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A multiagent design for self-healing in electric power distribution systems

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ABSTRACT

The out-of-service area after fault should berestored by changing the distribution system configuration by means of switching actions on the feeders. This paper proposes an agent-based approach for service restoration in smart distribution systems with distributed generations (DG). The proposed multi agent has four different types of agents: feeder agents, zone agents, switch agents and DG agents. The agents can communicate and cooperate with each other in order to supply services to out-of-service customers. An artificial neural network has been considered within DG agent to predict the DG generation. The restoration plan is built based on local data considering system conditions, operational constraints and fault location. Different loading conditions have been considered under different scenarios and the result of proposed multi agent approach for each scenario with and without DG have been compared. Simulation results show the efficiency of proposed agent architecture.

1. Introduction

The introduction of distributed generation (DG) brings fundamental and fast changes to power systems. The purpose of incorporating renewable energy such as photovoltaic (PV) system on the smart grid is to increase system reliability, reduce unrestored areas after fault in distribution systems and improve system conditions as well as environmental and energy concerns. The rapid growth in integrating PV system can cause problems if not managed properly.

Self-healing is the ability of distribution systems to automatically restore themselves after a permanent faults. It is the key characteristic of a smart grid by the report from National Energy Technology Laboratory (NETL) of the United States [1]. Service restoration aims to restore loads after a fault by changing system topology while meeting operational constraints [2]. Various studies have been done to address the service restoration problem, in either centralized or decentralized approaches, which having their own pros and cons [3] (i.e. heuristic algorithms [4], mathematical programing [5], fuzzy logic [6], etc.).

The main advantage of centralized approaches is that they can obtain the best solution to the problem. In these approaches, in order to obtain a solution a central controller (CC) process the gathered data from whole system. Therefore, they are prone to be affected by a single point of failure (SPOF). They also impose the challenge of managing big data and have to support heavy computing processes. Decentralized approaches are more common for large networks and mostly work on parallelizing the problem. These approaches are based on peer-to-peer communication. Local data is acquired via local sensors, processed locally without the need of any SCADA-based central station. The whole system behavior is sum of individual local actions [7].

Multi agent systems (MAS) have come to the light as a liable technology to apply distributed control strategies in power systems [8]. A MAS based self-healing approach for urban power grid which has five operating states and four sub controls, was presented in Ref. [9].

Agent-oriented designs offer multiple pros in Smart Grid simulations [10]. The MAS can solve problems much faster [11].

A multi agent system has been proposed in Ref. [12] to solve restoration problem of distribution network in distributed manner. The application of a MAS for improving voltage profile and DG optimal dispatch was proposed in Ref. [13]. A set of relay agents which communicate and cooperate to apply an adaptive current differential relaying function was proposed in Ref. [14]. In order to implement self-healing, the agents have to adjust to the conditions of the system. A MAS to restore outage area after fault in a distribution system was proposed in Ref. [15]. Although the load priorities, load shedding or increase backup capacity by load transfer from some feeders to the other ones had not been considered. An agent-oriented energy management system was proposed in Ref. [16], which control DGs in distribution systems in order to optimize system operation and efficiency. An adaptable agent based model is described in Ref. [17] to simulate the dynamic of smart city. A MAS model for the self-healing protection system was proposed in Ref. [18].

In Ref. [19], a multi-agent based system by help of unified data

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Nomenclature

Abbreviations

ANN	Artificial neural network
BDI	Believe-desire-intension
BFA	Backup feeder agent
CC	Central controller
DGA	Dg agent
EDLC	Electric double-layer capacitor
ESS	Energy storage system
FA	Feeder agent
GR	Group restoration
HSA	Head switch agent
MAS	Multi agent systems
MFA	Main feeder agent
MLR	Maximum load restoration
MSC	Minimum switching cost
NAR	Nonlinear autoregressive
NETL	National energy technology laboratory
PF	Power flow
PR	Partial restoration
PV	Photovoltaic
SA	Switch agent
SSA	Sectionalizer switch agent
SFA	Supporting feeder agent
SPOF	Single point of failure
SR	Sectional restoration
TSA	Tie switch agents
ZA	Zone agents
ZBM	Zinc bromide battery modules

Parameters and Variables

I_j	Currents in branch j
I_{Max}	Maximum allowable current
V_i	Voltages of nodes i
$V_{\min}$	Minimum allowable voltage
V_{Max}	Maximum allowable voltage
D_i	The demand of *ith* zone
S_i	The status of *ith* zone
P_i	The load priority of the *ith* zone
S_i^{tie}	The status of tie switch *ith*
S_j^{CB}	The status of CB *jth*
I^z	The available current in zone z
V^z	The available voltage in zone z
Z_f^o	The series impedance of path between node with minimum voltage and substation
I_{feeder}	The maximum additional load of feeder
SC_{BF}	The spare capacity of each backup/supporting feeder
I_{PV}	Light generated current of a PV cell
I_{SC}	Short circuit current of PV cell
G	Sun irradiance
K_I	The short-circuit current/temperature coefficient
T	Environment temperature
	Reference temperature
I_d	The diode current of the ideal PV cell
I_0	The diode ideality constant
a	The equivalent series resistance of the module
R_S	The equivalent parallel resistance
R_P	The equivalent parallel resistance
V_t	The thermal voltage of the module
k	The Boltzmann constant
q	Electron charge
P_{Solar}	The output of PV stations
P_{ESS}^{Max}	The maximum output power of ESS
P_{DG}	The power each DG station can deliver
P_{Nwk}	The available capacity of feeder to carry out DG output
$I_{\max}^{Path}$	The minimum of current upper bound of path between DG and respective tie switch
$f(w)$	The loss function of neural network
J	Jacobian matrix
E	Errors of loss function
τ	Damping factor
I	The identity matrix
H	Hessian matrix
W	Weight vector

platform for fault management was proposed. A MAS with fuzzy clustering algorithm was proposed in Ref. [20]. In Ref. [21] an agent-based platform for reconfiguration and fault diagnosis with high-level architecture was developed. In order to coordinate the operation of relays during faults, the distance between the sample data and the cluster center had been used. An autonomous MAS to control switching action is proposed in Refs. [22,23].

BDI (Believe–Desire–Intension)-based multi-agent architecture is proposed in Ref. [24]. The multiagent based load restoration algorithm based on Knapsack problem was presented in Ref. [25]. A fuzzy-multiagent self-healing scheme has been proposed in Ref. [26]. A fuzzy rule-based system is employed for decision-making support in MAS but it does not consider any topology related issue.

These studies did not consider an appropriate communication and control structure for each agent set. Furthermore, they did not consider DGs and the challenges involved with DG integration. The main issue to be considered is uncertainty of PVs and fluctuation of output power due to intermittent behavior of sun irradiance and temperature. To reduce the impact of fluctuations an appropriate prediction method has been used in this study, also an energy storage system considered along with PV to smooth out the output. On the other hand, a precise modelling of PV module should be considered to design a PV system for application in practical systems.

A well-designed multi agent framework for service restoration considering load priority, DG uncertainties and proper control and communication structure has been presented in this paper. The rest of the paper is organized as follows. Section 2 formulates the restoration problem. The PV generation forecast is presented in Section 3. The proposed multi agent system architecture is described in Section 4. The simulation result presented in Section 4 and finally Section 5 concludes the paper.

2. Restoration problem formulation

In this paper, the self-healing problem in a smart distribution network is modeled as a multiobjective problem. The objectives of restoration can be maximizing of restored load and/or minimizing the switching costs, number of switching. Many studies considered loss minimization during restoration process, but it is believed that when system is in emergency mode, losses are not a matter of importance.

The constraints of the service restoration problem are voltage and current limits and maintaining radial topology of distribution network.

The currents in all branches should be less than maximum allowable current:

$$I_j \leq I_{\text{Max}} \tag{1}$$

The voltages of nodes should be kept within their limits, which are 0.9 and 1.05 P.U. based on ANSI C84.1 standard:

$$V_{\min} \leq V_i \leq V_{\mathrm{Max}} \quad (2)$$

The first objective, maximum load restoration (MLR) is to restore as many loads as possible considering loads priorities:

$$MLR = \mathrm{Max}\left(\sum_i D_i \times P_i \times S_i\right) \quad (3)$$

The outage area consists of multiple zones. If there are N zones in the outage area, then there are 2^N combinations of zones to be restored. Some of these combinations for restoration are feasible and some of them are infeasible. After omitting the infeasible combination, then the MLR for each feasible combination is calculated based on Eq. (3). The D_i is the demand of ith zone, P_i is the priority of ith zone, S_i is a binary variable indicating the status of ith zone, if the ith zone is in the combination then it will be one, otherwise it will be zero. One of the objectives is to restore as many loads as possible considering their priorities, so the combination with the most MLR will be considered for restoration, regarding operational constraints.

The second objective, minimum switching cost (MSC), is minimizing the number of switching considering both ties and circuit breakers.

$$MSC = \mathrm{Min}\left(\sum_{Ties} S_i^{tie} + \sum_{CBs} (1 - S_j^{CB})\right) \quad (4)$$

where S_i^{tie} and S_j^{CB} are status of tie switch i_{th} and CB j_{th} respectively. The overall objective of restoration problem can be defined as follow:

$$OBJ = MLRMSC = \mathrm{Max}(\sum_i D_i \times P_i \times S_i) + \mathrm{Min}(\sum_{Ties} S_i^{tie} + \sum_{CBs} (1 - S_j^{CB})) \quad (5)$$

Three different types of restoration have been considered in this study. First *group restoration* (GR), where all out-of-service area are restored by closing one tie switch. Second, *sectional restoration* (SR), where out-of-service area are restored in turn, section by section and by number of switching (whether closing a tie switch or opening a CB), and third is *partial restoration* (PR), where some out-of-service area cannot be restored due to lack of spare capacity or violation of constraints and some loads have to be shed.

3. Proposed MAS architecture

The main goal of self-healing in this paper is to increase reliability of distribution system, minimize out-of-service area after a fault by using distributed control approaches. In order to make good decision, it is crucial to gather enough information. Thus for multi-agent based restoration, communication is a key technology. The communication infrastructure is independent of the physical structure of the smart distribution network. Hence, even if there is a fault in distribution line, the communications between two agents can still be persistent [25]. In this study, it has been assumed that the communication is reliable and will not encounter any problem. The communications among various agents are shown in Fig. 1.

In this study, it is also assumed that the location of fault is defined so fault location algorithm has been skipped. Only single fault cases have been considered for all of the systems.

3.1. Agent types

There are four types of agents in the proposed architecture:

1 Feeder Agents (FA) are responsible for energizing the respective feeder. They process the data from other agents and make decisions based on local data it gathers to restore loads. There are three types of feeder agents: Main Feeder Agent (MFA) the feeder agent of faulty feeder, Back-up Feeder Agent (BFA): the feeder agents of neighboring feeder of faulty feeder and Supporting Feeder Agent (SFA):

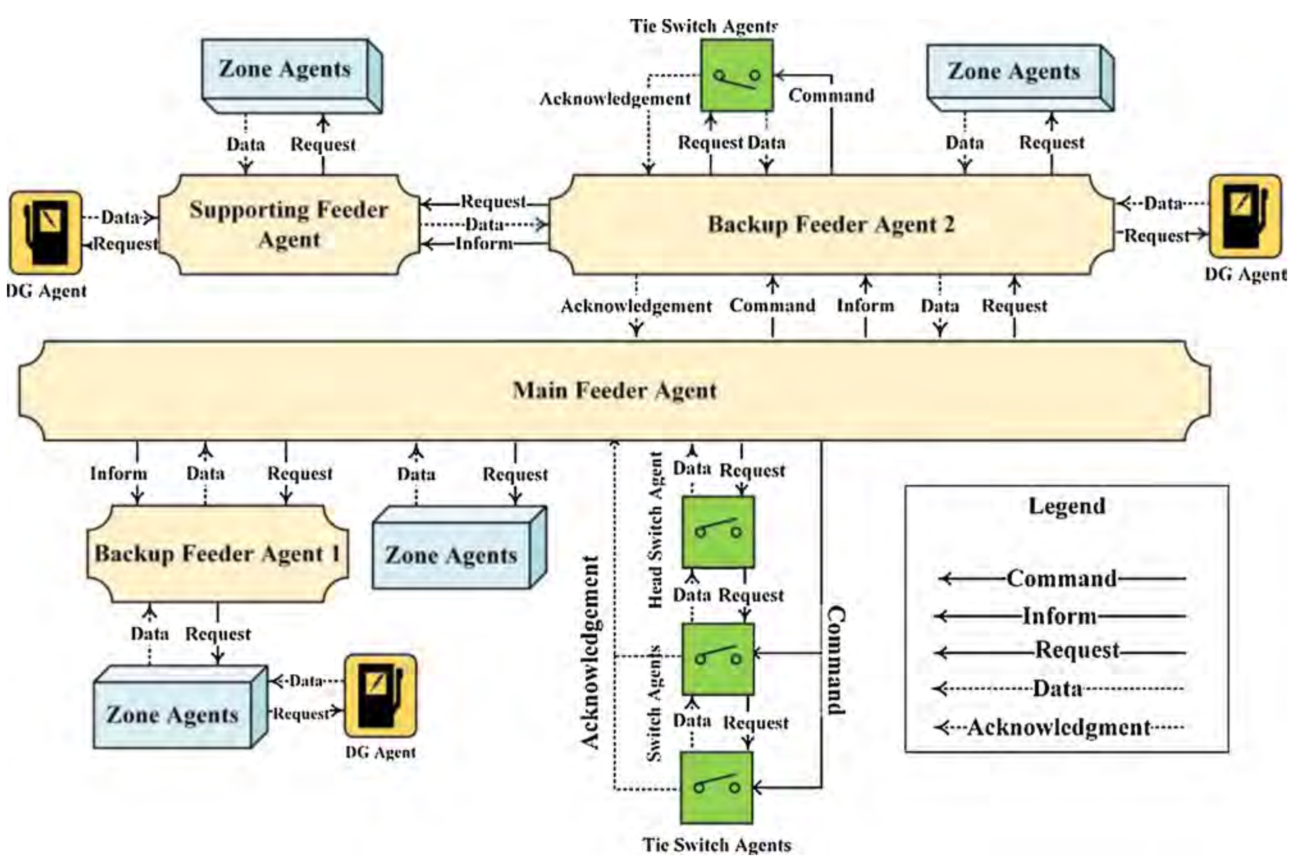

Fig. 1. Communications among agents.

the feeder agents of neighboring feeder of back-up feeders

2 Switch Agents (SA) distinguish the out-of-service area, all switches within the outage area and the topology of it. There are three types of switch agents: Head Switch Agent (HSA): the downstream switch agent of faulty section that is responsible for defining topology of healthy out-of-service zones, Sectionalizer Switch Agents (SSA) and Tie Switch Agents (TSA).
3 Zone Agents (ZA) are responsible for calculating remaining capacity, voltage and current of zones. The ZAs of out-of-service area are responsible for declaring the demand.
4 DG Agent (DGA) are responsible for calculating and declaring the power, which can be provided by respective DG.

The agents and their task will be described thoroughly in following section.

When a fault occurs in a feeder, the SSA of upstream circuit breaker (CB) opens and sends a message to the FA of respective feeder and declares the occurrence of a fault. After isolation the fault, the restoration process begin. Then this SSA called HSA and this FA called MFA, which stand for head switch and main feeder agents, respectively.

3.2. Strategy and tasks of agents

Agents are designed to energize out of service zones and make decisions based on local data. The pseudocode of the restoration process is shown in Fig. 2.

3.2.1. The procedure of calculating spare capacity

When the MFA sends *request messages* to BFAs and asks for SC, or when the BFA sends *request messages* to its SFAs and asks for SC following operation has to be done in order to calculate spare capacity of each backup/supporting feeder:

The BFA/SFA sends a *request message* to its ZAs and asks for current and voltage data to calculate maximum load they can supply.

Step 1: Each ZA replies with an *inform message* containing lowest voltage of its nodes and minimum difference between the current upper bound and its branches current before the fault.

$$I^z = \min(I_{\max} - I^z_{branch}) \tag{6}$$

$$V^z = \min(V^z_{node}) \tag{7}$$

Step 2: The BFA/SFA receives zones data and calculates SC by using following equations [27]:

$$I_{fv} = \frac{\min(V^z) - V_{\min}}{Z^o_f} \tag{8}$$

$$I_{fc} = \min(I^z) \tag{9}$$

Where $V_{\min}$ is minimum allowable voltage in network and Z^o_f is the series impedance of path between node with minimum voltage and substation. The shunt admittance in branches are neglected.

Step 3: The maximum additional load, without violation of current and voltage constraints in the backup feeder can be obtained by:

$$I_{feeder} = \min(I_{fc}, I_{fv}) \tag{10}$$

The spare capacity of each backup/supporting feeder can be calculated as follow:

$$SC_{BF} = I_{feeder} \times V_{\min} \tag{11}$$

```
IF a fault occurs in a feeder THEN
      The Main Feeder Agent (MFA) receives a signal to start restoration process
      The MFA starts:
            Spare Capacities (SC) negotiations with Backup Feeder Agents (BFAs)
            topology determination by Head Switch Agent (HSA)
            declaring demand and priorities by Zone Agents (ZAs)
      The MFA receives:
            Spare capacities from BFAs
            Topology from HSA
            Demand and Priorities from ZAs
      IF Max (SC) > Demand THEN
            Call Group Restoration:
            Close tie switch of the backup feeder with maximum spare capacity
      ELSE
            Call Sectional Restoration:
                  Make all possible combinations of out-of-service zones
                  Define each combinations index
                  Sort combinations by their indexes
                  WHILE remaining backup capacities > 0
                        Restore combinations by closing and opening of respective tie
                        switches and circuit breakers
                  ENDWHILE
                  IF there is still unrestored zone THEN
                        Call Load Transfer
                              IF there is any supporting feeder THEN
                                    Ask Supporting Feeder Agent (SFA) for spare
                                    capacity
                                    IF there is any spare capacity THEN
                                          Start switching sequence to transfer loads
                                          from backup feeder to supporting feeder
                                          Compute new spare capacity
                                          Send new Spare capacity to MFA
                                    ENDIF
                              ENDIF
                              IF there is still unrestored zone THEN
                                    Shed remaining unrestored zones
                              ENDIF

                  ENDIF
      ENDIF
ENDIF
```

Fig. 2. Pseudocode of proposed restoration process.

Step 4: If BFA receives a request for additional capacity, it starts load-transfer process.

Step 5: The BFA sends a *request message* to its SFA (if available) and asks for more spare capacity.

Step 6: When the BFA receives an *inform message* from SFA, it can define new SC as following:

$$SC_{BF}^{new} = \min(D^{out} - SC_{BF}^{old,rem}, SC_{SF}) \quad (12)$$

Step 7: Where SC_{BF}^{new} is new SC of backup feeder, $SC_{BF}^{old,rem}$ is remaining SC of backup feeder, D^{out} is demand of remaining unrestored zones and SC_{SF} is SC of supporting feeder.

3.2.2. The procedure of topology determination

When an occurrence of a fault is detected, the respective switches are opened to isolate the fault. The healthy part of outage area can be rstored before clearing the fault which is called outage area or out-of-service zone in the rest of the paper.

Step 1: The MFA sends a *request message* to HSA to define topology of outage area.

Step 2: Then the HSA starts defining topology of out-of-service zones and available paths to restore them.

Step 3: The HSA sends a *request message* to downstream SSA and ask about its status. The status of a switch can be either "open" or "close". If there are more than one downstream switch the request message passes to all of them. In this case, an *inform message* will pass to HSA to inform identification of new branch, so HSA becomes aware of number of branches at its downstream side.

Step 4: The downstream SAs send topology information to HSA. If the status of a switch is "close", it passes the request to its downstream SSA(s) and continue the procedure.

Step 5: This procedure continues until it reaches a tie switch or feeder terminal. Then it will start from another point left behind.

Step 6: When all outage area has been searched and available paths have been defined, the HSA sends this information including topology of outage area and available paths to MFA.

Whether the group, sectional or partial restoration execute in the system, there are two lists of switches. CBs to be opened and ties to be closed. The MFA sends switches on this list *command messages* and ask them to open/close.

Step 8: When a SSA receives "open" command, it should acknowledge and open the respective switch.

Step 9: When a TSA receives "close" command, it should acknowledge and close the respective tie switch.

3.2.3. The calculation of DG output

The use of renewable energies has been increased considerably, in order to diminish the effects of global warming and energy crisis. Photovoltaic (PV) gets lots of attentions among all potential renewable energy resources. PV integration with power grid requires the ability to deal with the uncertainty of power output. An accurate forecasting is a key factor to handle uncertainty, which provides the grid operators with significant information to manage the demand and supply of power grid.

A method for forecasting PV generation should handle non-linearity due to dynamic and non-linear behavior of meteorological data. Artificial neural network (ANN) is an appropriate method in comparison to other statistical ones. The forecasting process is brought in Appendix A.

If a DG Agent (DGA) receives a request from its FA, it declares the power it can provide. The DGA has the result of ANN and it can calculate the output of DG by environmental factors, PV model and time of the day.

The solar modules can be modeled as shown in Fig. 3. There are N_s cells connected in series and N_p cells of parallel connections in each module

$$I_{PV} = I_{SC}\cdot \frac{G}{1000}.\ (1 + K_I.\ (T - T_{ref})) \quad (13)$$

where I_{PV} is light generated current of a PV cell, I_{SC} is short circuit current of PV cell, G is sun irradiance, K_I is the short-circuit current/temperature coefficient, T is environment temperature in Kelvin [K] and is reference temperature which is 298.5.

$$I_d = I_0\cdot(e^{\frac{V+R_S I}{a.V_t}} - 1) \quad (14)$$

where I_d is the diode current of the ideal PV cell, I_0 is the diode saturation current, a is the diode ideality constant.

$$I = I_{PV}.\ N_P - I_0.\ N_P.\ (e^{\frac{V+R_S I}{a.V_t}} - 1) - \frac{V + R_S I}{R_P} \quad (15)$$

R_S is the equivalent series resistance of the module and R_P is the equivalent parallel resistance, V_t is the thermal voltage of the module which is given by equation

$$V_t = \frac{N_S.\ k.\ T}{q} \quad (16)$$

where k is the Boltzmann constant [J/K] and q is electron charge [C]

$$P_{PV} = V.\ (I_{pv}^{cell}.\ N_P - I_0.\ N_P.\ (e^{\frac{V+R_S I}{a.V_t}} - 1) - \frac{V + R_S I}{R_P}) \quad (17)$$

In order to smooth out PV power fluctuations various types of energy storage technologies have been proposed such as electric double-layer capacitor (EDLC) [28] and battery energy storage [29]. In this study, zinc bromide battery modules (ZBM) has been considered to deliver uninterrupted power, efficiently. The energy of ESS at time t is calculated as follows:

$$E_{ESS}(t) = E_{ESS}(t-1) + \Delta t \times P_{ESS}^{Ch} - \Delta t \times P_{ESS}^{Dch} \quad (18)$$

Since $\Delta t = 1$ we will have:

$$E_{ESS}(t) = E_{ESS}(t-1) + P_{ESS}^{Ch} - P_{ESS}^{Dch} \quad (19)$$

The energy storage is charged through PV and discharged if the solar station is connected to the network, hence:

$$E_{ESS}(t) = E_{ESS}(t-1) + P_{PV} - P_{ESS}^{Dch} \quad (20)$$

Which is the energy of storage in solar station at time t. The power output of solar station considering the maximum rated power of ESS at which the system can be discharged is calculated as follows:

$$P_{Solar} = \min(P_{ESS}, P_{ESS}^{Max}) \quad (21)$$

The power each DG station can deliver considering operational constraints of the network is calculated as follows:

$$P_{DG} = \min(P_{Solar}, P_{Nwk}) \quad (22)$$

where P_{Nwk} is the available capacity of feeder to carry out DG output.

$$P_{Nwk} = V_{\min} \times (I_{\max}^{Path} - I_{feeder}) \quad (23)$$

where $I_{\max}^{Path}$ is the minimum of current upper bound of path between DG and respective tie switch.

4. Simulation results

To demonstrate the effectiveness of the proposed method, it has

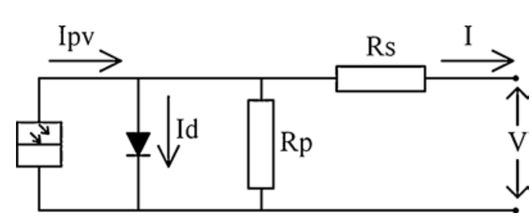

Fig. 3. The equivalent circuit of PV module.

been applied to a distribution system including 4 feeders, 70 nodes and 78 branches [30] and shown in Fig. 4. Before the fault, all CBs are normally closed and all ties are normally opened and tie lines are shown by dash lines.

In this study, BP SX 150 solar module has been considered, which is made of 72 multi-crystalline silicon solar cells in series. A Raytheon Ktech's 30 kW energy storage system (ESS) has been used to manage PV ramp rates. The 30 kW/120 kW h ESS has 12 RedFlow® ZBM and designed to deliver uninterrupted power, efficiently.

A NARNN has been used to predict sun irradiation and environment temperature. It has 10 hidden layers and two delays.

There are three DGs in the network, which are shown in the Fig. 4. Each DG consists of a solar station and an ESS. There are 10 modules in each solar array and 10 arrays in each solar station.

The proposed algorithm has been applied to different scenarios. In the first scenario, system is in off-peak mode and/or the demand of outage area is less than the capacity of at least one backup feeder, so the group restoration is possible. In the second scenario, the demand of outage area is more than maximum capacity of backup feeders and the summation of all backup capacities is enough to restore all loads, hence the sectional restoration should be done. In the third scenario, the demand of outage area is more than maximum capacity of backup feeders but the summation of all backup capacities is not enough to restore all of loads, so load transfer from supporting feeders should be done. In fourth scenario, not all capacities from back up and supporting feeder are enough for load restoration and therefore some of loads should be shed.

The occurrence of each scenario depends on peak hours and demand of outage area. If the distribution system is in peak hours the possibility of load shedding is high, but during off-peak hour, load shedding is unlikely to happen.

In order to implement proposed multi agent systems, Netlogo [31] environment has been used. In order to check the feasibility of each scenario, the feeder agent has to run a power flow (PF) for that scenario. In this study the fast-decoupled power flow algorithm for radial distribution systems presented by Ref. [32] has been used. The PF has been coded in Matlab and a Matlab–Netlogo extension has been used for this purpose [33].

The output power of each PV module and energy stored in ESS without any discharge are shown in Fig. 5

When a fault occurs, the respective switched will be opened to isolate the fault, and then the downstream feeder will be out of service. After isolating the fault, the HSA will sends a signal to MFA. After that, the HSA tries to find possible paths for restoration and at the same time, MFA talks with BFAs and asks for available capacities. Then the MFA runs PF for available paths. If it ran successfully the MFA keeps the combination, otherwise the combination will be omitted.

In this study, it has been assumed that the location of fault is defined so fault location algorithm has been skipped. Only single fault cases have been considered in this paper. There are many possibilities for fault location. Some of possibilities are shown in Fig. 6. The worst case for fault to happen is where all of loads in the feeder is out-of-service and should be restored as shown in Fig. 6(a).

The loading data, which is used for defining loading factor, is based on real data from Jackson Associates' MAISY Utility Customer Energy Use and Hourly Loads Databases [34]. Then by applying an ANN, loading factor of the network for different hours based on one-year data has been calculated. Even in the peak hours and the worst case, the load will not exceed 115% of average load, but in order to show the efficiency of proposed method, it has been applied on different loading conditions varying from 100% to 210%, which is unlikely to happen.

The required switching to restore out-of-service zones are shown in Table 1 for each scenario. There are four possibilities for supply and demand:

- If the demand of outage area is less than maximum capacity of any backup feeder, then the group restoration is possible. As can be seen in Table 1, the restoration can be done by closing just one tie switch.
- If the maximum capacity of backup feeders is less than demand of outage area and hence the group restoration is not possible and

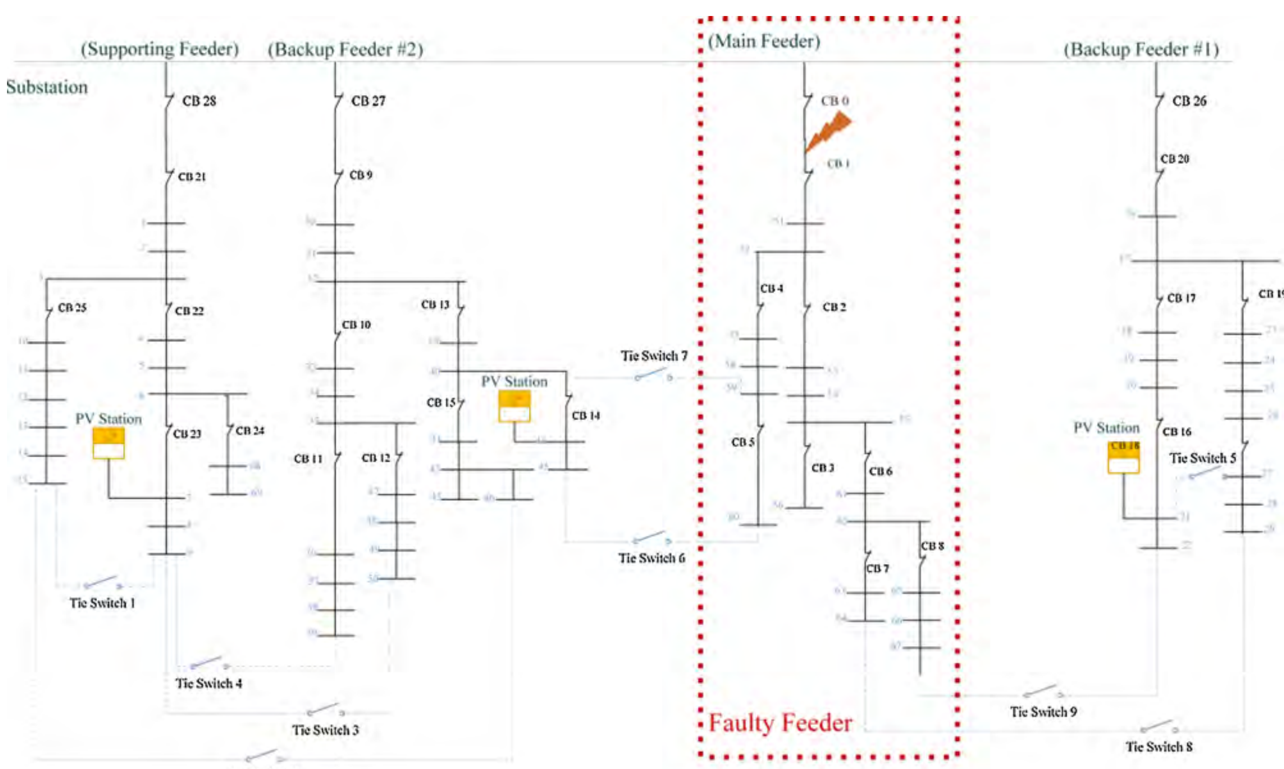

Fig. 4. Under study 70-bus distribution system.

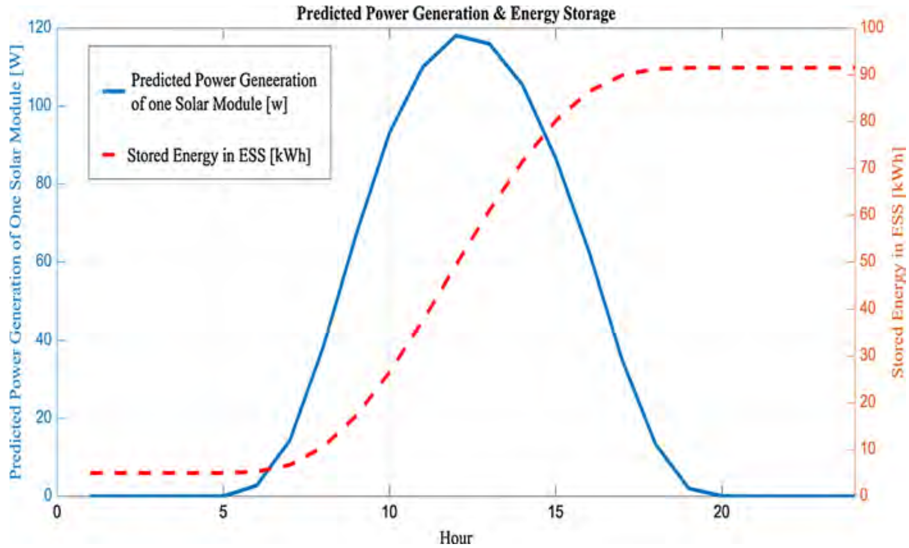

Fig. 5. The output power of PV module and energy of ESS.

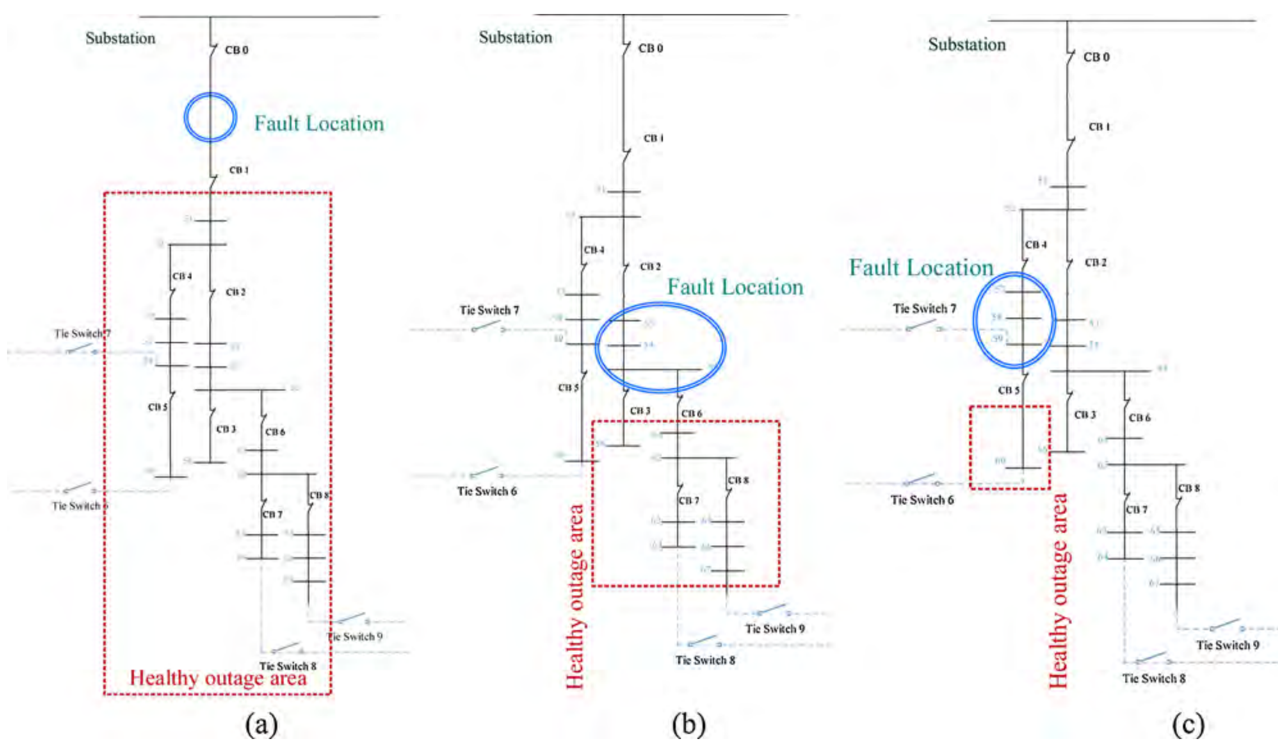

Fig. 6. Different fault location and respective healthy outage area.

Table 1
The simulation resultfor different scenarios.

Scenario	Loading condition	Tie switch #number	CBs #number
1	100%	#6	–
2	130%	#3, 7, 9	#8, 10, 11
3	160%	#4, 6, 8, 9	#5, 7, 8, 11
4	190%	#6, 8	#5, 7
5	210%	–	–

sectional restoration has to be done.

- If the capacity of all backup feeders cannot meet demand of out-of-service area then the load transfer has to be done.
- If after load transfer and partial restoration, there are still some unrestored zone, they have to be shed.

The restored areas along with number of switching for scenarios with and without DGs are shown in Fig. 7.

As can be seen, when the loading increases, the percentage of restored load decreases due to less spare capacity by backup and supporting feeders as well as more demand of outage area.

Furthermore, as can be seen in Fig. 7 the number of switching increases as the loading increases but at a specific point (after 160%), when there is not enough capacity to restore load it will reduce till a loading condition where 0 % of outage area restored due to lack of capacity (210% loading).

5. Conclusion

In this paper, a multi agent system to implement self-healing in smart distribution network has been designed. The proposed control

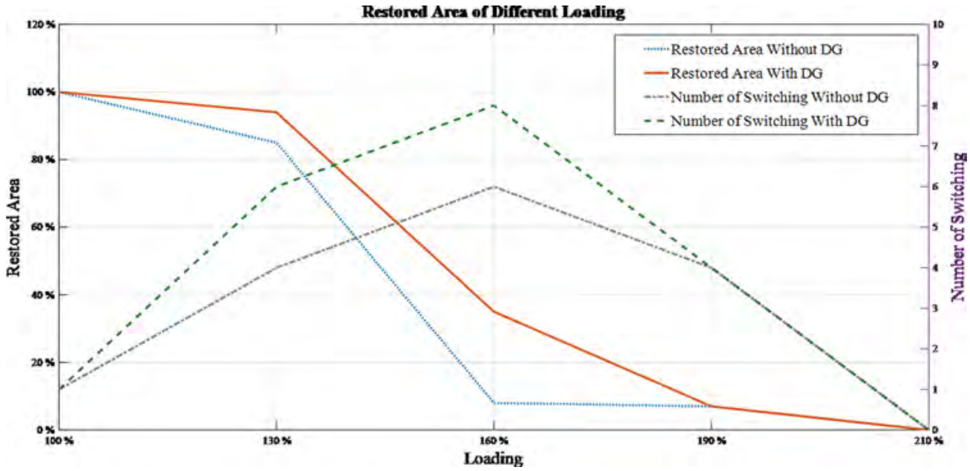

Fig. 7. Comparison of restored load and number of switching in different scenarios.

structure consists of three main types of controllers: feeder, switch and zone. The operating strategy and tasks of each controller has been designed regarding the multiagent system concept. Operational constraints of system such as voltage and current limits in the agents design. In order to achieve cooperation among various agents, a two-way communication has been implemented. To show the capability of the proposed model, it has been applied on a sample distribution network and a simulation model was developed. The results of applying the scenarios have been analyzed and compared. This scheme worked efficiently by representing how fast load restoration could be done with distributed control by means of local data. Moreover, simulation results evidenced that the proposed MAS model offers a feasible solution to optimal service restoration problem in smart distribution network. With the proposed multi agent frame work an autonomous and effective service restoration can be obtained.

Appendix A

Training is a basic operation of an ANN, which tries to figure a relationship between data set and target by updating the weight vector. The representation of a nonlinear autoregressive (NAR) NN can be seen in Fig. A1, where N is a neuron of ANN.

The training of neural network is the process of learning. The learning problem can be formulated as minimization of a loss function, which is consist of errors and regulation terms. These terms are used for evaluation of fitting ANN to data and preventing overfitting, respectively.

The loss function depends on the biases and synaptic weights in the neural network considered as a single weight vector w. The W^* is the point where loss function takes minimum. To determine the minimum of loss function, the gradient vector and Hessian matrix should be calculated which are first and second derivatives respectively.

$$\nabla_i f(w) = \frac{df}{dw_i}(i = 1, \ldots, n) = 0, \ldots, m \tag{A.1}$$

$$H_{i,j} f(w) = \frac{d^2 f}{dw_i.\ dw_j}(i, j = 1, \ldots, n) \tag{A.2}$$

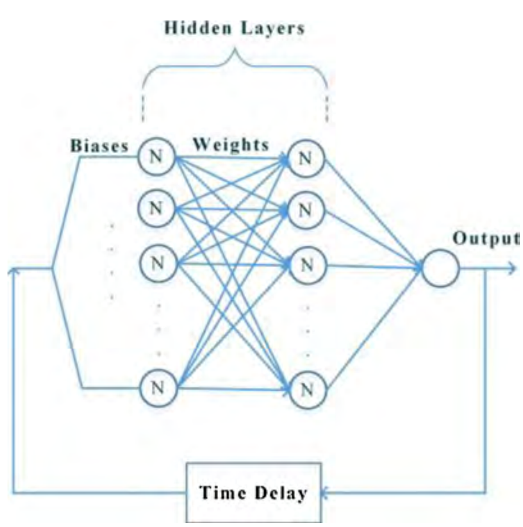

Fig. A1. Representation of ANN.

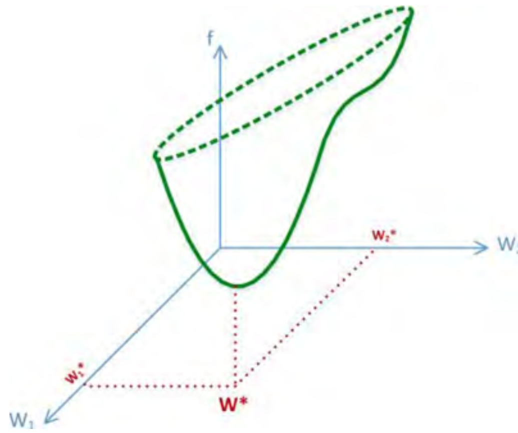

Fig. A2. Minimization of loss function in ANN.

In this study, the Levenberg-Marquardt (LM) algorithm has been used to calculate the minimum of loss function. Consider a loss function which can be expressed as a sum of squared errors

$$f = \sum e_i^2,\ i = 0, \ldots, m \tag{A.3}$$

where m is the number of elements in the data set (Fig. A2).

The gradient vector of loss function is defined as:

$$\nabla f = 2J^T.\ e \tag{A.4}$$

where the J is Jacobian matrix and can be defined as derivatives of errors:

$$J_{i,j}f\,(w) = \frac{de_i}{dw_j}(i = 1,\ \ldots, m \,\&\, j = 1,\ \ldots, n) \tag{A.5}$$

where m and n are number of elements in data set and parameters of ANN, respectively. The Hessian matrix can be approximated as:

$$H \approx 2J^T.\ J + \lambda I \tag{A.6}$$

where λ is damping factor and I is the identity matrix. The damping factor is used to ensure the positiveness of the H. At the beginning, it is large so it will lead to small steps updates. The damping factor will decrease as the loss decreases. When λ is large, the method takes a small step in the gradient direction. As the method nears a solution, λ is chosen to be small and the method converges quickly via the Gauss–Newton method. The basic strategy behind choosing the damping term uses the observations that the square of the step size $\Delta^2 = \delta w^T \cdot \delta w$ is a monotonically decreasing function of λ. Therefore, for a sufficiently large value of λ, the algorithm will take an arbitrarily small step in a descent direction. If a proposed step is unacceptable, one need only increase the damping term until a smaller, more acceptable step has been found. Because choosing λ is equivalent to choosing the step size, the Levenberg-Marquardt method can be considered a trust-region method. There are two broad classes of methods for determining the appropriate damping. This can be done by either adjusting λ directly, or, by first choosing an acceptable step size Δ and then finding a λ such that $|\delta w| \leq \Delta$. We will refer to these two types of schemes as direct and indirect methods respectively. Many schemes have been developed to efficiently adjust λ or Δ.

The simple method originally suggested by Marquardt is usually adequate. In this scheme, if a step is accepted, then λ is decreased by a fixed factor, say 10. If a step is rejected then λ is appropriately raised by a factor of 10. The qualitative effect of the damping term is to modify the eigenvalues of the matrix $J^TJ + \lambda I$ to be at least λ. Often, the eigenvalues of J^TJ are well spaced on a log-scale; it is therefore natural to choose the factor by which λ is either raised/lowered to be comparable to the eigenvalue spacing of J^TJ.

The LM algorithm defines the parameters improvement process as follows:

$$w_{i+1} = w_i - (J_i^T.\ J_i + \lambda_i I)^{-1}.\ (2J_i^T.\ e_i),\ i = 0,\ 1,\ \ldots \tag{A.7}$$

The first step of LM algorithm is to calculate the loss function, the gradient vector and the Hessian matrix approximation. Then the damping factor is tuned to reduce errors at each iteration.

The LM algorithm is a very fast algorithm to train ANN in forms of sum of squared errors.

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