IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 26, 2021, accepted February 4, 2021, date of publication February 9, 2021, date of current version February 19, 2021.
Digital Object Identifier 10.1109/ACCESS.2021.3058308

A Fully Decentralized Multi-Agent Fault Location and Isolation for Distribution Networks With DGs

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This work was supported in part by the Hunan Provincial Natural Science Foundation of China under Grant 2020JJ4158 and Grant 2019JJ50028, in part by the Scientific Research Fund of Hunan Provincial Education Department under Grant 19A084 and Grant 19B100, and in part by the National Natural Science Foundation of China under Grant 11904092 and Grant 11947088.

ABSTRACT The modern distribution automation suggests to enable decentralized self-healing of distribution networks using advance metering and controlling infrastructure. Decentralized fault location and isolation, as an essential and vital component of self-healing, has attracted considerable attention over the years. In this paper, an integrated fault location and isolation strategy based on fully decentralized multi-agents system (FDMAS) is presented for distribution system with distributed generators (DGs) by combining the primary protection with device failure protection (i.e., backup protection). The proposed FDMAS strategy can locate and isolate electrical fault rapidly even under device failures with minimum fault clearance time and range by using expert logical rules, meanwhile can detect and identify device failure adaptively. Furthermore, a unified programming framework is developed for generalization and application of the proposed strategy. The simulation studies are carried out on 22-bus distribution system by using dynamic model test platform. The test results show that the proposed strategy has an excellent performance on fault clearance time, fault isolation range and device failure detection.

INDEX TERMS Multi-agents, device failure protection, device failure detection, distribution networks.

I. INTRODUCTION

A. BACKGROUND

Distribution systems present the final link between utilities and customers. Generally, a distribution system works in radial configuration for a simple design, protection coordination and the minimum of fault current [1]. However, the ever-increasing structural complexities of distribution networks bring greater risk of fault occurrence [2], on the other hand, the volatility and uncertainty of renewable distributed generators (DGs) becomes a new challenge for system management and operation [3], [4]. Furthermore, the quality of electric power service is put on a high level in some high-quality-service areas such as industrial manufacturing center and Hi-tech Zone [5], [6]. In this connection, some new technical specifications [7], [8] have been issued currently, in which the power service interruption is limited to milliseconds and the device failure protection (i.e., backup protection) is recommended to be deployed aggressively and the backup fault isolation area is limited to the upper relay (or circuit breaker (CB)) level correspondingly. Hence, new self-healing operating paradigm equipped with intelligent measurement, communication and control infrastructures is suggested for modern distribution [9]. As a key building block of the self-healing capability, the fault detection is to discover and locate a fault by alarms based on high currents and/or low voltages, and fault isolation must segregate the fault from both directions by opening the first upstream and downstream switches quickly. While the device failure protection aims to furnish backup fault location and isolation with device failure detection function under primary protection failure (which, after all, must be caused by failed devices such as communication, current transducer (CT) and CB) [1]. In recent years, the multi-agent-based approaches, especially,

The associate editor coordinating the review of this manuscript and approving it for publication was Yichuan Jiang.

the decentralized ones, have gradually cut a striking figure regarding these above aspects [10].

B. PREVIOUS RESEARCH

The local protection methods, including time-overcurrent protection, device (recloser-fuse or relay) coordination protection [11], adaptive device coordination protection [12], [13], adaptive distance protection [14], time-domain differential protection [15], are the currently mainstream and effective ones because they can provide rapid and reliable protection solution by using local information, especially for radial distribution system. However, these conventional local protection methods used in radial distribution systems, are prone to miscoordination in distribution system with DGs or in flexible distribution network (FDN) because of the change in the magnitude and direction of currents during the fault period [2]. Moreover, it is difficult to be integrated into modern self-healing control system of distribution system for these local methods. The wide area measure-based protection methods such as phasor measurement unit-based protection methods [16], the wide area-based distance protection [17], [18], wide area intelligent protections [19] and wide area differential protection [20], [21] have been recently applied to distribution systems. However, these methods are extremely dependent on control center based on supervisory control and data acquisition (SCADA). Consequently, it is very difficult to handle all calculations and communications in real time when all decisions are taken by such a control center for large-scale power systems [22].

Owing to their extensibility, maintainability and concurrency, the intelligent multi-agent-systems (MASs) have been employed as a new protection technology for distribution systems in recent years [23]. As distributed problem-solving systems, MASs can collaboratively address complex problems by decomposing a complex problem into many simpler sub-problems. According to control architectures, the MAS-based methods can be classified into centralized, hierarchical (or hybrid) and decentralized (or distributed) ones. Centralized multi-agent system (CMAS) involves a single entity as a central agent that determines the status of the network based on the information available from other agents [24]. However, these CMAS methods have distinct disadvantages on data jams and intensive communication and computation, and are prone to single point failure, which in turn, may cause a large-scale blackout [25].

The hierarchical multi-agent-systems (HMASs), including two-layer, multi-layer and other hybrid structures, have been recently presented to solve the aforementioned problems. In [26], a control structure with two layers (i.e. zone and feeder) is proposed for fault detection and isolation operations. The zone agents collect information and take control actions through protective devices, while the feeder agents are engaged in fault location and isolation by binary status signals after their CBs tripping. A resembling structure is presented by [27], where the MASs are divided into three layers (i.e., response, coordination and organization). In [28], an HMAS with a hybrid centralized-decentralized structure is proposed. The HMAS method in [28] locates and isolates fault by a fuzzy controller based on binary signals and can partially provide device failure protection (i.e., backup protection) function. In contrast to CMAS, the HMAS approaches have lower complexity on computation and communication [10]. However, with the increase of time consumption in hierarchical communication and computation, their real-time performance on operations will be deteriorated gradually.

In the decentralized (or fully decentralized) multi-agent system (DMAS or FDMAS), all of agents are at the same structural lever and the decision-making agent is not fixed but varied with the fault point [29]. A decentralized method based on Q-leaning in [30] locates fault by using current differential principle and current change rate. Nevertheless, it is difficult to guarantee the real-time performance on the above operations due to three times of recloser implementations. In [31], a DMAS-based adaptive protection scheme is presented for distribution system with DGs. Though the presented protection scheme can detect and isolate fault rapidly by using fuzzy controller and possesses online backup protection function, it requires hundreds of milliseconds of operation time. Another DMAS-based protection strategy is proposed by [32], which is composed of integrated primary and backup fault location and isolation schemes and can be online employed in distribution system with DGs. However, its hand-to-hand communication architecture and its device failure detection-based backup protection scheme make it difficult to be combined into integrated self-healing systems of distribution networks with other service restoration methods.

C. RESEARCH GAP

Although many MAS-based methods or strategies have been presented in the previous works for fault location and isolation, to the best of our knowledge, several important aspects have not been considered as follows:

1) The majority of previous so-called decentralized methods are based on hybrid centralized-decentralized structures that are suitable for remedial and non-real time control.

2) The coordination between primary and backup protection that prevents protection misoperation, has not been captured in the previous works.

3) The majority of previous studies have rarely considered all of device failures, as a consequence, they cannot offer complete backup protection function.

4) The conventional methods in the literatures cannot detect device failure which causes primary protection failure.

D. CONTRIBUTIONS

To address such drawbacks, this study introduces an integrated FDMAS strategy of fault location and isolation for distribution network with DGs by combining primary protection with device failure protection. The main contributions of this paper are summarized as follows:

1) This paper presents an FDMAS architecture, where the decision-making agents depend on the fault point making the

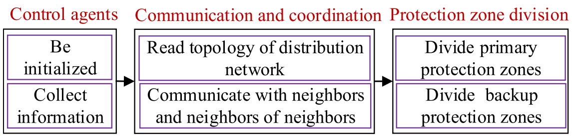

FIGURE 1. The system diagram of the proposed architecture.

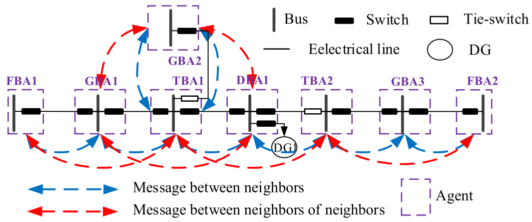

FIGURE 2. The messaging propagation between agents.

technique fully decentralized. Compared to existing structures, the presented FDMAS one with a low communication cast is more adaptive to real-time protection scenarios.

2) The new aspects in the proposed strategy are as follows:

a) An integrated fault location algorithm is presented in the basis of binary logical rules through which the communication time between agents is reduced significantly and the fault can be quickly located by both primary and backup protection.
b) Under no device failures, the proposed strategy can coordinate the primary and backup action to ensure priority of primary operation and prevent backup misoperation by expert coordination rules.
c) The proposed strategy can adaptively detect and classify device failures by expert detection rules.
d) Especially, the device failure-related backup protection of the proposed strategy is started in advance to accelerate backup operation by forecasting the failed primary protection caused by device failure, consequently, which can minimize backup fault clearance time and range.

3) A unified programming framework is developed for the proposed strategy, which may make the proposed strategy be applied to distribution system independently or be seamlessly embedded into integrated self-healing system with other DMAS-based service restoration methods.

The rest of this paper is organized as follows. Section II presents the FDMAS architecture including the control agent definition, communication and coordination between agents and protection zone division. The methodology composed of primary and backup protection algorithms and integrated programming framework, is developed in Section III. In Section IV, case studies are given. Finally, conclusions are drawn in Section V.

II. THE PROPOSED FDMAS ARCHITECTURE

As depicted in Fig. 1, an FDMAS architecture including control agents, communication and coordination between agents and protection zone division, is presented in this section.

A. CONTROL AGENTS

In this paper, the fully decentralized control agents are composed of bus agents (BAs) including general bus agents (GBAs), feeder bus agents (FBAs), tie-bus agents (TBAs), DG-bus agents (DBAs). These BAs gather bus voltage as well as branch current and share voltage and current information with their neighbors in real time. All of BAs are coequally in the same structural layer and cooperate with each other to implement common tasks for fault location and isolation.

B. COMMUNICATION AND COORDINATION BETWEEN AGENTS

With The Development Of Distribution Automation System, The wide area communication system (WACS) based on IEC 61850 [29], [30] and the intelligent electronic devices (IEDs) have been currently utilized in synchronous measurement and control for distribution networks [15]. The interoperability of IEDs from different manufactures improves the development of IEC 61850 standard, which, in turn, permits the manufactures to insert their automation codes into the IEDs. Therefore, the IEDs are used as control agents in the context of this paper. The peer-to-peer (P2P) model of IEC 61850 protocol is employed in the synchronous communication between control agents by the generic object oriented substation events (GOOSE) messages, which is widely applied for protection and control of IEDs in the distribution system due to its high probability of transmission success [16].

Fig. 2 illustrates the coordination between control agents. Each agent collects its bus voltage and branch current information, then shares them with its neighbors and neighbors of neighbors by the way of request/response message. In this way, all agents can obtain the real-time information required for protection control. As shown in Fig. 2, the information from agents themselves and their neighbors (blue dotted lines) is mainly used for primary and backup protection and the information from their neighbors of neighbors (red dotted lines) is utilized for communication failure detection and communication topology self-adaption.

C. PROTECTION ZONE DIVISION

A primary protection zone (PPZ) is a minimal protection unit, which can be divided into two types: primary branch protection zone and primary bus protection zone which are abbreviated as PRPZ and PUPZ respectively for distinguishing each other in this paper. The former is used to locate and isolate branch line fault, while the latter is applied for protecting bus bar. Fig. 3 also gives an especial PPZ (PRPZ3) updated by communication structure self-adaption (see also Section III. C for more detailed description).

A backup protection zone (BPZ) is defined as a minimal extension of the PPZ in this paper. In general, the BPZ (red) is composed of two PPZs (i.e. a PRPZ (blue) and a PUPZ

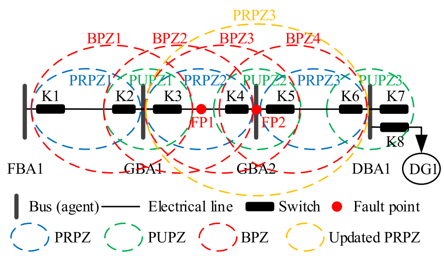

FIGURE 3. The primary protection zone and backup protection zone.

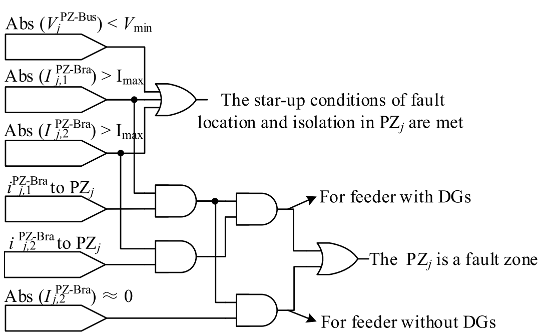

FIGURE 4. The logical rule control structure for primary and backup fault location algorithm.

(green)). From Fig. 3, one can see that the primary and backup protection operations only require the information in their own protection zones. Note that the above switches represent CBs in this paper unless they are explained specifically.

III. METHODOLOGY

An integrated primary and backup protection strategy based on FDMAS is presented in this section, which is composed of an expert logical rules-based fault location algorithm, primary fault isolation algorithm, backup fault isolation algorithm and a unified programming framework.

A. PROPOSED PRIMARY AND BACKUP FAULT LOCATION ALGORITHM (ALGORITHM 1)

In consideration of the radial topology of distribution feeders, once a permanent electrical fault occurs in a distribution feeder, according to Kirchhoff's Current Law (KCL), the current and voltage (or zero sequence voltage) of the branch line or bus in fault zone have the following characteristics:

1) The current at one of the branch ends in fault zone will exceed their limits, while the bus voltage will be undervoltage.

2) If there exist the downstream DGs connected with the fault area, the currents at two ends of the branch in fault zone will flow into this area; otherwise, the current at one end of the branch will flow to fault zone while the other will be close to zero.

Based on the aforementioned fault characteristics, a binary logic rule control-based fault location algorithm (i.e., ***Algorithm 1***) is developed for primary and backup protection in this paper. The detailed logical rule control structure is depicted in Fig. 4, where V_j^{PZ-Bus} is voltage amplitude of the bus in protection zone, PZ$_j$ and PZ represent PPZ (PRPZ or PUPZ) and BPZ,$I_{j,1}^{PZ-Bra}$, $i_{j,1}^{PZ-Bra}$, $I_{j,2}^{PZ-Bra}$ and $i_{j,2}^{PZ-Bra}$ are current amplitudes and directions at the two ends of branch in PZ_j respectively, V_{min} and I_{max} are the undervoltage and overcurrent thresholds which should be set as 85% of rated bus voltage and maximum load current (i.e., 1.2 times of rated current) of feeder respectively [29], [32]. As shown in Fig. 4, when a fault occurs at a feeder, the branch currents or bus voltages in the feeder are overcurrent or undervoltage (i.e. the start-up conditions are met). Hence, these agents, which of PPZs and BPZs cover the fault point, can locate the fault by using the proposed binary logical rules based on the current and voltage signals from themselves and neighbors, while others do not (i.e., without misoperation).

B. PROPOSED PRIAMRY FAULT ISOLATION ALGORITHM (ALGORITHM 2)

After fault location, making a decision on fault isolation to minimize fault clearance range and time becomes next critical process for the related agents. Since the aforementioned primary and backup fault locations are synchronous, some operation rules must be made to ensure correctness of primary isolation operation and prevent backup misoperation under no related device failures, which are described as follows:

Rule 1: The primary fault isolation has priority over backup fault isolation to avoid the expansion of fault range caused by the latter.

Rule 2: The backup fault isolation operation is activated until the primary protection fails due to device failures and the fault is located by backup protection.

In the above two rules, the former ensures that the primary fault isolation is operated correctly and preferentially, and the latter prevents the backup misoperation in case of no related device failures.

C. PROPOSED BACKUP ISOLATION ALGORITHN (ALGORITHM 3)

Once a fault occurs and a fault-related device such as communication device, CT or CB fails, the relative backup protection should be activated in place of the failed primary protection. In this paper, a backup fault isolation algorithm (i.e., ***Algorithm 3***) is presented in the basis of expert logical rules, which consists of three sub-algorithms under communication, CT and CB failures.

1) Backup fault isolation under communication failure

Communication failure detection. In this paper, the communication channel failures between agents are detected by communication frame detection method proposed in [32]. In this way, the communication failure of any agent itself can be determined if the agent cannot communicate with all of its neighbors (i.e., ***Rule 3***). Moreover, the communication failure of an agent can be also diagnosed by its neighbors if its neighbors detect that the failed agent cannot communicate with all of its neighbors (i.e., ***Rule 4***).

Communication structure and protection zone self-adaption. When a communication failure of an agent is detected by itself and all of its neighbors, all of its neighbors will be updated to become new neighbors with each other and report the communication failure to substation in time (i.e., the related communication topology is adjusted adaptively). Furthermore, the PPZs and BPZs of neighbors of the failed agent are updated accordingly. The PRPZ3 in Fig. 3 is an example for an updated PPZ. It is noted that the above two operations are performed at normal operation stage (before electrical fault) and the proposed sub-algorithm can be also applied to multiple communication failure scenarios.

Backup fault isolation under communication failure. Owing to communication structure and protection zone self-adaption before electrical fault, once an electrical fault occurs, the adaptively updated agents will correctly locate and isolate the electrical fault through their updated communication structures and updated PPZs as same as other primary protections. Thus, the backup clearance time under communication failure is equal to that of primary protection and the backup fault isolation range is minimal in this case.

2) Backup fault isolation in presence of CTs failure

*Backup fault isolation in presence of CTs failure and the position detection of the failed CTs(i.e., **Rule 5**)*: Once an fault occurs, if an agent locates the fault in its BPZ by its backup but the agent and its neighbor agents in the BPZ fail to detect the fault in their PPZs by primary protection, the agent can assert that a CT failure occurs at the overlap between the two PPZs within the BPZ, then the agent trips its CBs at the outermost boundary of the BPZ to isolate the fault accordingly.

CTs failure types identification. Furthermore, the failure types of the CTs can be diagnosed by the following rules: after the position of the failed CT is detected by *Rule 5*, if the current from the failed CT is close to zero, the CT must be disconnected from its own branch line; else if the current is greater than zero and less than the overcurrent threshold, the CT must be saturated (i.e., ***Rule 6***). After that, the position and type of the failed CT will be reported to substation in real time.

3) Backup isolation in the case of CB rejection

CB rejection detection by agent itself: After a trip instruction is output by an agent of a CB, if the status of CB tripping in right place is not detected by the agent itself after a delay time (that equals a maximum time of the CB trip plus a margin time between primary and backup action), the CB rejection is determined (i.e., ***Rule 7***). Then, the CB rejection information will be notified to its neighbor agents.

*CB rejection detection by neighbor agent (i.e., **Rule 8**)*: After an agent located a fault in its BPZ by backup protection and detected that its neighbor agent had located the fault and output a CB trip command by primary protection, if the agent detects that the branch line in its BPZ is still overcurrent after an aforementioned preset delay, then the agent can determine that the CB of its neighbor is rejected.

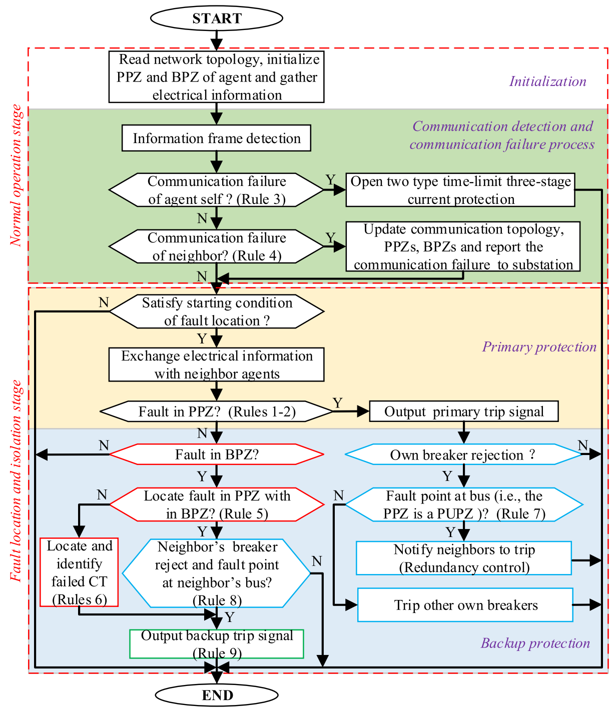

FIGURE 5. The integrated flowchart of the proposed strategy.

Backup isolation under CB rejection. For a rejected CB of an agent, if the fault occurs at a branch line, other CBs of the agent are backup of the rejected CB; else if the fault occurs at a bus bar of the agent, its neighbor CB at opposite end of the rejected CB is backup of the rejected CB (i.e., ***Rule 9***). Hence, if a CB rejection of an agent occurs, based on *Rules 7-9*, the agent or its neighbor agent will trip their backup CB to isolate the electrical fault quickly.

D. PROPOSED UNIFIED PROGRAMMING FRAMEWORK

In this subsection, an integrated and unified programming framework (Fig. 5) is developed for the proposed protection strategy in the basis of the aforementioned algorithms and rules. According to the proposed framework, the whole process of the strategy is mainly divided into two stages: normal operation stage (before fault) and fault location and isolation stage (after fault). The former provides preparation for speeding up the latter, while the latter makes a decision on primary and backup fault locations and isolations.

1) Normal operation stage

Initialization: After the initial identities of agents are configured, each agent reads and stores its distribution network topology in adjacency list, initializes their PPZs and BPZs and collects electrical information in real time.

Communication detection and communication failure process: After periodic information frame detection, if an agent detects a communication failure of itself by *Rule 3*, the agent will open its two type time-limit three-stage current protection as a fault-tolerance protection measure; else if the agent detects its neighbor's communication failure by *Rule*

4, it will update its communication topology, PPZs and BPZs and report the communication failure to substation in time; otherwise, goes to the next step.

2) Fault location and isolation stage

Primary protection: Once a fault occurs, the starting conditions of protection are met, then the agents on the failed feeder will start to locate the fault by exchanging their gathered electrical binary logical information with their neighbors in real time (*Algorithm 1*). If the fault is detected by an agent in its PPZ (PRPZ or PUPZ), the agent will output its primary trip signal to isolate the fault without backup misoperation by *Rules 1-2*; otherwise, goes to the next step. Note that the *backup protection under communication failure* is contained within the proposed primary protection by updating the communication topology, PPZs and BPZs.

Backup protection under CT failure (the red block diagrams in Fig. 5): If a backup agent locates the fault in its BPZ and the agent itself and its neighbors in its BPZ fail to locate the fault in their PPZs by their primary protections, the agent determines that a CT fails in its BPZ and trips its backup CBs to isolate the fault by *Rule 5*, and further detects the failure type of the CT by *Rule 6* and reports the failed CT to substation; otherwise, goes to the next step.

Backup protection under CB rejection (the blue block diagrams in Fig. 5): When an agent detects its CB rejection by *Rule 7* and if the fault occurs at its branch line, the agent will trip its other CBs to isolate the fault quickly; else if the fault occurs at its bus, the agent will notify its neighbors at the opposite end of its rejected CB to isolate the fault. Besides if an agent detects its neighbor's CB rejection by *Rule 8* (or receives a redundant trip instruction from its neighbor), and if the fault occurs at its neighbor's bus, the agent will output a backup trip signal to isolate the fault; otherwise, goes to the end of the framework.

In the proposed integrated framework, every agent is an independent actuator in the location and isolation process, their tasks may vary with different fault points, and all of them complete general objective of fault location and isolation collaboratively. Consequently, the proposed strategy can be applied to distributed automation system independently, especially can be combined into integrated self-healing system with other DMAS (or FDMAS) service restoration methods such as in [29], [33].

IV. CASE STUDIES

As shown in Fig. 6, a 22-bus distribution system of China City Power Company (CCPC) described in [29], is applied to validate the proposed method. The rating voltage of the system is 10kV. The test FDMAS platform (Fig. 7) developed by us is composed of agents (IEDs) and IEC 61850-based communication system. To be safe, the 10kV CCPC system is simulated by using a low voltage system whose rated phase voltage is 220V and whose loads and DG capacity are reduced to three-thousandth of those in the original system. In following simulation tests, all operation switches are set to CBs. Due to the practical limitations, the grounding fault is simulated by increasing the load current, which results in an increased branch current. The rated line current is set to 3A, the undervoltage and overcurrent thresholds in the starting conditions are set as 187V and 6A respectively. For the feeder lines with DGs, the CTs upstream of fault points collect branch current positively, while the CTs downstream of fault points are in reverse. Note that the tested trip signals are shown in different scales for better experimental observation. For the purpose of comparison, other DMAS methods proposed in [28], [31], [32] are also applied to resolve the same question.

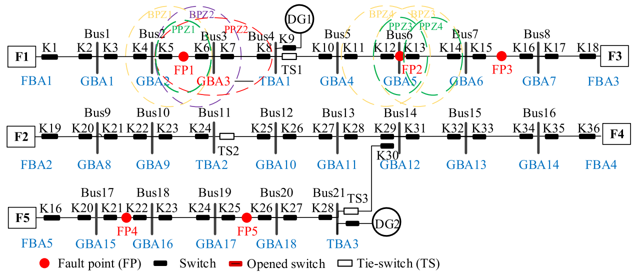

FIGURE 6. The CCPC 22-bus system.

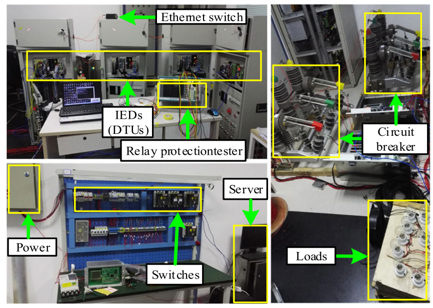

FIGURE 7. The test platforms.

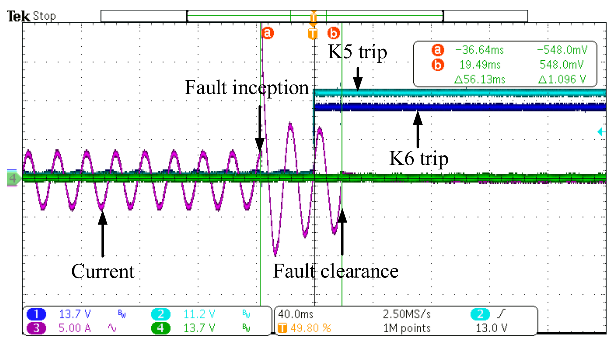

FIGURE 8. The primary protection trip.

A. PRIMARY PROTECTION

Scenario 1 (primary fault location and isolation): After a three-phase grounding fault (TPGF) occurs at FP1, the protective starting conditions of GBA2 and GBA3 are satisfied, then the two agents locate the fault in PPZ1 by using *Algorithm 1*. After that, they trip K5 and K6 respectively to

TABLE 1. Result of primary and backup fault location and isolation compared with other methods.

Scenario	Fault point (Fault type)	Failed device	Switch off (maximum outage zones (downstream of fault point (DFP)) or whole feeder with fault (WFF))				Fault clearance time (s)			
			[28]	[31]	[32]	Proposed	[28]	[31]	[32]	Proposed
1	FP1 (TPGF)	NO	K5, K6 (DFP)	K5, K6 (DFP)	K5, K6 (DFP)	K5, K6 (DFP)	0.857	0.206	0.063	0.056
2	FP1 (SPGF)	Communication failure of GBA3	K5, K8 (DFP)	/	K5, K8 (DFP)	K5, K8 (DFP)	1.857	/	0.150	0.058
3	FP1 (SPGF)	CT saturation at K6	/	K5, K7 (DFP)	K5, K7 (DFP)	K5, K7 (DFP)	/	0.506	0.065	0.060
4	FP2 (SPGF)	CT disconnection at K13	/	K12, K14 (DFP)	K12, K14 (DFP)	K12, K14 (DFP)	/	0.406	0.063	0.060
5	PF2 (PPSCF)	K13 Rejection	K12, K13 (WFF)	K12, K13 (WFF)	K12, K14 (DFP)	K12, K14 (DFP)	/	/	0.151	0.145
6	FP3 (TPGF)	K15 Rejection	K15, K16 (WFF)	K15, K16 (WFF)	K14, K16 (DFP)	K14, K16 (DFP)	/	/	0.153	0.141

isolate the fault without backup misoperation due to *Rules 1-2*. Fig. 8 and Table 1 give the results. It is noted that K*i* in Figs. 8-11 denotes a control relay of a corresponding CB, whose control voltage is 24V. From Fig. 8 and Table 1, one can see that the fault clearance time of the primary protection is 56ms (about 3 cycles), where the fault location time is about 37ms and the time of K5 trip from sending a trip signal to the fault clearance is about 19ms. Remarkably, all of the four methods (i.e. in [28], [31], [32] and this paper) can detect and isolate the fault very well. Furthermore, compared with other methods in [28], [31], [32], the proposed DMAS strategy achieves the same or better performance on fault location time due to less time consumption in communication and computation. It is noted that the time of above fault clearance may be increased slightly in presence of higher voltage due to the impact of electric arc of higher voltage on CB tripping operations.

B. BACKUP PROTECTION UNDER DEVICE FAILURE

Scenario 2 (communication failure): In this scenario, the GBA3's communication fails at normal operation stage (before fault) and a single-phase grounding fault (SPGF) occurs at FP1. At normal operation stage, each agent checks its own communication channels in cycle, once the communication failure between GBA3 and its neighbors occurs, GBA2 and TBA1 will detect the communication failure by *Rule 4*. After that, GBA2 and TBA1 become neighbors with each other by communication structure self-adaption and updating their protection zones. Therefore, when the electrical fault occurs at FP1, GBA2 and TBA1 will locate the fault by using the updated PPZ2 (red) and trip K5 and K8 to isolate the fault. As shown in Fig. 9, the fault clearance time of backup trip under communication failure is about 58ms (close to 3 cycles). The other two methods in [28] and [32] can also detect and isolate the fault under communication failure through time overcurrent protection which results in a greater delay (about 1s). In contrast to the two methods, the proposed FDMAS strategy detects and handles communication failure before fault adaptively, and its backup protection under communication failure is essentially an updated primary protection after communication topology self-adaption (see more detailed description in Section IV. C), as a consequence, its backup fault clearance time equals its primary fault clearance time.

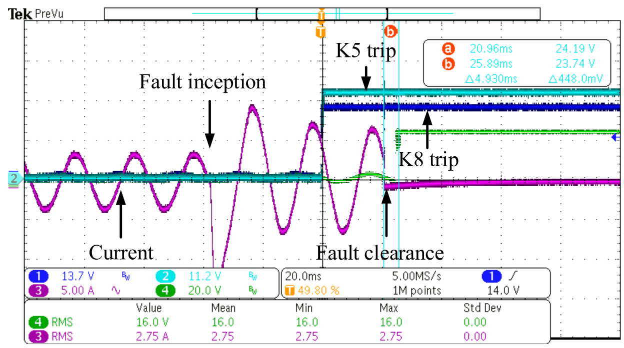

FIGURE 9. The results of backup trip under communication failure.

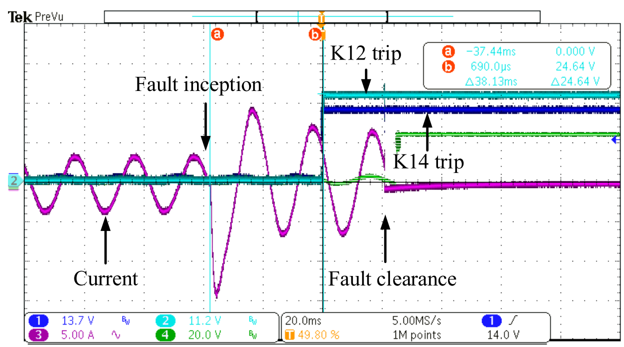

FIGURE 10. The results of backup trip under CT failure.

Scenario 3 (CT saturation): In this scenario, the CT of K6 is saturated. Consequently, when an SPGF occurs at FP1, GBA2 and GBA3 fail to locate the fault within their PPZ1 by using primary protection because their starting conditions of protection are not met. Yet their backup protection can utilize BPZ2 (purple) composed of K5 and K7 to locate the fault correctly by *Rule 5*. After that, GBA2 and GBA3 trip K5 and K7 to isolate the fault respectively. As a supplement, the saturated CT is detected and located by *Rule 6*. As depicted in Fig. 10 and Table 1, the backup fault location time from fault inception to relay tripping is about 38ms (close to 2 cycles), and the backup fault clearance time is about 59ms (3 cycles).

Scenario 4 (CT disconnection): Furthermore, the backup trip under CT disconnection is also tested, where an SPGF occurs at FP2 and a CT is disconnected from K13. Though the CT disconnection leads to the primary protection failure in PPZ3, the GBA5 and GBA6 use their backup protection in BPZ3 to trip K12 and K14 to isolate the fault by *Rule 5* successfully. Moreover, the disconnected CT is detected and reported to the substation by *Rule 6*. The results are given in Table 1. From Table 1, it can be observed that the fault clearance time is about the same as that under CT saturation which equals that of the primary protection approximately.

In addition, other two methods in [31], [32] can be applied to resolve the questions in Scenarios 3 and 4. However, the former needs a coordination time interval (a 0.3s delay) to do that, and the latter demands a periodical complex detection algorithm before fault. In contrast, the proposed strategy achieves the same or better performance on fault clearance time without a delay or extra computation on CT failure detection.

Scenario 5 (CB rejection with fault point at bus): A backup trip in presence of CB rejection with fault point at bus is investigated in this scenario. When an AB phase to phase short-circuit fault (PPSCF) occurs at FP2, GBA5 uses its primary protection to locate the fault in PPZ2 successfully, then trips K12 and K13 to isolate the fault firstly. K12 implements break-brake operation successfully but K13 fails. After a predefined delay, GBA6 detects the neighbor's K13 rejection by *Rule 8*, then trips K14 to isolate the electrical fault remedially. Fig. 11 gives the test result. From Fig. 11, it can be seen that the trip time (K13) of primary protection is about 48ms, the backup trip time (K14) is about 122ms and the backup fault clearance time is close to 145ms, where the predefined delay is set as 110ms in this paper. It is noted that the predefined delay should be set according to practical communication delay, voltage classes and types of CBs, i.e., shorter communication delay, lower voltage level and CBs with better time performance bring shorten predefined delay and fault clearance time.

Scenario 6 (CB rejection with fault point at branch line): In this scenario, a TPGF occurs at FP3 (a branch line), GBA6 locates the fault correctly by using primary protection and outputs the command of K15 trip, yet K15 refuses to operate. Thus, after a predefined delay, GBA6 detects the rejection of K15 by *Rule 7*, then instructs the backup K14 to trip. As shown in Table 1, the backup fault clearance time in this scenario is about 141ms. Moreover, the method in [32] is employed to test Scenarios 5 and 6, while other methods in [28], [31] are without this backup function. Compared with the method in [32], the proposed strategy has slightly better performance on the fault clearance time.

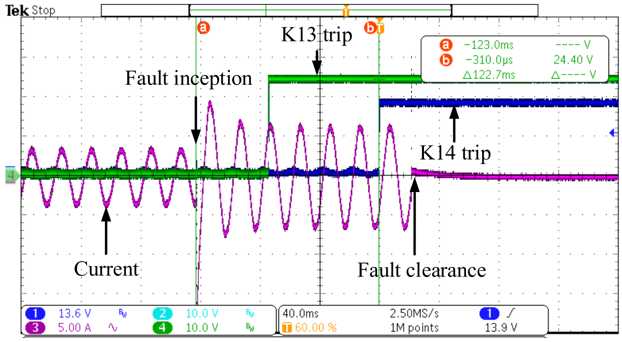

FIGURE 11. The results of backup trip under primary CB rejection.

In the above scenarios, the DGs of the test distribution system are based on inverters. It is evident from the above test results that the proposed strategy is effective for distribution system with the inverter-based DGs. Besides that, the proposed strategy can be applied for distribution network with rotating machines-based DGs naturally because the fault location algorithm of the proposed strategy is based on KCL, i.e., if the currents at ends of fault point are greater than the overcurrent threshold (maximum load current) and flow to the fault point, the fault can be located by the proposed strategy successfully (see also Section III.A for more details).

From the above case studies, and based on the results on Figs. 8-11 and Table 1, it can be concluded that: 1) the proposed FDMAS-based strategy can correctly locate fault by binary logical rules for distribution network with DGs, and outperforms other methods in [28], [31], [32] on calculation and detection time; 2) in comparison with other methods, the proposed strategy can provide complete and comprehensive backup protection function based on expert logical rules, and can minimize the backup fault clearance time and isolation range; 3) in contrast to other methods, especially in [32], the proposed strategy can detect and identify device failures without extra and complex detection of device failure; 4) the presented unified programming framework could enable the proposed strategy to be employed and generalized to the realistic distribution systems independently or to be embedded into an integrated self-healing system by combining with other DMAS-based service restoration methods such as in [29], [33]. Due to the advantages in fault clearance time, isolation range, device failure detection and fully decentralized technology, the proposed strategy is more applicable to high-quality-service areas such as industrial manufacturing center.

V. CONCLUSION

In this paper, an integrated FDMAS strategy, including fault location algorithm and primary and backup isolation algorithms, is proposed for distribution systems with DGs, which has the following five characteristics.

1) The proposed FDMAS architecture facilitates a unified programming framework for online application of the proposed strategy, which can be utilized independently

or be seamlessly embedded into integrated self-healing systems for distribution networks.

2) Base on binary logical rules, the proposed fault location algorithm can locate fault correctly and reduce communication and computation time significantly.
3) The proposed primary fault isolation algorithm based on priority rules is able to clear fault quickly without backup misoperation.
4) Under device failures, the proposed backup isolation algorithm can elaborate backup isolation by using expert logical rules. As a consequence, the proposed algorithm minimizes the backup fault clearance time and range, especially, the backup fault clearance time under communication and CT failure is closed to the primary fault clearance time.
5) The proposed backup isolation algorithm can detect the device failures adaptively.

The efficacy of the proposed methodology is validated through exhaustive case studies on CCPC 22-bus system. The test results demonstrate that the proposed strategy performs better than other methods with respect to fault clearance time and range and device failure detection.

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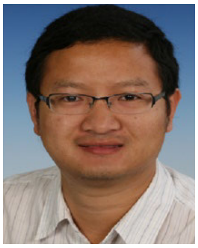

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