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A Multi-Agent-Based Self-Healing Framework Considering Fault Tolerance and Automatic Restoration for Distribution Networks

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ABSTRACT Increasing penetration of distributed generators (DGs) brings new challenges to the control and protection of distribution networks. This article proposes a control and protection framework based on Multi-agent System (MAS), in which situation awareness of zone agents plays an important role. The main protection is designed to locate and isolate faults based on the peer-to-peer communication among the zone agents. Fault-tolerant mechanisms, including self-inspection and backup protection, are developed to cope with the malfunction of individual MAS and local communication failure. An automatic parallel restoration scheme that doesn't require complete grid information is proposed to restore the power supply. Comprehensive simulation studies are carried out on a 71-bus distribution network with DGs using DIgSILENT, and the results have shown the effectiveness of the proposed self-healing framework.

INDEX TERMS Self-healing framework, fault-tolerant mechanism, multi-agent system, distribution network.

I. INTRODUCTION

The penetration level of distributed generators (DGs) in electricity distribution networks increases rapidly, which converts the power flow in the distribution network from the traditional unidirectional mode into a bidirectional one [1]. Nowadays, the installation of more and more monitoring and controlling devices, including DG controllers, sensors and protection relays, is driving the distribution system to be smarter and more reliable. Distribution network has much more circuit breakers, switches and branches compared than the high-voltage networks, but the communication system is less reliable. Hence, a decentralized or distributed architecture, integrating both the control and protection functions, can provide more economical, flexible and reliable solutions to a smarter distribution network.

Fast fault isolation, autonomous recovery and robustness of the intelligent terminals are the main objectives in this transition, among which the self-healing features and intrinsic safety against cyber system attacks are the most concerned.

Multi-agent System (MAS) is regarded as a promising technology to build a smart decentralized control system. Multiple agents can collect and process data in parallel, respond to changes of environment swiftly and cooperate with each other in a highly efficient way. Various applications of MAS in the distribution network have been explored, covering protection and control [2], [3], voltage regulation [4] and load management [5]–[7]. The state-of-art achievements on MAS-based self-healing techniques are summarized in [8]. Reference [9] proposes a fault locating scheme based on exchange of the fault current information among agents. The scheme works well in unidirectional power flow network. In [3], a MAS-based adaptive protection scheme employs the inverse-time directional overcurrent relays. The protection strategy should be realized by the corporation of distributed relays and DG controllers. Considering that future distribution network may switch from open-loop operation to closed-loop and DGs exhibit different transient behaviors according to their types and controls, more improvements on the protection schemes are expected, confronting with variation in operating modes and communication conditions.

Reliability is highly concerned in protection systems. Efforts are made from two aspects. Back-up protection enables protection agents to provide mutual support, while fault tolerance mechanism enhances the decision-making of agent against communication failures. Backup protection has

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been widely applied in the transmission system [10] and the MAS-based wide-area backup protection gains much interest recently [11]–[13]. Different information, such as the differential current [11], directional distance [12], are collected for centralized decision. In [13], a reputation value is assigned to each backup protection agent and only the trusted agents with large reputation ratios can trip the breakers. For distribution system with many laterals and less reliable communication, more research works are expected on the development of backup protection schemes as well as fault-tolerant mechanisms.

After fault clearance, automatic reconnecting of the islanded sections and users to the main grid is another research hotspot, which is commonly denoted as the self-healing technique. Reference [14] designs a hierarchical MAS-based self-healing framework. On the bottom layer, the zone agents collect load power, load priority and feeder currents, and upload them to the feeder agents. On the top layer, the feeder agents set up restoring plans, negotiate with other feeder agents and send orders to the zone agents to restore the loads. The service restoration problem is formulated as a multi-objective and multi-constraint optimization problem and solved by the expert-based decision-making algorithm to govern the control agents. Reference [15] provides a serial restoration approach, where the outage area is sectionalized into small zones by the feeder agent and these zones are restored one by one through communication among the feeder agents. In [16], an optimization model is proposed to decompose the outage section into several microgrids considering the power support from DGs in the islanded duration. In [17], electric vehicles are treated as dispatchable DGs in the restoration process. S&C Electric Company developed a MAS-based commercial product, named as IntelliTEAM, and applied them in Canada and Britain [18], [19]. In IntelliTEAM, the agent collects the capacity limits of all available backup feeders as well as their power-supply substations, selects the one with enough capacity as the new power supply feeder for the out-of-service sections. The situations requiring multiple backup feeders to share the heavy loads are not considered.

In this article, we adopt the MAS-based framework and propose several new designs on the fault-tolerance and self-healing mechanisms. All the strategies are based on the concept of decentralized decision-making and the information exchange scale among agents is strictly restrained. The primary and backup protection schemes can adapt to both the open-loop and close-loop operation modes. Compared with self-healing strategies in the literature [14], [20], [21], the proposed restoration strategy requires no pre-set plans or global network information to deal with complicated network structure, where the out-of-service sections have several possible recovery paths. According to the proposed self-healing scheme, agents can work in parallel to decompose the sections and switch them to different backup feeders with consideration of the capacity constraints. The whole recovery process demands no central optimization.

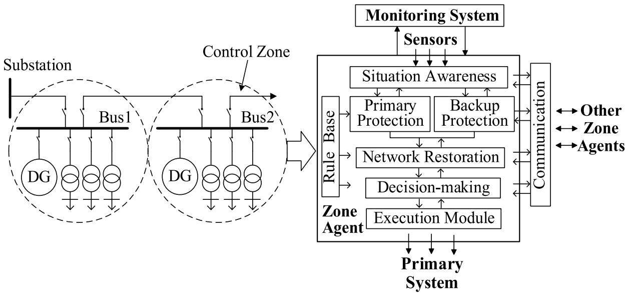


FIGURE 1. Framework of MAS.

The remaining of the paper is organized as follow: Section II describes the MAS framework, and Section III introduces the situation awareness of zone agents. The MAS-based protection scheme, together with the fault-tolerant mechanisms, is presented in Section IV. Section V describes the automatic network restoration scheme. All the strategies are verified by simulation studies on the DIgSILENT platform, as presented in Section VI. Finally, the paper is concluded in Section VII.

II. THE MAS-BASDE SELF-HEALING FRAMEWORK

For a typical cable feeder as shown in Fig. 1, each bus in the main loop, together with all the switches and laterals connected to it, comprises a control zone. In our design, each control zone is equipped with a zone agent (ZA) which is responsible for the protection and control of equipment within the zone.

The structure of a ZA is also depicted in Fig. 1. Sensors collect the operation information within the zone. Real-time and historical data are stored and refreshed. ZA evaluates the situation based on observations and exchanges its judgment with the neighbouring ZAs periodically through bidirectional communication. Procedural tasks as well as the rules for protection and recovery controls are stored in the rule base. The decision-making module generates task sequence according to the situation and objectives.

Different from the communication system for SCADA [22], the agents exchange their judgment and decision instead of the original observation data. Hence, the requirement on communication bandwidth is reduced greatly. We suggest that the communication between agents adopts IEC61850 protocol. In this article, we will focus on the protection and control strategies for an agent, and do not discuss further about the hardware and software implementation.

III. SITUATION AWARENESS DESIGNS

Correct awareness of the system situation is an important prerequisite for successful control decision. The following three main situations are defined to support the decision-making process.

(1) Normal Situation (N): The normal situation means there are no faults or abnormal states detected. Then the task of the ZA is to repeat the routine work periodically, including observation and analysis, uploading data to the monitoring system, sending periodic beacons to neighbor ZAs etc.

TABLE 1. Description of zone situations and criteria.

Zone situation	Criteria
Normal operation (N)	$V_{\min} \le V_j \le V_{\max}$ & $I_m < I_{set}$
Faults of feeders (F01)	$V_j \le V_{\min}$ & $I_m > I_{set}$
Islanding operation or blackout (F02)	$\{V_j \le V_{\min}$ or $V_j \ge V_{\max}\}$ & $I_m < I_{set}$
Faults of communication network of ZAs (A01)	Messages from other ZAs are not received, or false messages are received.
Faults of measurement modules (A02)	Local information is not received.

(2) Fault Situation (F): When the currents and voltages within the zone exceed the limits (F01), or some branches are out-of-service (F02), the zone falls into the fault situation. When F01 or F02 are detected, the ZA should interrupt its routine work, and then trigger the protection (F01) or the restoration control (F02) to isolate the fault and restore the power supply.

(3) Abnormal Situation (A): In the abnormal situation, the power supply is not interrupted, but some abnormal events are detected, such as the failures of the communication system (A01) or sensors (A02). In this situation, the ZA may lock part of its functions and inform the monitoring system as well as the neighbor ZAs.

The typical criteria for situational judgment are presented in Table 1, where I_m is the current flowing through branch m, V_j is the voltage of bus j, $V_{\min}$ and $V_{\max}$ are the minimum and maximum limits of bus voltage, and I_{set} is over-current protective setting. The realization of the situation evaluation is discussed in Section IV.

IV. MAS-BASED PROTECTION SCHEME WITH FAULT-TOLERANT MECHANISMS

A. PRIMARY PROTECTION SCHEME

Distribution of the short-circuit currents shows different patterns in the open-loop and the close-loop operation mode. Conventionally, the distribution network is running in the open-loop operation mode, where there is only one path connecting a node to the main power grid. Hence, only the short-circuit current injected along this path to the fault point can stably maintain high values much greater than the normal current. There is no significant change after DGs access. Wind generators will inject high short-circuit current at the fault instant (usually about 3-7 times of the rated current). Then the current will be limited to near normal value by the controller within 1-2 cycles. Photovoltaic sources are inertia-free [23] and the instant fault currents they provide are usually within 1.2-1.5 times of their rated values. In the closed-loop operation mode, there are more than one path to the main power grid. All these paths will inject steady short-circuit currents to the fault point. Therefore, the protection scheme design for the open-loop operation mode is commonly different from that for the closed-loop mode. The protection schemes that are suitable for both the open-loop operation and the closed-loop operation of the distribution networks are rarely found in the literature.

TABLE 2. Rules for message exchange and fault location in primary protection.

Rule No.	Prerequisite	Action of ZAs
1	Fault current is detected and flows from neighbouring zone into local zone.	ZA sends F01-Up messages to neighbouring ZA at the opposite end of the line.
2	Fault current is detected and flows from local zone to neighbouring zone.	ZA sends F01-Down messages to neighbouring ZA at the opposite end of the line.
3	Local zone is under F02 situation.	ZA sends F02 messages to all the neighbors.
4	({message out = F01-Down or F02} & {message in = F01-Down or F02}) or ({has only one neighbor} & {message in = F01-Down})	ZA in F01 zone detects fault in the line where fault current flows out of zone, and ZA in F02 zone detects fault in the line towards F01 zone. ZA trips the breaker on the line connecting to the neighbor.
5	Otherwise	Fault is not detected in local zone, and no breaker is tripped.

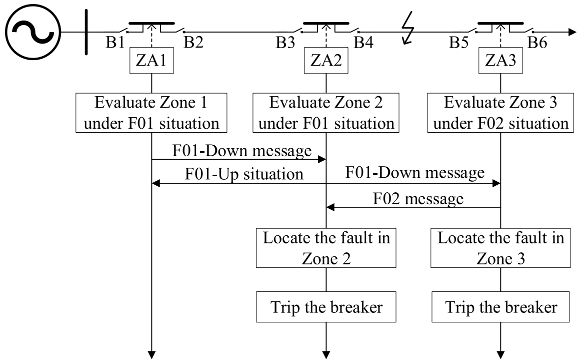


FIGURE 2. Coordination among zone agents for primary protection.

In the proposed scheme, the ZA locates the fault by exchanging its judgment with the neighbors. The messages they exchange are preset, which are standard codes from the code set of {"F01-Up", "F01-Down", "F02"}. It indicates both the zone situation and the direction of the fault current. Table 2 shows the rules for the message exchange and the fault location applied in the main protection.

Fig. 2 gives a typical scene of open-loop operation to illustrate the main protection scheme. There are three ZAs named ZA1, ZA2 and ZA3. When a short-circuit fault occurs in the line section between the zones of ZA2 and ZA3, the fault detection and clearance process is described as step 1 to step 3.

Step 1: According to the observation, ZA1 and ZA2 perceive their situations as F01, and ZA3 finds its zone under F02 situation.

Step 2: Based on Rules (1)-(3) listed in Table 2, ZA1 sends F01-Down message to ZA2 and receives F01-Up message from ZA2. Meanwhile, ZA2 sends F01-Down message to ZA3 and receives F02 message from ZA3.

Step 3: When Rule (4) is satisfied in ZA2 and ZA3, breakers B4 and B5 will be tripped by ZA2 and ZA3, respectively. Rule (5) applies to ZA1 so that ZA1 will not open any breakers.

In closed-loop operation, if the right branch of the feeder is connected to other substations, as shown in Fig. 2, ZA2 will receive F01-Down message from ZA3, which will also trigger Rule (4) in both ZA2 and ZA3 and then clear the fault successfully. Thus, the proposed primary protection scheme is adaptive to different topologies and operation modes.

B. SELF-CHECKING MECHANISM

Usually, the MAS-based protection scheme depends strongly on the reliability of communication system. If a local communication failure occurs, the main protection may fail to make the right decision to clear the fault. Thus, two fault-tolerant mechanisms are designed.

a) The self-checking mechanism, where the ZAs check the state of communication network and sensors to detect A01 or A02 situation.

b) The backup protection mechanism, which takes over the protection task in case of A01 or A02 that the main protection fails.

1) REALIZATION OF SELF-CHECKING MECHANISM IN ZA COMMUNICATION

To check the communication links, each ZA will send periodical beacons to the neighbouring ZAs. The beacon contains a status counter, which adds one automatically in the next beacon. The ZA can easily determine whether there are wrong or lost beacons. Set the checking cycle to be the maximum number of the beacons, N_{totalb}; for instance, N_{totalb} equals 10. In case the criterion in (1) is met in both ZAs, the communication link between two ZAs is identified as failed and the A01 situation alarm will be sent subsequently.

$$\frac{N_{wrongb} + N_{lostb}}{N_{totalb}} > K \tag{1}$$

where N_{wrongb} and N_{lostb} are the number of wrong beacons and lost beacons respectively. K is the trust threshold. In this article, we set K to 50% which is much higher than usual packet loss and error rate of a communication system, so that the A01 judgment will be sound enough.

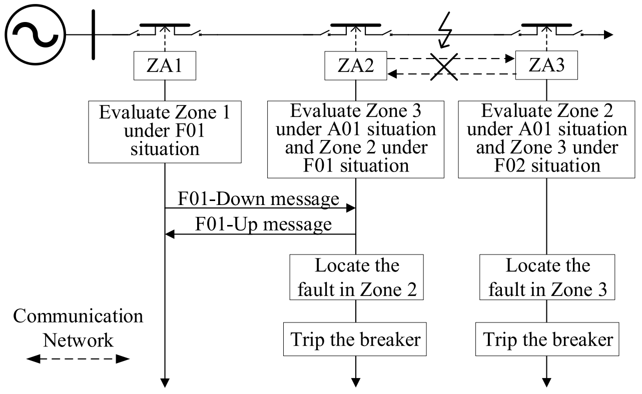
2) REALIZATION OF SELF-CHECKING MECHANISM IN ZA MEASUREMENT

It is important for ZAs to check whether the information of branch currents and bus voltages is collected accurately. The Kirchhoff's Current Law (KCL) is adopted to detect the failures of current sensors in the ZA. The criterion is depicted as follows:

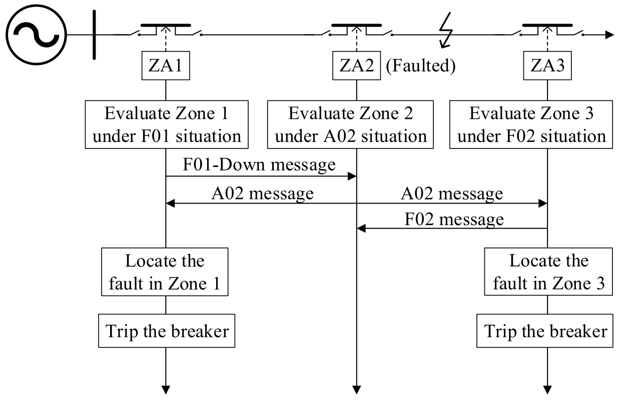
$$\left|\sum_{m=1}^{n} \dot{I}_{bm}\right| > I_{th} \tag{2}$$

where I_{bm} is the current flowing through branch m to the zone, n is the number of the branches on the boundary, and I_{th} is the current threshold for measurement errors. The ZA will send A02 situation alarm and lock its protection function if criterion (2) is met.

The fault-tolerant mechanism is also designed for the measurement of bus voltage. If ZA finds the bus voltage exceeds the limits (e.g. $[0.8V_{\mathrm{N}}, 1.2V_{\mathrm{N}}]$), it will send requests to the adjacent ZAs for their bus voltage values. If the absolute difference between two adjacent buses exceeds the confidence interval, the ZA will infer that a fault occurs in its voltage sensor. The zone situation is then classified as A02 and the protection function of the ZA is self-locked under this situation.



(a) Fault of communication network.



(b) Fault of measurement modules

FIGURE 3. Coordination among zone agents for backup protection under different condition.

C. BACKUP PROTECTION MECHANISM

There are two prerequisites for the backup protection to trip the breakers: (1) F01 or F02 situation lasts for longer than 150∼200ms. (2) The adjacent zones in the "F01-down" direction are under A01 or A02 situation, or there are not any messages received from their ZAs. If these two prerequisites are satisfied, the ZA will trip the breaker on the line towards the A01/A02 zone.

Fig. 3 shows the coordination between ZAs during backup protection. Two examples are proposed, one for communication faults and the other for measurement failures. The decision process of the backup protection is described as follows:

1) COMMUNICATION FAILURE

As shown in Fig. 3(a), if a fault occurs in the communication link between Zone2 and Zone3, ZA2 and ZA3 will detect A01 situation, which leads to the lock of the main protection and the activation of the backup protection.

After a short-circuit fault occurs, ZA1 and ZA2 detect the F01 situation, and ZA3 is aware of F02 situation. After 150-200 ms, the above two prerequisites are met, and then ZA2 and ZA3 will trip the breakers of the fault line.

2) AGENT FAILURE

In Fig. 3(b), after the occurrence of the short-circuit fault, ZA1 and ZA3 perceive their situations as F01 and F02 respectively, but ZA2 fails to work properly. Then ZA1 and ZA3 can activate the backup protection to isolate the fault after 150-200ms.

The MAS with the fault-tolerant mechanisms can work properly even after the fault occurs in the MAS. Besides, this mechanism is cost-effective and requires little communication cost.

V. THE AUTOMATIC NETWORK RESTORATION SCHEME

In the open-loop operation mode, after the ZAs cut off the fault line, the downstream zones will be isolated from the main grid. An automatic restoration scheme is proposed in this section to reconnect them to the power grid through multiple backup paths. In the proposed scheme, the isolated part is firstly decomposed into the independent zones by their ZAs actively. Then the ZAs work in parallel to search for the restoration path. With periodic exchange of the state information among the ZAs, the isolated zones can be restored step by step automatically. The restoration flow chart is shown in Fig. 4

A. DECOMPOSITION OF THE ISOLATED PART

After fault clearance, all the ZAs on the downstream part of fault feeder will be aware of the F02 situation. If such state lasts longer than a preset threshold, each ZA will actively trip the breakers on the lines connecting to other ZAs and switch to the microgrid control mode. After this active decoupling process, the isolated part of the feeder is converted into multiple islanded microgrids. Consequently, the ZA's control target turns to balancing between the DG outputs and local loads, and maintaining the power supply of the loads as much as possible. In the meantime, ZA also initiates the network restoration step.

B. PARALLEL NETWORK RESTORATION

In the second stage of the restoration scheme, each ZA initiates communication with all its adjacent ZAs to search for suitable backup feeders. All the ZAs working in the microgrid mode start the search in parallel and the goal is to reconnect their control zones to the main grid again.

Take the network shown in Fig. 4 as an example. A fault occurs on line L1, and the main protection of ZA1 and ZA2 opens breakers B3 and B4. Then the first stage of restoration begins where ZA2-ZA6 trip the breakers B5-B14 on their interconnected lines. ZA2-ZA6 operate their control zones in the microgrid mode; see Fig. 5(a). The information exchange, decision rules and restoration process are introduced in detail in the following paragraph.

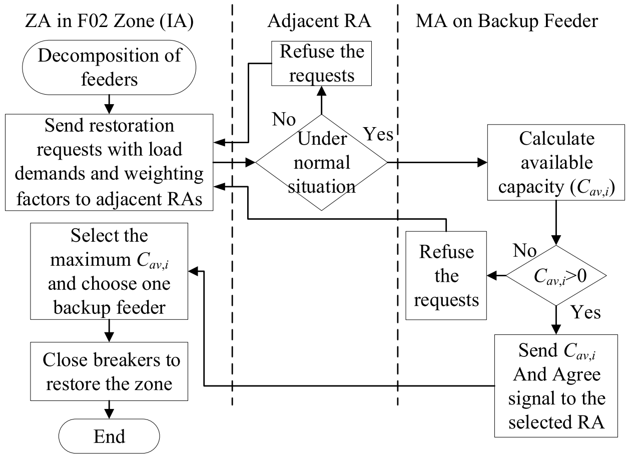
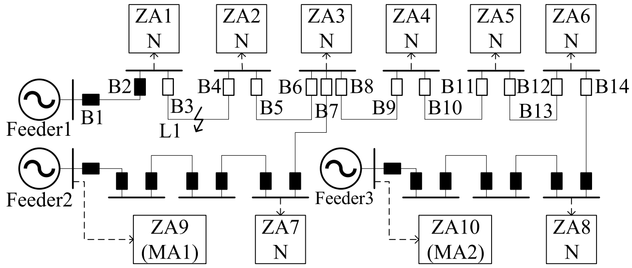
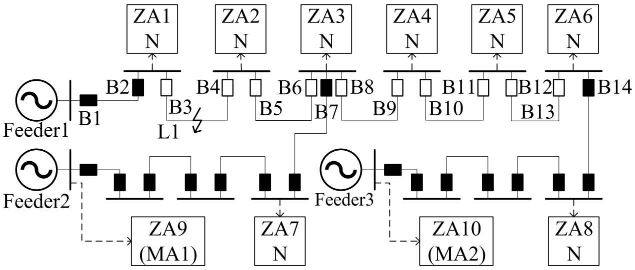


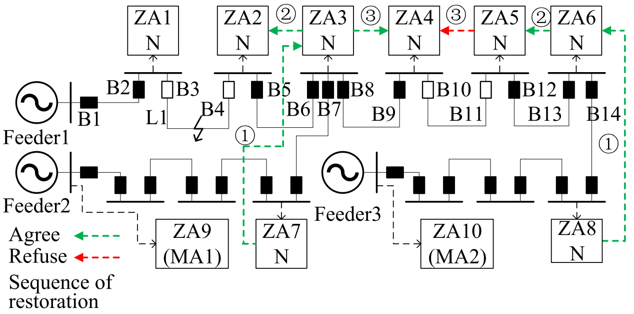
FIGURE 4. The restoration flow chart.



(a) Decomposition of the isolated part



(b) Restoration result after the first round



(c) Final restoration result

FIGURE 5. Diagram of network restoration scheme.

Step 1: ZAs in the microgrid mode (initiator agent, IA) send restoration requests to all adjacent ZAs (responder agent, RA), except for the ZA on the fault section. For the convenience of followed description, we denote the first ZA of a feeder which is located in the main grid substation as MA. For the example in Fig. 5, ZA9 and ZA10 are two MAs.

As shown in Fig. 5(a), ten IA-RA sessions are initiated, i.e. {ZA2-ZA3, ZA3-ZA2, ZA3-ZA4, ZA3-ZA7, ZA4-ZA3, ZA4-ZA5, ZA5-ZA4, ZA5-ZA6, ZA6-ZA5, ZA6-ZA8}. Together with the restoration request, IA also sends its load demand (P_D+jQ_D) and weighting factor (W) as additional information. They are calculated according to (3) and (4):

$$P_D + jQ_D = \sum_{k=1}^{H_1} S_{Lk} - \alpha \sum_{i=1}^{H_2} S_{dgi} \tag{3}$$

$$W = \sum_{k=1}^{H_1} w_k, \quad (w_k = 1, 2, 3) \tag{4}$$

where S_{Lk} and S_{dgi} are the apparent power of customer k and DG i, H_1 and H_2 are the number of customers and DGs in the zone, w_k is the weighting factor of customer k and the customer with high priority is assigned with a high weighting factor, α is the discount coefficient of DG which considers the potential decrease of DG output power after the zone is reconnected to another feeder. For fluctuant DG, such as wind generator or PV source, typical value of α is between 0.3 and 0.6.

Step 2: RA handles the request of IA. The RA whose zone is not under normal situation will reject the request. If the zone is in normal situation, then RA will forward the request information to MA. In Fig.5, only Zone7 and Zone8 are in normal situation, so they will forward {restoration request, $P_D + \mathrm{j}Q_D$, W} to MA1 and MA2.

Step 3: The MA calculates its expected available capacity after receiving restoration request i, $C_{av,i}$, by (5).

$$C_{av,i} = \frac{S_{\max} - \sqrt{(P_f + P_{D,i})^2 + (Q_f + Q_{D,i})^2}}{S_{\max}} \tag{5}$$

where $P_{D,i}$ and $Q_{D,i}$ are the load demand from request i, P_f and Q_f are the active power and reactive power of the first section on the feeder, and $S_{\max}$ is the capacity of the feeder.

If a MA receives more than one request, only one request is accepted at one round. The selection rule is $\{i$: $(C_{av,i} > 0)$ & (the highest W_i) & (the smallest $C_{av,i}$)$\}$. Then MA replies to the selected RA with {Agree} signal as well as the value of $C_{av,i}$, and rejects all other requests. RA forwards this reply to the IA. In the example, if there are enough capacities in Feeder2 and Feeder3, ZA7 and ZA8 will send Agree signals and the values of $C_{av,i}$ to ZA3 and ZA6, respectively.

Step 4: IA confirms the restoration plan with the RA. Then both the IA and RA close the breakers on their interconnected line section to carry out the restoration. In the example, ZA3 closes breaker B7, while ZA6 closes breaker B14.

Steps 1-4 form a restoration round. For the example demonstrated in Fig. 5, the restoration result after the first round is shown in Fig. 5(b). After the first round, power supply in Zone3 and Zone6 has been recovered. Such restoration round repeats until all the outage zones are restored. Fig. 5(c) shows the network structure after three restoration rounds, in which the load levels of different backup feeders are well balanced.

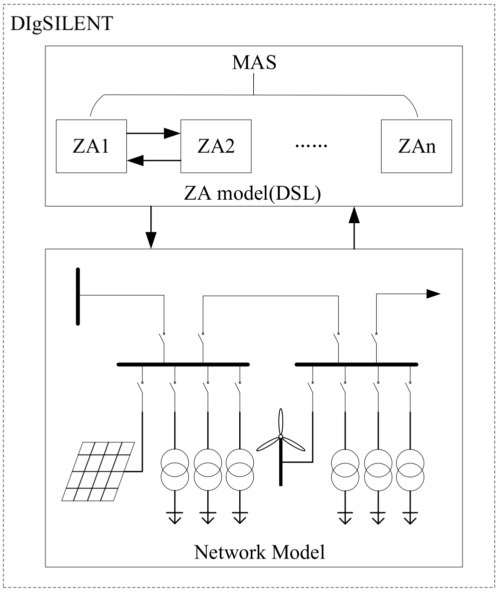


FIGURE 6. Schematic diagram of MAS implemented on DIgSILENT.

TABLE 3. The specific data types of ZA.

Number	Data types of ZA	Number	Data types of ZA
1	F01-Up	8	Restoration request
2	F01-Down	9	Load demand (P_D+jQ_D)
3	F02	10	Weighting factor (W)
4	A01	11	Agree signal
5	A02	12	Refuse signal
6	Bus voltage (V_j)	13	Expected available capacity after receiving restoration request i ($C_{av,i}$)
7	Periodical beacon		

It is noticed that neither preset strategies nor global operation and structure information are needed by the ZAs to make the restoration decision. The mechanism is applicable to large-scale distribution networks with complex feeder connections, and the restoration can be implemented in a relatively short time with little communication cost.

VI. CASE STUDY

To demonstrate the effectiveness of the proposed framework, we set up simulation models on the DIgSILENT platform. We apply the DIgSILENT Simulation Language (DSL) to develop all above mentioned protection and control strategies and form the user-defined ZA model. Also, the communication links are modeled so that ZA models can communicate with one another in the simulation.

All the electrical elements are built in DIgSILENT as Network Models. ZAs can get operation data from the Network Models and also control the breakers.

Fig. 6 depicts a schematic diagram of the MAS implemented on DIgSILENT. The specific data types exchanged among ZAs are showed in Table 3.

We take the distribution network shown in Fig. 7 as the test system, which is modified from the grid reported in [24] with two substations, four feeders and 71 buses. The test system is operated in open-loop mode while the switches on the

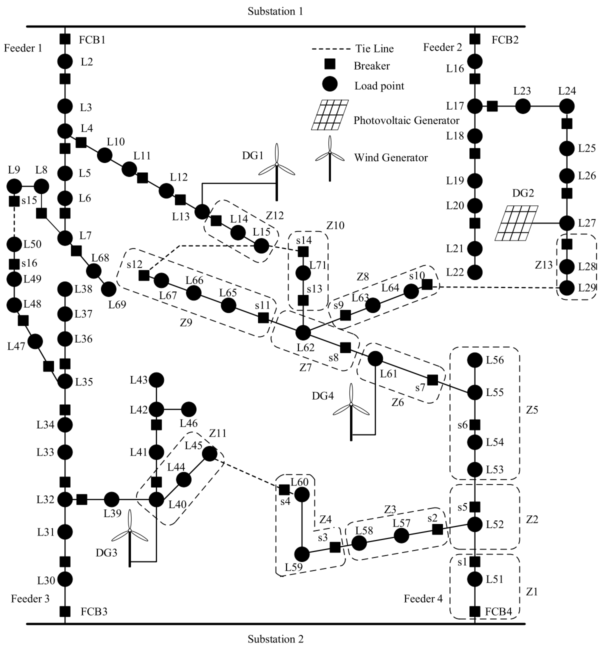


FIGURE 7. Topology of a distribution network.

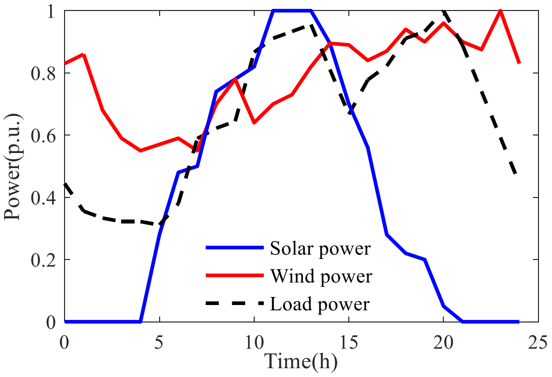


FIGURE 8. Load power and DG output profiles.

back-up branches (shown as dot line in Fig. 7) are normally open. Fig. 8 indicates the fluctuant load power [14] and DG output [17] profiles in 24 hours.

In order to consider different load priority, the loads in Zone11 are assumed to have a higher priority than other loads. Besides, four renewable DGs with capacity of 0.5 MVA and power factor of 0.95 are integrated in the distribution network. It is noted that we use circuit breakers instead of sectionalizes or disconnecting switches so as to match the requirement of the protection.

A. TEST OF THE PROTECTION SCHEME

A three-phase short circuit fault is simulated to occur in the line between L53 and L54 within Zone5 at 1.0000 s (simulation time). Three cases are carried out to test the behavior of ZA1, ZA2 and ZA5, where the MAS operates correctly in Case 1, communication failure between ZA2 and ZA5 occurs in Case 2, and a current sensor in the zone controlled by ZA2 is out-of-service in Case 3. The test results are shown as follows. Power flow of these cases adopts the load data at 5 AM in Fig. 8. Simulation results are as follows:

TABLE 4. Sequence of events for Case 1.

Number	ZA1	ZA2	ZA5
1	1.0108s: F01, send F01-down to ZA2	1.0108s: F01, send F01-up to ZA1 and F01-down to ZA5	1.0108s: F02, send F02 to ZA2
2	1.0131s: receive signal from ZA2	1.0131s: receive signal from ZA1 and ZA5	1.0131s: receive signal from ZA2
3	——	1.0150s: start primary protection	1.0150s: start primary protection
4	——	1.0610s: trip breaker s5	1.0610s: trip breaker s6

TABLE 5. Sequence of events for Case 2.

Number	ZA1	ZA2	ZA5
1	——	0.2000s: evaluate Zone5 under A01	0.2000s: evaluate Zone2 under A01
2	1.0108s: F01, send F01-down to ZA2	1.0108s: F01, send F01-up to ZA1 and F01-down to ZA5	1.0108s: F02, send F02 to ZA2
3	1.0131s: receive signal from ZA2	1.0131s: receive signal from ZA1	——
4	——	1.1510s: start backup protection	1.1510s: start backup protection
5	——	1.1970s: trip breaker s5	1.1970s: trip breaker s6

Case 1: At 1.0108 s, agents ZA1 and ZA2 detect their zones to be under F01 situation, and ZA5 perceives F02 situation. After that, ZA2 and ZA5 start their primary protection. At 1.0610 s, breaker s5 and s6 are tripped off and the fault line is isolated. Table 4 lists the sequence of events.

Case 2: The backup protection is triggered successfully. The sequence of events is shown in Table 5.

Case 3: The backup protection operates correctly and Table 6 lists the event sequence.

According to section IV.C, there is a starting time delay for the backup protection. In the simulation, we set the delay to be 100ms. In case 2 and case 3, F01 and F02 situations lasted until the backup protection initiate. The fault section is successfully isolated at 197ms after the fault occurrence, considering the circuit breaker opening time of 50ms.

As for ZA6, the current provided by the wind generator in zone 6 is about $3I_N$ (I_N refers to its rated current) at the fault occurrence period and then decreased to no more than $1.8I_N$. Hence, when the backup protection works, the situation of ZA6 is F02.

After breaker s1 and s6 are switched off by the backup protection, Zone 3, Zone 4 and Zone6-Zone10 will be de-energized. This will initiate the restoration process to reconnect these zones to the backup feeders in a series of parallel operations. Details of the restoration process are presented in section VI.B.

B. TEST OF THE NETWORK RESTORATION SCHEME

Two cases with different load levels are designed to test the restoration behavior. Case 4 is a light load case with load at 5 AM and Case 5 is the heavy load case from 8 PM in Fig. 8. The fault is set on the line between FCB4 and L51 in Zone1 of

TABLE 6. Sequence of events for Case 3.

Number	ZA1	ZA2	ZA5
1	——	0.1108s: A02, send A02 to ZA1 and ZA5	——
2	0.1131s: receive signal from ZA2	——	0.1131s: receive signal from ZA2
3	1.0108s: F01, send F01-down to ZA2	——	1.0108s: F02, send F02 to ZA2
4	——	1.0131s: receive signal from ZA1 and ZA5	——
5	1.1510s: start backup protection	——	1.1510s: start backup protection
6	1.1970s: trip breaker s1	——	1.1970s: trip breaker s6

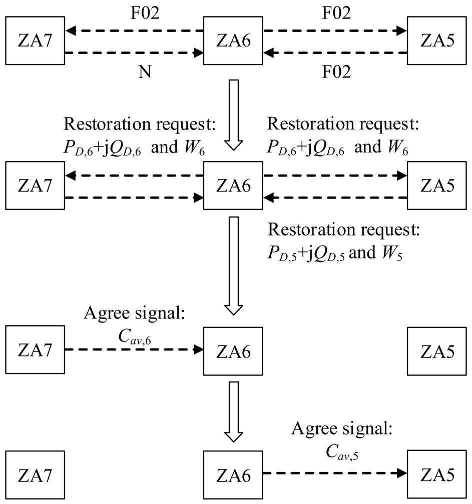


FIGURE 9. Messages exchange between ZA6 and its adjacent ZAs.

TABLE 7. Traffic and change of breaker status for Case 4 and Case 5.

Scenario	Case 4		Case 5	
Index	Traffic (packet)	Change of breaker status	Traffic (packet)	Change of breaker status
Method A	70	open s6, s9, s11 close s4, s10, s12, s14	70	open s6, s9, s11; close s4, s10, s12, s14
Method B	129	close s4	132	open s8, s11, s13, s16 close s4, s10, s12, s14, s15

TABLE 8. Restored zones, minimum voltages and power losses for Case 4 and Case 5.

Scenario	Case 4			Case 5		
Index	Restored zones	Minimum voltage (p.u.)	Power loss (kW)	Restored zones	Minimum voltage (p.u.)	Power loss (kW)
Method A	Zones 2-10	0.962	31	Zones 2-10	0.852	532
Method B	Zones 2-10	0.946	43	Zones 2-10	0.837	513

Feeder 4 at 0.1s. The proposed restoration scheme (Method A) is compared with the scheme reported in [15] (Method B). The test results are shown as follows.

Case 4: First, the fault is isolated by tripping breaker FCB4 and s1. Then, Zone2-Zone10 switch into F02 situation. Their ZAs trip breakers s2, s3, s5-s9, s11, s13 to decompose the downstream feeder into 9 isolated zones. The control modes of ZA2-ZA10 convert to the microgrid mode as well. In these cases, only Zone6 has DGs and ZA6 can maintain limited power supply to part of the loads in Zone6, while other zones are de-energized. After that, all the 9 ZAs send requests to their adjacent ZAs. Since only Zone11-Zone13 are in normal situation, they are the RAs that react to the requests. These requests come from 4 IAs, namely ZA4, ZA8, ZA9 and ZA10, while ZA12 gets two requests from ZA9 and ZA10.

The three RAs forward the requests to their MA. Among the two requests sent by ZA12, it is the request from ZA10 being accepted since the loads in Zone10 have higher weighting factor. Then ZA11-ZA13 reply to the requests of Zone4, Zone10 and Zone8 with Agree signals. After the first round, Zone4, Zone10 and Zone8 are switched to Feeder3, Feeder1 and Feeder2, respectively.

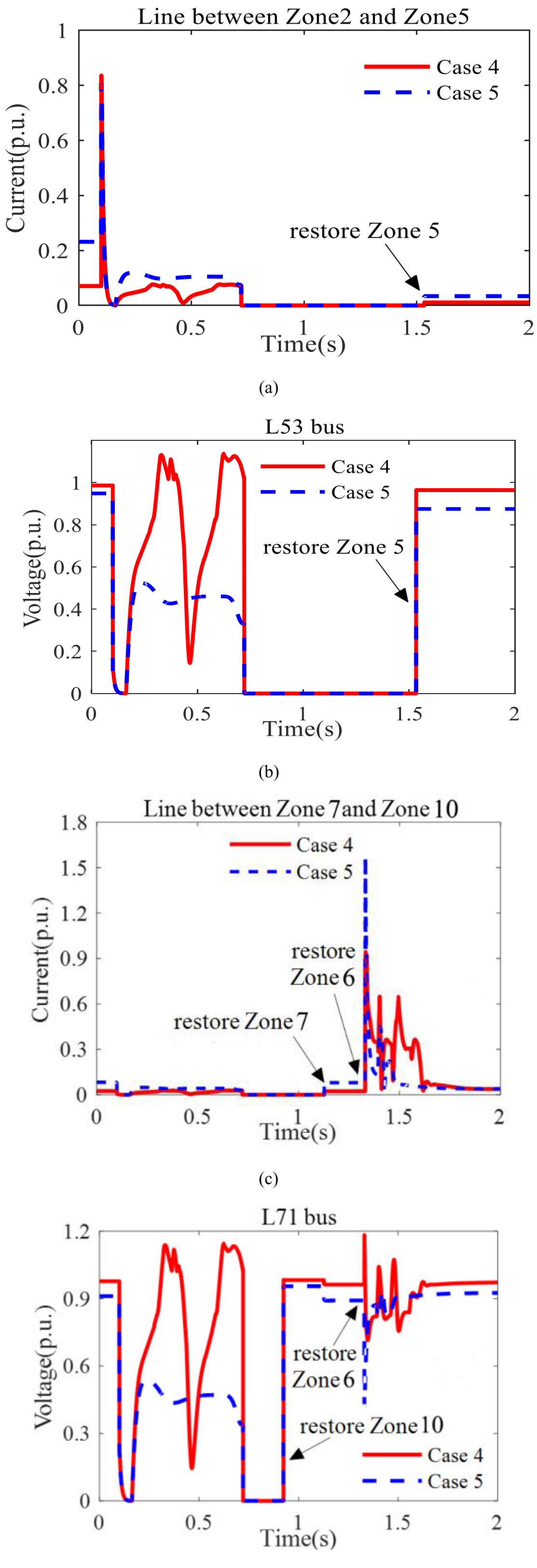
Finally, after 4 rounds, L55, L56, Zone6, Zone7, Zone 9 and Zone 10 are fed by Feeder1, Zone8 connects to Feeder2, L53, L54, and Zone2-Zone4 connect to Feeder3. Compared with Method A, Method B transfer all the loads to Feeder 3 by closing breaker s4.

To illustrate the messages exchange between adjacent ZAs during the process of restoration, Fig.9 shows the packets exchange between ZA5, ZA6 and ZA7. In such situation, Zone7 have been recovered to normal situation (N) and connected to Feeder 1 through Zone10. Zone 6 and Zone5 are still in islanding situation (F02).

Case 5: The result of Method A is the same as that in Case 4. The restoration plan of Method B is listed in Table 7 for comparison.

The tests show that within 1.4330s all the out-of-service loads are restored by the proposed scheme. The restoration time relies on the number of the out-of-service zones and the backup feeders. That is why we set the fault on the first section of Feeder4, which costs longer restoration time to recover all the 9 zones.

Table 8 compares the restored zones, minimum voltages and power losses of the two cases to evaluate Method A and Method B. Method B is a partially centralized approach, with which the feeder agents exchange the information of their load levels. In the light load case, the feeder agent on the fault feeder transfers the downstream loads to one feeder. If the loads are heavy, the feeder agent will obtain the optimal restoration plan with the aim to minimize the power loss. On the other hand, Method A is based on a fully decentralized architecture. The multiple ZAs utilize the local information to search for the restoration path in parallel, which enhances the reliability and reduces the traffic cost in decision making. This method also makes the load levels of multiple feeders evenly distributed under different operation



(a)

(b)

(c)

(d)

FIGURE 10. Line current and bus voltage during restoration process by Method A.

conditions. Hence, the minimum voltage of Method A is higher than the one of Method B in two cases, while the power loss of Method A is slightly higher than Method B in Case 5.

Fig. 10 shows the bus voltage and the line current during the restoration process, which are obtained from the DIgSLIENT simulation.

In both Case 4 and Case 5, Zone10 is restored and connected to Z11 firstly, then Zone7, Zone6 and Zone5 are restored in turn. Fig. 10 (c) and Fig. 10 (d) show that, there is a large impulse current at 1.33s, when Zone 6 and Zone 7 are connected. Then, the controller of the wind generator automatically adjusts the output power. Zone 5 is restored at 1.55s. After a period of fluctuation, from 1.33s to 1.65s, the current and voltage turn to a stable state. The situation of Zone6 changes from F02 to N.

VII. CONCLUSION

This article presents novel fault tolerance and automatic restoration schemes under a MAS-based self-healing framework. All the agents share the same protection and control strategies and require no global information about the interconnected feeder group to make decision, which simplifies the deployment of the system. Moreover, low communication bandwidth is required by the proposed scheme. The protection scheme can adapt to the wide penetration of DGs in distribution network as well as the change of operation modes. With the help of the fault-tolerant mechanism, short-circuit fault can be isolated within 200ms, even if local failure occurs on part of the communication link or sensors. The flexible network restoration scheme can share loads among multiple backup feeders properly and work rapidly by agents in parallel, with the consideration of the load priority. The proposed schemes is modeled and tested on the DIgSILENT platform. It is verified that the proposed framework can realize fast and reliable protection, and can reconfigure the post-fault network with complex structure by little communication cost.

To further improve the function of control and protection system based on multi-agent, the challenges that DG resources provide for the system protection and restoration, the cooperative control strategy of ZA and DG, as well as the active and reactive power control of isolated zones will be in our future research work.

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