agent for decision making which makes it centralized. Also, the method does not consider the load priority or the presence of DGs. The methods in [7]-[9] solve the restoration problem using a decentralized approach. However, the operational limits after restoration, the load priority and the presence of DGs are not considered. In [10] and [11], two different MAS based restoration strategies are implemented in the presence of DGs. However, both strategies have fixed locations for the decision making agent for each group of faults. Also, the load priority and the voltage limit in the restored sections are not considered. The MAS framework in [12] considers the DGs and load priority and uses the concept of zone agents. However, the method relies on one decision making agent only, the feeder agent, for all faults on the same feeder. Moreover, the voltage limits of the restored sections are not considered properly in this approach. The method in [13] presents a fully decentralized restoration strategy by placing an agent at each bus, which is impractical for large networks. Moreover, the voltage limits in the restored sections are not considered. In [14], the Artificial Bee Colony optimization is used with MAS to obtain the service restoration schedule. The method aims to compromise between network losses and load shedding of high priority loads. Although the method is based on five types of agents, however, it does not utilize the full capabilities of the MAS properly as it is completely centralized. The method in [15] implements a decentralized MAS for restoration using controlled DG islanding and vehicle-to-grid facility of electric vehicles. The method requires the use of large number of agents, one to three agents at each bus. In addition, it does not provide details about how the voltage limits in the restored sections are calculated. Another decentralized method that uses one or more agents at each bus is the one presented in [16]. This method takes into consideration the load priority and the presence of DGs. The MAS architecture in this method is based on three types of agents; Switch, Load, and Generator Agents. Thus, the total number of agents in the system exceeds the number of buses,

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which might not be suitable for large networks. Moreover, the method does not consider the voltage limits in the system after restoration. The method in [17] uses a hierarchical coordination strategy for restoration while considering the presence of DGs and load priority. The method is based on three types of agents; zone, feeder, and substation. Similar to [12], the feeder agent is responsible for service restoration for all faults on the same feeder. Moreover, the restoration problem is formulated as 0-1 knapsack problem which is NP-complete. For such problem, exact solution for a large input is practically impossible to obtain [18]. Thus, the method needs to be tested for large systems to validate its effectiveness.

This paper attempts to overcome the limitations of other studies by presenting a fully decentralized restoration technique using MAS. The technique is based on carefully designed expert system rules to allow the agents to perform their tasks autonomously. The advantages of the proposed technique can be summarized as follows: (1) the MAS architecture is based on one type of agents only which simplifies its practical implementation; (2) the agents are distributed in zones along the feeder, thus, the number of agents is reduced; (3) the decision making agent depends on the fault location making the technique fully decentralized; (4) a backup agent for the decision making agent can be easily implemented to increase the reliability of the technique; (5) acceptable operation of the system after restoration is ensured by enforcing the current and voltage limits in both the healthy and restored sections; (6) customers' priority and the presence of DGs are both considered. The following sections provide the details of the proposed technique.

II. Proposed MAS Architecture

In this work, each distribution feeder is divided into a number of zones. Each zone is bounded by two switches in case of the main feeder or three or more switches in case of a main feeder with one or more laterals. The feeders can be connected to each other through normally open tie switches. The MAS architecture is based on placing one agent in each zone, Zone Agent. According to its location with respect to the fault, each Zone Agent identifies itself as one of the following:

- Faulted Zone Agent (FZA)
- Down Zone Agent (DZA)
- Zone Tie Agent (ZTA)
- Healthy Zone Agent (HZA)

The FZA is the agent of the faulted zone and it is the decision making agent. The DZAs are the agents of the zones which lost power due to the fault. The ZTA is the agent of the healthy zone containing a tie switch. Finally, the HZAs are the agents of the zones in the healthy feeder along the restoration path. Before the fault occurs all agents have the same behavior as they monitor the measuring devices on the switches at the boundary of their zones. In addition, all agents have the same initial knowledge. When a fault occurs, each of these agents is capable of identifying its type based on a specific condition. Hence, starts performing its role as will be explained in detail in Section IV. The common initial knowledge, the knowledge required by each agent once it identifies its role and the conditions of self-identification for each agent are all displayed in TABLE I. The communication between agents is done by the Agent Communication Language [19] developed by the Foundation for Intelligent Physical Agencies (FIPA) [20]. Fig. 1 illustrates the communication paths between different agents after the occurrence of a fault.

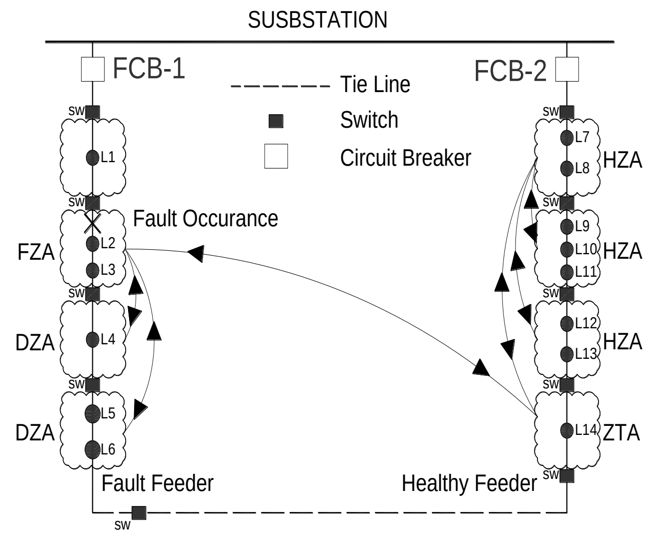

Fig. 1. Communication between agents along the feeders

III. Restoration Problem Formulation

The restoration problem is formulated as a combinational problem due to the different possible combinations of switching operations [13][21]. The main objective of the problem is to restore as many out of service loads as possible following a fault using a reduced number of switching operations. The problem is subject to several technical constraints that must be maintained to ensure an acceptable operation of the distribution system after restoration. These constraints can be summarized as follows:

1. Maintain the radial structure of all feeders
2. Maintain the current limit for all feeder branches
$$I_j \leq I_{\max j} \tag{1}$$
where I_j is the magnitude of current through branch j, and $I_{\max j}$ is the maximum allowable current for this branch
3. Maintain the voltage limit at all buses of the healthy feeder; this is achieved by calculating the current limit corresponding to the voltage limit as in [22]:
$$I_{v_h} = \frac{V_{bh} - V_{min}}{Z_{ph}} \tag{2}$$
where I_{v_h} is the maximum additional current that can flow through the healthy feeder without violating its voltage limit, V_{bh} is the voltage magnitude of bus h having the lowest magnitude along healthy feeder, V_{min} is the minimum allowable bus voltage magnitude (e.g., 0.9 p.u.), and Z_{ph} is the magnitude of impedance for the portion of the healthy feeder contributing to the restoration path starting from the substation to the bus closest to bus h [22] as shown in Fig.2.

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TABLE I
Initial knowledge and self-identification of different agents

Initial Knowledge (IK)	Agent	Required IK	Agent Identification
(1) Feeder circuit breaker (2) Downstream zones (3) Downstream switches (4) Upstream zones (5) Tie switches and their zones (6) Zone's impedance (7) Zone's priority (8) Zone's demand (9) Switches of the zone (10) Maximum allowable and actual branches currents in the zone (11) Minimum allowable and actual bus voltage in the zone (12) For zones with a tie switch: a) Zones along the restoration path b) Impedance of the restoration path from the substation to the tie bus c) Tie bus voltage	FZA	(1), (2), (3), (5), (9)	1) upstream incoming current is high compared to normal conditions while downstream outgoing or incoming current is close to normal, OR, 2) both incoming upstream and incoming downstream currents are high
	DZA	(6), (7), (8), (9)	Loss of power in the zone and none of the conditions of the FZA
	HZA	(6), (10), (11)	After receiving a Request for Information (RFI) message from its corresponding ZTA as explained in Section IV
	ZTA	(4), (11), (12)	After receiving a Call for Proposal (CFP) message from the FZA as explained in Section IV

4. Maintain the voltage limit at all buses of the restored part of the faulted feeder; this can be achieved by calculating the current limit corresponding to the voltage limit of the restored part by:

$$I_{v_f} = \frac{V_{bt} - V_{min}}{Z_{pf}} \tag{3}$$

where I_{v_f} is the maximum additional current that can flow through the restored feeder without violating its voltage limit, V_{bt} is the magnitude of the tie bus voltage of the healthy feeder, V_{min} is the minimum allowable bus voltage, and Z_{pf} is the magnitude of impedance for the portion of the total path of restoration including the restored part. Z_{pf} is calculated by $Z_{pf} = \left|Z_{pt} + 0.5Z_f\right|$ where Z_{pt} is the impedance of the restoration path from the substation to the tie bus along the healthy feeder and Z_f is the equivalent impedance of the down zones. Z_{pf} is calculated considering the assumption that the out of service loads are uniformly distributed along the faulted feeder [23]. The impedances used for calculations are shown in Fig.2.

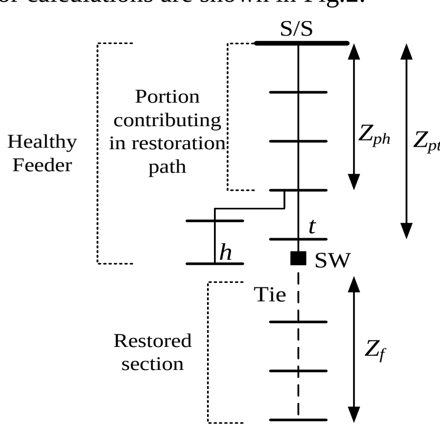

Fig.2. Impedances for voltage limit calculation

The following practical assumptions are considered while implementing the proposed technique:

1. Power loss in the feeders is not considered in the restoration process as this is an abnormal operating condition.
2. The bus voltage angles of the healthy feeder are not significantly changed after restoration [12][23].
3. The out of service loads are assumed to be uniformly distributed along the faulted feeder.
4. The DGs in the faulted feeder are turned off to avoid operating in an island.
5. The distribution feeder is balanced. For the unbalanced case, the proposed technique can be adapted by performing the same analysis for each phase. In this case, the decision is taken based on the limits imposed by the most loaded phase.

IV. Restoration Process Using the Proposed MAS Architecture

The restoration process is initialized after detecting a fault inside one of the zones and tripping the feeder circuit breaker. At this instant, the zone agents start to identify their roles according to their location with respect to the fault. According to its role, each agent has a specific list of actions that should be executed in order to achieve the required restoration objectives while considering the technical constraints.

The role of each agent will be explained in detail in the following sub-sections. The flow chart of the restoration process is shown in Fig.3 and the messaging between different agents is shown in Fig.4.

A. Faulted Zone Agent (FZA):

The FZA identifies itself if a fault occurs inside its zone and one of the following conditions occur; 1) the upstream incoming current is high compared to normal conditions while the downstream outgoing/incoming current is close to normal, or, 2) both the incoming upstream and downstream currents are high. Thus, when the FZA detects one of these conditions, it initiates the restoration process. After the tripping of the circuit breaker, the FZA isolates the fault by opening the switches at the terminals of the zone. Then, it sends a signal to the circuit breaker to reclose and restore the upstream zones of the faulted feeder. The FZA then communicates with the DZAs to calculate the required power for restoring the down zones. It also communicates with the ZTAs to identify the available power that can be supplied through each tie.

Accordingly, the FZA is considered as the decision making agent and its sequential operation during restoration is:

1. FZA sends Request for Information (RFI) messages to each DZA requesting the zone's impedance, demand and priority.
2. FZA sends Call for Proposal messages (CFP) to all ZTAs that have a tie connection with the faulted feeder. These ties are pre-defined in the FZA.
3. DZAs respond with inform messages containing the required information of the down zones.
4. Each ZTA responds with an inform message containing the tie bus voltage, the value of Z_{pt}, and allowable power for restoration without violating the current or voltage limits of the healthy feeder, AP_h,. This will be explained in the operation of ZTAs.
5. FZA calculates the power that can be restored from each healthy tie without violating the voltage limit of the restored zones, AP_{vf} by:

$$AP_{vf} = |V_L| * |I_{vf}| \tag{4}$$

   where $|V_L|$ is assumed to be 1 p.u.
6. FZA calculates the maximum allowable power that can be restored from healthy Tie i without violating the voltage or current limits in both the healthy and restored zones using:

$$AP_{T_i} = \min_{i \in n_T} \left(AP_{h_i}, AP_{vf_i} \right) \tag{5}$$

7. FZA compares the AP_{T_i} for each healthy feeder with the total demand of the down zones to perform group restoration through a single switching operation. This is based on the condition:

$$\max_{i \in n_T} (AP_{T_i}) \geq \sum_{j=1}^{n_z} |S_j| \tag{6}$$

   where S_j is the demand of zone j, n_z is the total number of down zones, and n_T is the number of available ties.
8. If the condition in Equation (6) is satisfied for any healthy tie, the FZA sends accept proposal message to the ZTA of this tie to close the tie switch.
9. If group restoration is not possible, the FZA initiates the zone restoration process by building the Zone/Switch relation table [24]. Accordingly, the FZA identifies all possible combinations of zones that can be restored through different switching operations for each tie. These combinations are obtained by:

$$Z_c = \left\{ Z_{C_x} = \bigcup_{j=1}^{n_z} Zone_j \right\} \tag{7}$$

   where Z_c is the set of all possible zone combinations, Z_{C_x} is zone combination number x which is calculated based on the zones demand.
10. FZA calculates the total demand of each combination that can be restored through each tie and calculates the corresponding AP_T. The table is arranged in a descending order, first by the zone priority and then by the demand power that can be restored.
11. For the combinations related to Tie i with total demand less than or equal AP_{T_i}, FZA selects the combination with the highest priority to be restored. If all combinations have the same priority, then the combination with highest demand is selected.
12. FZA sends request messages to the zones of the combination to be restored. The message contains the switches to be opened and closed to reach the desired combination.
13. FZA sends an accept proposal message to ZTA of Tie i to close the tie switch and restore the power.

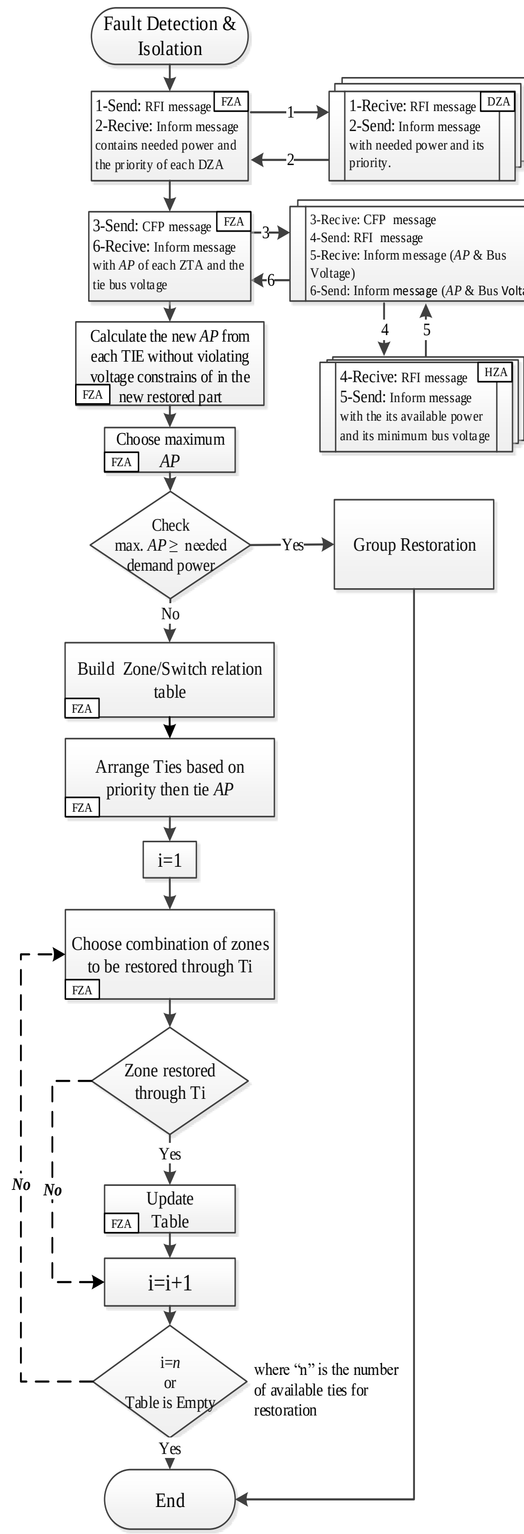

Fig.3. Restoration process flow chart

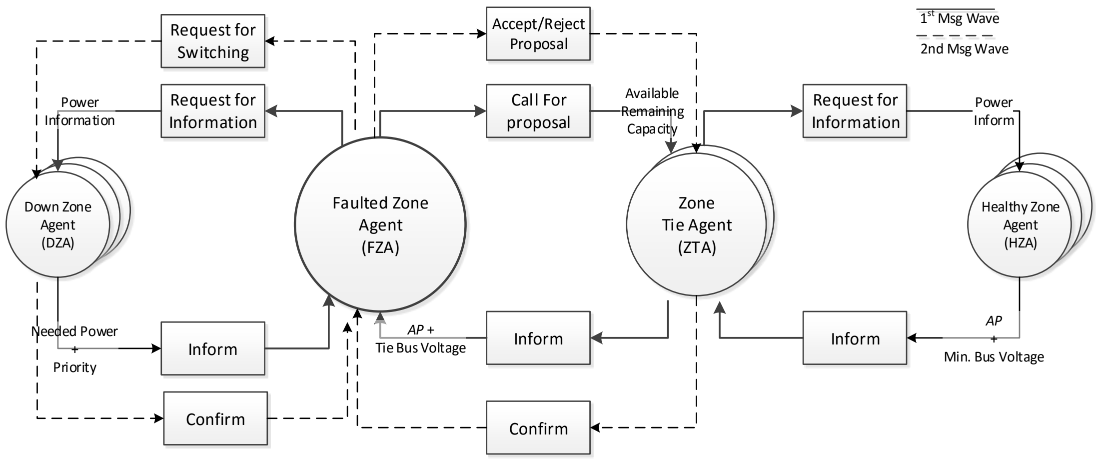

Fig.4. Messaging propagation between agents

14. FZA updates the Zone/Switch table after eliminating the combinations that include any zone that has been already restored to avoid violating the radiality constraint.
15. FZA repeats the steps from (10-14) till the last tie is reached or till the table is empty.

Due to the importance of the FZA, it is useful to assign a backup decision making agent in case of failure of the FZA. This backup agent can be the DZA of the down zone which is adjacent to the faulted zone. If the FZA is malfunctioning, the DZAs do not receive any RFI messages after clearing and isolating the fault. Thus, the backup plan is initiated after a preset time to assign a new decision making agent. To achieve this task, each DZA sends RFI messages to its *N* adjacent DZAs, which are predefined, and waits to receive *N* inform messages. The DZA that receives only *N*-1 inform messages from its adjacent agents, identifies itself as the new FZA and initiates the restoration process. If the faulted zone is adjacent to two down zones, one of these zones is predefined to have its agent as the backup FZA. On the other hand, if the faulted zone is adjacent to the zone at the end of the feeder, then the agent of this zone will be the backup FZA by default. In all cases, the zone of the backup agent and the faulted zone are combined in one zone. A similar approach can be adapted to cover for faults between zones. This is possible when a fault occurs on a switch connecting two zones. In this case, when the FZA communicates with the switch to open and isolate the faulted zone, it identifies that it is malfunctioning. Thus, the FZA communicates with the agent of its neighboring downstream zone to combine the two zones in one zone with the FZA acting as its agent.

B. Zone Tie Agent (ZTA) operation:

The agent of the zone having a tie switch identifies itself as a ZTA after receiving a CFP message from the FZA. The role of this agent is to collect the information related to its feeder to identify the amount of power that can be supplied without violating the current or voltage limits of the healthy feeder. The detailed operation of this agent is as follows:

1. ZTA receives CFP message from the FZA.
2. ZTA sends RFI messages to the HZAs, which are along the restoration path of its feeder, requesting the minimum bus voltage and spare capacity of each zone. This can be calculated by:

$$I_{ava\ j} = \min_{k}\left(I_{\max k-j} - I_{k-j}\right) \tag{8}$$

where $I_{ava\ j}$ is the available spare current of Zone *j*, $I_{max\ k-j}$ is the maximum current carrying capacity of Branch *k* in Zone *j* along the restoration path, I_{k-j} is the magnitude of the current flowing in Branch *k* of Zone *j*.

3. ZTA receives the required information from the HZAs and then calculates the voltage limit for the healthy feeder I_{v_h} using Equation 2. It also calculates the available spare current that can be fed by the healthy feeder without violating the current limit of its branches, I_{ch}:

$$I_{ch} = \min_{j}\left(I_{ava\ j}\right) \tag{9}$$

4. ZTA calculates the allowable power that can be supplied through its tie by:

$$AP_h = |V_L| * \left|I_{spare}\right| \tag{10}$$

$$I_{spare} = \min(I_{ch}, I_{vh}) \tag{11}$$

where $|V_L|$ is 1 p.u. and I_{spare} is the available spare current that can be supplied for restoration without violating the current and voltage limits of the healthy feeder.

5. ZTA sends an inform message to the FZA containing the allowable power, the tie bus voltage and the value of Z_{pt}.
6. ZTA waits until it receives an accept proposal message from the FZA if it is required to close the tie switch.

C. Down Zone Agent (DZA) operation:

The agent of each zone with no power due to the isolation of the fault is classified as a DZA. This agent identifies itself once its zone loses the power and after receiving a message from the FZA to send the demand of its zone. The operation of this agent is as follows:

1. DZA receives RFI message from the FZA to send the demand and the priority of its zone.
2. DZA sends the required information.
3. DZA perform the required switching operation once it receives a request message from the FZA.

D. Healthy Zone Agent (HZA) operation:

The agent of each zone along the restoration path in the healthy feeder is classified as a HZA. This agent identifies itself once it receives the RFI message from its corresponding ZTA to send the available spare capacity of the zone branches

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and the minimum bus voltage of the zone buses. The operation of this agent is as follows:

1. HZA receives RFI message from its ZTA, requesting information about the limits of the zone.
2. HZA calculates the I_{ava} using Equation 8.
3. HZA replies with an inform message containing the available spare current of the zone and the minimum bus voltage within the zone.

V. Case Studies

To demonstrate the effectiveness of the proposed restoration technique, five cases studies are simulated on the 11 kV radial distribution system shown in Fig. 5 [25]. The case studies investigate the different scenarios for group restoration, zone restoration and restoration while considering zone priority and DGs injections. In this study, the pre-fault demand of the zones is used to calculate the required power for restoration. The MAS is implemented in JADE [26], [27] which enables the agents to communicate together according to the FIPA standards. To validate the correctness of the agents' decisions, power flow calculations are performed after restoration in MATLAB [28] to check the current and voltage limits. The results for the five case studies are summarized in TABLE II.

1) *Case 1 – Group Restoration:*

The aim of this case is to investigate the performance of the proposed technique for group restoration without considering the load priority or DG injection. In this case, a fault is assumed to be in Zone Za7 of Feeder "a". When the fault occurs, FCB-1 trips and the agent of Zone Za7 identifies itself as the FZA and sends a signal to the switches of its zone to isolate the fault. The FZA then sends a signal to FCB-1 to reclose and energize the upstream part of the faulted feeder. In this case, the down zones are Za8, Za9 and Za10 with total demand of 0.137 p.u. The available ties are Tie 2 at Feeder "c" and Tie 3 at Feeder "d". The FZA starts the restoration process by sending RFI messages to the DZAs to identify the required demand for restoration. It also sends CFP messages to the ZTAs to send the allowable power for restoration and the tie bus voltage. Accordingly, each ZTA sends RFI to its corresponding HZAs requesting the minimum available spare capacity of their branches and the minimum bus voltage within their zone.

After receiving the required information from the HZAs, the ZTA calculates the allowable power that can be supplied through its tie using Equation (10), where AP_h for Tie 2 is 0.265p.u. and for Tie 3 is 0.089 p.u. Then, each ZTA sends an inform message to the FZA containing the AP_h for its tie and the tie bus voltage (0.931 p.u. for Tie 2 and 0.909 p.u. for Tie 3). The FZA then calculates the AP_{T_i} for each healthy tie using Equation (5), where AP_{T_2} for Tie 2 is 0.190 p.u. and $AP_{T_3}$for Tie 3 is 0.060 p.u. The FZA compares the highest AP_{T_i}, AP_{T_2}in this case, with the required demand of the DZAs using Equation (6). The condition of group restoration is satisfied in this case, thus, the FZA sends an accept proposal message to the ZTA at Tie 2 to close switch S12 and restore all the down zones. To validate that the operational limits are not violated after restoration, power flow calculations are performed. The results indicate that minimum bus voltage is 0.906 p.u. at L64 in Zone Za9, which does not violate the ±10% limit. Also, none of the feeder sections exceeds their current limit.

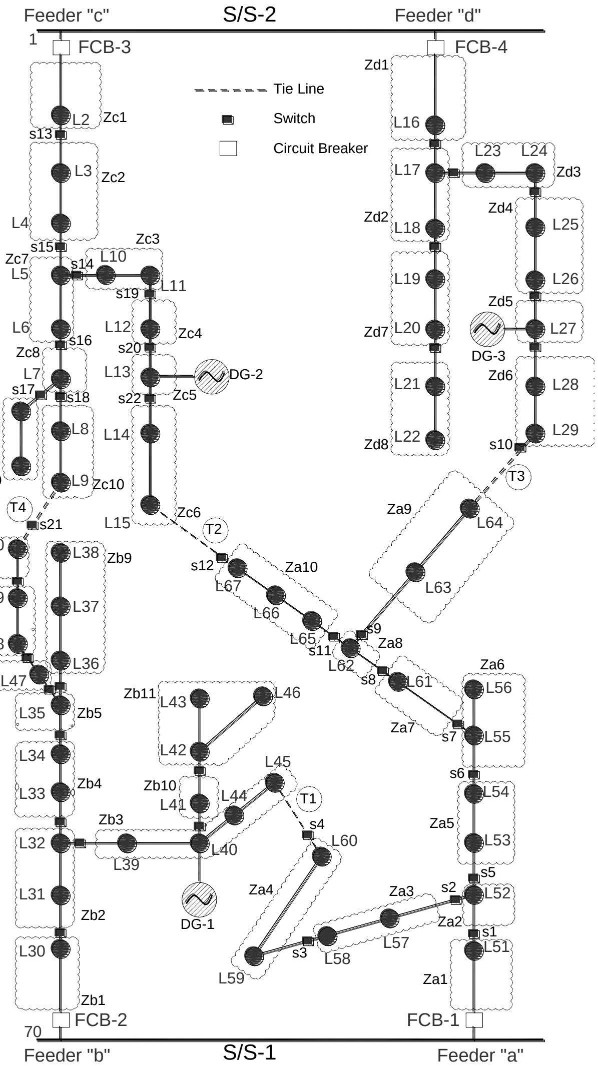

Fig. 5. Test distribution system

2) *Case 2 –Zone Restoration:*

The aim of this case is to investigate the zone restoration without considering the load priority or DG injection. In this case a fault is assumed to occur in Zone Za1 of Feeder "a". The detection and isolation of the fault is the same as Case 1, where the Zone Agent of Zone Za1 is the FZA. Since Za1 is at the beginning of the feeder, thus, the FZA does not send a signal to the circuit breaker to reclose. The down zones are Za2 to Z10 and they require a total demand of 1.372 p.u. The available ties are Tie 1, Tie 2 and Tie 3.

The sequence of restoration is the same as in Case 1 till the point where the allowable power for group restoration, AP_{T_i}, is calculated. The FZA receives an inform message from each ZTA containing its AP_h and tie voltage. These are 0.678 p.u. and 0.954 p.u. for Tie 1, 0.265p.u. and 0.931 p.u. for Tie 2, and, 0.089 p.u. and 0.909 p.u. for Tie 3. The FZA then calculates the AP_{T_i} for each tie, where $AP_{T_1}$for Tie 1 is 0.362 p.u., $AP_{T_2}$for Tie 2 is 0.147 p.u. and AP_{T_3} for Tie 3 is 0.045 p.u. Accordingly, the FZA compares the highest AP_{T_i} with the required demand by all DZAs. In this case, group restoration through a single tie is not possible. This is because the highest AP_{T_i} (0.362 p.u.) is less than the total demand of the down zones (1.372 p.u). Thus, zone restoration is initiated and the FZA builds the zone/switch relation table using Equation (7). The FZA calculates the new AP_{T_i} for each zone combination and arranges the combinations in a descending order according to the required demand. It then compares the AP_{T_i} for each combination with the load demand of this combination. After searching the combinations throughout the table, the possible combinations from the available ties are identified to be:

1. Za4 from Tie 1, as the required demand power is 0.232 p.u. while AP_{T_1} for this combination is 0.607 p.u. Restoring Za3 is not possible because the total demand of both zones is 0.667 p.u, which exceeds AP_{T_1}.
2. Za7to Za10 from Tie 2, as the total required demand is 0.137 p.u. while AP_{T_2} for this combination is 0.1981p.u. Restoring Za6 is not possible as this combination needs a total demand of 0.243 p.u.
3. No possible combinations can be restored from Tie 3 as Za9 has been already restored from Tie 2.

To achieve the required combinations, the FZA sends request messages to the DZAs of Za4 and Za7 to open switches S3 and S7, respectively. Then, the FZA sends accept proposal messages to Tie 1 and Tie 2 to close S4 and S12, respectively. After the restoration is done, the minimum bus voltage along the feeders involved in restoration is 0.906 p.u. at L64 in Zone Za9.

3) *Case 3 – Zone Restoration with DG Injection:*

This case aims to investigate the impact of DGs present in the healthy feeder on the zone restoration process. Thus, this case is the same as Case 2 but with DG injection. The DGs considered are: DG-1 (0.36 p.u.at 0.83 p.f. lag), DG-2 (0.25 p.u. at 0.8 p.f. lag) and DG-3 (0.36 p.u.at 0.83 p.f. lag).

The FZA calculates AP_{T_i} for each tie, where AP_{T_1} for Tie 1 is 0.502 p.u., AP_{T_2} for Tie 2 is 0.276 p.u. and $AP_{T_3}$for Tie 3 is 0.230 p.u. In this case, zone restoration is initiated and the possible combinations from available ties are:

1. Za2, Za3, and Za4 from Tie 1, as the needed demand is 0.781 p.u. while AP_{T_1} for this combination is 0.787 p.u. Restoring Za5 is not possible as this combination needs a demand of 0.8932p.u.
2. Za6, Za7, Za8, Za9, and Za10 from Tie 2, as the needed demand is 0.243 p.u. while AP_{T_2} for this combination is 0.269 p.u. Restoring Za5 is not possible as this combination needs a demand of 0.314 p.u.
3. No possible combinations can be restored from Tie 3 as Za9 has been already assigned to Tie 2.

Thus, the FZA sends request messages to the DZAs of Za2 and Za6 to open switches S5 and S6, respectively. Then, the FZA sends accept proposal messages to Tie 1 and Tie 2 to close S4 and S12, respectively to restore the power. The minimum bus voltage along the feeders after restoration is 0.901 p.u. at L52 in Zone Za2. It should be noted that the presence of DGs allowed to restore more power in Case 3 (1.024 p.u.) as compared to Case 2 (0.369 p.u.).

4) *Case 4 – Zone Restoration with DG Injection:*

This case is similar to Case 3 but with a fault occurring in a different location. The fault is assumed to be inside Zc2 of feeder "c", and thus, the Zone Agent of Zone Zc2 is the FZA. The DGs considered are: DG-1 (S = 0.036 p.u.at 0.83 p.f. lag), DG-3 (0.025 p.u. at 0.8 p.f. lag) and DG-2 is turned off due to the islanding requirements.

After the fault isolation and circuit breaker reclosure, the down zones are Zc3 to Zc10 with a total demand of 1.025p.u. The available ties are Tie 2 and Tie 4 with AP_h and tie voltage of 0.399 p.u. and 0.959 p.u. for Tie 2, and, 2.612 p.u. and 0.968 p.u. for Tie 4. The FZA calculates AP_{T_2} for Tie 2 as 0.253 p.u. and AP_{T_4} for Tie 4 as 0.386 p.u. In this case, group restoration is not possible, and the possible combinations that can be restored from Tie 2 and Tie 4 are:

1. Zc4 to Zc6 from Tie 2, as the needed demand is 0.334 p.u. while AP_{T_2} for this combination is 0.338 p.u. Restoring Zc3 is not possible as this combination needs a total demand of 0.383 p.u.
2. Zc7 to Zc10 from Tie 4, as the total needed demand is 0.642 p.u. while AP_{T_4} for this combination is 0.747 p.u.

Thus, the FZA sends request messages to the DZAs of Zc4 and Zc7 to open switches S19 and S14, respectively. Then, the FZA sends accept proposal messages to Tie 2 and Tie 4 in order to close closing S12 and S21, respectively to restore the power. The minimum bus voltage after restoration is 0.901p.u. at L12 in Zone Zc4.

5) *Case 5 - Zone Restoration with DG Injection and Load Priority:*

The last case investigates the impact of considering the load priority on the restored zones. This is achieved by repeating Case 4 while giving one of the unrestored zones, Zc3, the highest priority. Thus, when the FZA builds the zone/switch table, it arranges the combinations in a descending order, first according to the priority of zones, and then according to the required demand. The possible combinations that can be restored are:

1. Zc3, Zc4, Zc7, Zc8, and Zc10 from Tie 4, as their total demand is 0.568 p.u. while AP_{T_4} for this combination is 0.705 p.u. Restoring Zc9 is not possible as the new combination requires a total demand of 0.760 p.u.
2. Zc5 and Zc6 from Tie 2, as their demand is 0.258 p.u. while AP_{T_2} for this combination is 0.343p.u.

To perform the switching actions, the FZA sends request messages to the DZAs of Zc9 and Zc5 to open switches S17and S20, respectively. Then, the FZA sends accept proposal messages to Tie 2 and Tie 4 in order to close S12 and S21, respectively. After restoration, the minimum bus voltage is 0.912 p.u. at L12 in Zone Zc4.

It is worth mentioning that the total restored power in this case (0.826 p.u.) is less than that of Case 4 (0.976 p.u.). This is because the high priority of Zc3 forced the algorithm to restore power to this zone and to disconnect Zc9 which has a high demand (0.200 p.u.) as compared to Zc3 (0.049 p.u.).

The voltage profiles for the feeders involved in restoration process in all five cases are presented in Fig.6 to Fig.9. The figures show that the voltage at all displayed buses are within acceptable limits.

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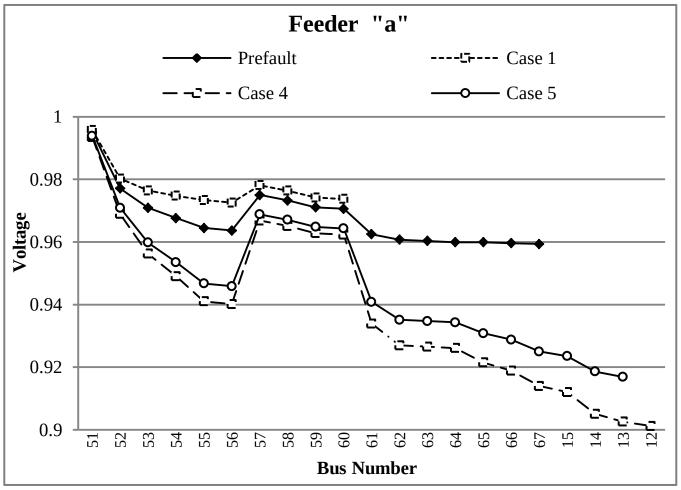

Fig.6. Feeder "a" Voltage profile

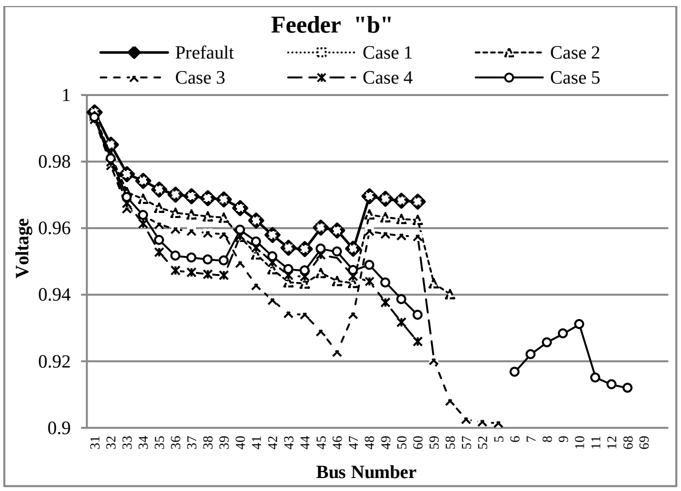

Fig.7.Feeder "b" Voltage profile

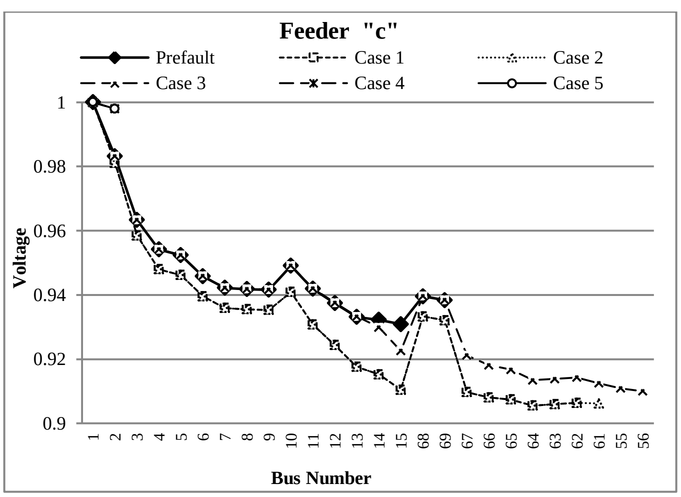

Fig.8. Feeder "c" Voltage profile

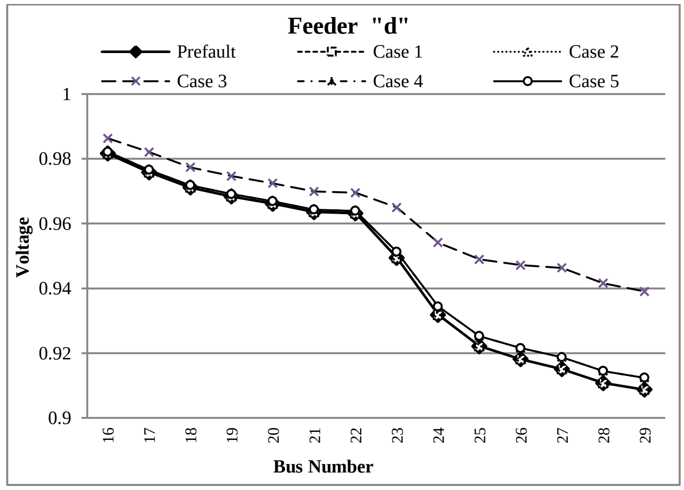

Fig.9. Feeder "d" Voltage profile

VI. Conclusion

This paper presented a fully decentralized technique for service restoration in active radial distribution systems. The technique is based on a novel MAS architecture that uses expert system rules to solve the restoration problem. The proposed architecture uses only one agent at each zone of the feeder. Each agent can perform one of four different roles according to its location with respect to the faulted zone. This role is identified automatically, thus, allowing for autonomous operation of the system which is essential for smart grids. The proposed technique attempts to maximize the restored power from each tie. However, in case of high priority loads, the technique aims to restore these loads which can be on the expense of reducing the total amount of restored loads. To investigate the effectiveness of the proposed technique, several case studies are simulated on an 11 kV radial distribution system with and without DG injection and load priority. The results of the simulations show the ability of the technique to achieve the required restoration objectives while preserving the radial structure of the system and the voltage and current limits in both healthy and restored sections. Therefore, it can be concluded that the proposed technique provides a simple and efficient self-healing capability to active distribution networks.

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TABLE II
Summary of restoration results for the five case studies

Case/ Type of restoration	**Fault Location**	**Down Zones / Total Demand**	**Restoration Ties/ AP_{Ti} Restored Zones/ Zones demand**	**Switches Opened / Closed**	**Minimum Bus Voltage/ Bus Number**
Case 1 (No DG or Load Priority) / Group	Zone Za7 of Feeder "a"	Za8 to Za10/ 0.137 p.u.	Tie 2/ 0.190 p.u. Za8 to Za10/ 0.137 p.u.	- / S12	0.91 p.u. at L64 in Zone Za9
Case 2 (No DG or Load Priority) / Zone	Zone Za1 of Feeder "a"	Za2 to Z10/ 1.372 p.u.	Tie 1/ 0.607 p.u./ Za4/ 0.232 p.u. Tie 2/ 0.198 p.u./ Za7 to Za10/ 0.137 p.u.	S3/ S4 S7/ S12	0.91 p.u. at L64 in Zone Za9
Case 3 (same as Case 2 but with DG injection)/ Zone	Zone Za1 of Feeder "a"	Za2 to Z10/ 1.372 p.u.	Tie 1/ 0.787 p.u./ Za2 to Za4/ 0.781 p.u. Tie 2/ 0.269 p.u./ Za6 to Za10/ 0.243 p.u.	S5/ S4 S6/ S12	0.901 p.u. at L52 in Zone Za2
Case 4 (with DG injection)/ Zone	Zone Zc2 of feeder "c"	Zc3 to Zc10/ 1.025 p.u.	Tie 2/ 0.338 p.u./ Zc4 to Zc6/ 0.334 p.u. Tie 4/ 0.747 p.u./ Zc7 to Zc10/ 0.6417 p.u.	S19/ S12 S14/ S21	0.901p.u. at L12 in Zone Zc4
Case 5 (same as Case 4 but with Zc3 having highest priority)/ Zone	Zone Zc2 of feeder "c"	Zc3 to Zc10/ 1.025 p.u.	Tie 4/ 0.705 p.u./ Zc3, Zc4, Zc7, Zc8, Zc10/ 0.568 p.u. Tie 2/ 0.343 p.u./ Zc5 & Zc6/ 0.2575 p.u.	S17/ S21 S20/ S12	0.912 p.u. at L12 in Zone Zc4

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