A Multi-Agent Based Technique for Fault Location, Isolation and Service Restoration

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Abstract— **This paper presents a communication-assisted fault localization, isolation and restoration method for microgrids based on a multiagent system (MAS). The proposed system comprises distributed agents, located in the middle and at the two ends of a protection section, which will detect a fault through phase angle comparison of current signals at both sides of a given distribution line. The agents then send trip signal to corresponding circuit breakers accordingly. The importance of the proposed protection technique is twofold: first, it eliminates the use of voltage transformers and thus reduces costs. Second, it does not require transfer of data along long distances which decreases the delay time for fault isolation. Power restoration processes following the fault clearance considering voltage, frequency and power flow constraints in the microgrid under study was also performed. Simulation of the proposed protection methodology was presented followed by experimental verification. The experimental results showed excellent agreement with the simulated protection scheme.**

Index Terms— **Protection, Microgrid, Multi Agent Systems (MAS), Information and communication technology, synchrophasor.**

I. INTRODUCTION

Communication-assisted microgrid protection schemes are becoming an important research area due to the complex and changing architecture of the contemporary smart grid resulting from dynamically connecting and disconnecting different types of distributed generators (DGs) and loads [1]. Thus, it is important to find a suitable communication-assisted protection method between transducers and agents in order to obtain updated fault current values and increase the reliability of the grid.

In [2]-[4], the authors introduced modeling of a relay and different types of DGs that can be used in a microgrid network. This system can be used to monitor a microgrid over communication lines and react to dynamic changes of the grid. While such a diverse deployment of microgrids provide important advantages, they possess key challenges as well. Such systems depend on a microgrid central protection unit (MCPU) that features complex communication unit due to the different signals from many components in the network, in order to determine the relay that must operate to isolate the fault section from the network.

Authors in [5] calculate both the system's and the microgrid's impedances by measuring the voltage and current fault in a real-time manner. This method is valid within 2 cycles of the fault occurrence and suitable only for inverter interfaced distributed generator based microgrid.

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In [6] an adaptive protection scheme is suggested which modifies and updates the relay settings by observing the change in the microgrid configuration. However, this method requires an advanced communication system to work efficiently with the fast instructions and settings.

The author in [7] changes the time current characteristics for short circuit and overload conditions by observing the difference in voltage drops during these two events respectively. The accuracy of this technique is a major concern in context of defining the drop of the voltage for two cases and adjusting the rating of protective device with respect to the inverter's power electronics device current limitation.

The conventional schemes that are used to protect transmission line face a lot of challenges. The traditional protection techniques use the phasor components of voltage and current to trip circuit breakers [8].

However, these techniques can be affected by the problems of fault resistance and short circuit lines [9]. Current differential line protection schemes have been widely used for detecting and isolating fault sections. However, the operation of these algorithms is based on identifying the vector difference quantity between the measured currents at both sides of a transmission line. This requires high communication channels bandwidth and thus increases the cost of communication channels [10]. Also, with the high penetration of distributed generations that are connected through power converters, the short circuit current at different nodes of the microgrid will be close to the nominal current, this leads to a significant source of error for conventional overcurrent protection. Therefore, a malfunction of these algorithms based on current magnitude measurements is expected to happen due to the difficult task of detecting the branch under fault.

The literature shows that the phase differential protection method serves as a better option for transmission line protection due to its simplicity, sensitivity, selectivity and comprehensibility [11].

The work in [8] proposes a pilot protection scheme based on the phase jump measured in the current waveform during fault conditions. At each node, the phase jump is registered and used locally to detect changes in the current direction. The change in current direction is determined by the difference between the pre-fault and fault current phase angles. The communication channel requirement and cost of communication equipment can be reduced by considering the phase angle comparison of the positive sequence component of line currents. This leads to an increase in sensitivity and security of the relay or the combination of positive and negative sequence components to give robust discrimination to all types of faults. However, these techniques cannot determine the faulty phase [12].

Complementary to protection, self-healing schemes have been studied in distribution networks. The study in [13] introduces a negotiation process between multi-agent systems exchanging messages among the agents to detect, isolate and restore power to the faulted regions. The work in [14] presented a fast fault location, isolation and service restoration (FLISR) algorithm which can significantly reduce outage time at the customers' end. A significant disadvantage to the formal is that they are centralized approaches and depend on a huge number of data exchange requiring high communication capabilities and exhaustive computation powers to accomplish power restoration.

Accordingly, this paper presents a distributed protection technique to locate and determine fault types on distribution lines which addresses the shortcomings of centralized and resource intensive communication requirements in the surveyed literature. The main idea behind this work is that the phase angle of the currents of each of the three phases at both terminals of each section in the network is measured using Phasor Measurement Units (PMU) and is communicated to Section Agents (SA) that located in the middle of each section. SAs then calculate the phase angle differences and send trip signal to circuit breakers (CBs) that are connected at the two ends of the distribution line in case of abnormal operation. The advantages of the proposed method are:

- the sole dependency on current measurements thus reducing overall costs by eliminating the use of the voltage transducers;
- minimized communication delays for fault isolation as this technique depends on transferring data between two ends of the distribution line and a SA located at the middle length of the line;
- stable phase comparison techniques by the use of numerical relays and time synchronized measurements which are communicated to relays (synchronization needs to be implementonly on SAs only instead of on the two relays at both sides of each section);
- protective devices of smart and fault-resilient microgrid are not expected to trip the healthy phases during unbalanced short-circuit. Thus, some utilities and relay manufactures have started contemplating single and double pole tripping for distribution systems [15]. This scheme is able to distinguish the faulty phase reliability and significantly improves the speed of relaying without sacrificing security and enhance the stability and power transfer capabilities of a transmission system after an earth fault;
- power restoration process: As a result of isolating the fault, some DGs will disconnect from the network and cause loss of power to some loads. In order to maintain the reliability of the system, a power sharing operation must be applied to feed these loads through the communications between MAS.

II. Microgrid Configuration and MAS Framework

The microgrid under study is shown in Fig. 1. The system consists of two circuits each having 4-nodes and 2 DGs. DG1 is a 13.8 KVA, 208 V, 60 HZ, and the others are modeled with ratings of 10 KVA, 208 V, 60 HZ. The four loads have a 14.5 Ampere current ratings. Each circuit has one Restoration Agent (RA) and comprises three sections having one SA, two PMUs and two circuit breakers (CB). CB is connected between the two circuits and is normally closed to satisfy the synchronization conditions between the generators and enable power flow among the circuits in case of abnormal operation at any section in the system.

A MAS is defined as a collection of autonomous computational entities (agents), which can be effective in broad applications performing tasks based on goals in an environment that can be difficult to define analytically [16]. Four types of agents can be used in this paper: Load Agents (LA), Section Agents (SA), Restoration Agents (RA) and Generator Agents (GA). A description of the communication between the agents of the system can be shown as follows:

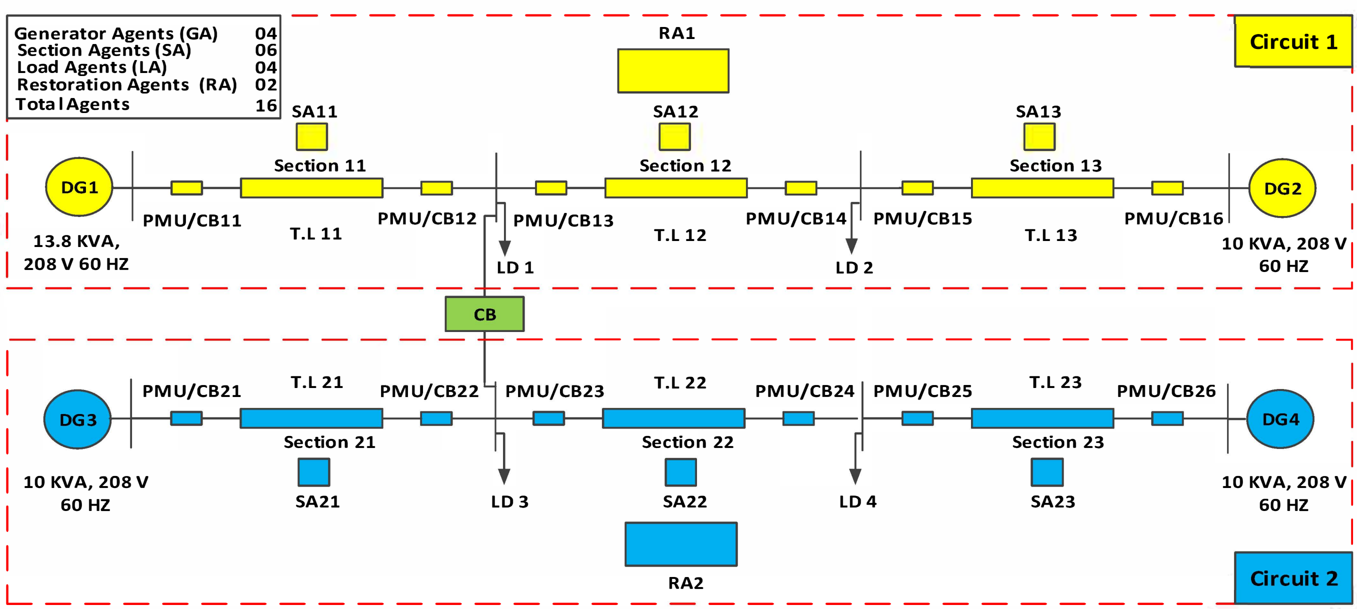

Fig.1. The suggested microgrid configuration

Load Agent (LA): Determines the parameters of voltage, current, frequency, active and reactive power of the connected loads and communicates these values with other agents to restore power in case of a fault.

Section Agent (SA): This agent is located mid- length of each section. According to the phase angle comparison of currents between both sides of the section, it will send a trip signal to circuit breakers to isolate the fault section.

Restoration Agent (RA): Operates as a manager of the circuit and can communicates with all SAs in the circuit in order to verify the connection and disconnection areas in the circuit and communicate with other RAs in another areas to restore the power for the loads.

Generator Agents (GA): Communicates with the RA and determine different parameters of the generator to verify the ability to feed the loads in case of fault.

III. Proposed Fault localization Method

The three phase current angle signals at the sending and receiving terminals of each section are measured using PMUs. These measurements are forwarded to SAs.

The current at each node is passed to the PMUs at each side of the protected section in case of an abnormal condition to obtain the current phase angles (φ^a, φ^b, φ^c) of the current component.

At each terminal, the current phase angle (φ^a) is offset by 120° from the current phase angle (φ^b) and 240° from the current phase angle (φ^c). For both sides of the section, the phase angle of each terminal (φ^a, φ^b, φ^c) is compared to the phase angle of the other terminal ($\varphi^{a'}$, $\varphi^{b'}$, $\varphi^{c'}$), respectively.

The difference between the phases can be determined as follows:

$$\Delta\varphi^{a,b,c} = \sum_{j=1}[\varphi^{a,b,c}(j) - \varphi^{a',b',c'}(j)] \tag{1}$$

where,

$\Delta\varphi^{a,b,c}$	phase angle difference between the starting and ending terminals of each section;
j	index;
$\varphi^{a,b,c}(j)$	phase angle current of phases A, B and C at the sending terminal;
$\varphi^{a',b',c'}(j)$	phase angle current of phases A, B and C at the receiving terminal.

According to the difference $\Delta\varphi^{a,b,c}$, the location and type of the fault can be determined.

For normal operation:

$$\Delta\varphi^{a,b,c} \approx \Delta\varphi^{a,b,c}_{pre} \tag{2}$$

For abnormal operation:

$$\Delta\varphi^{a,b,c} \gg \Delta\varphi^{a,b,c}_{pre} \tag{3}$$

where "*pre*" refers to the values in the previous cycle.

The SA of the fault section send trip signals to both circuit breakers that are located at both sides of this section to isolate the fault from the system.

IV. Proposed Restoration Method

Power restoration is defined as the capability of a system to automatically detect and recover functionality when faced with a single or multiple events. For a power system, this definition is somewhat refined to include the rapid identification of problems, actions to minimize any adverse impacts from casualties, and the prompt recovery of the system to a stable operating state. During restoration, a series of reconfigurations may take place to improve the overall system condition involving breaker manipulations and generation startup or shutdown. Two factors appear to have influenced the recent research direction. First, conglomerating communication, sensory, and control functions in a central manner allows decisions to be made with a global perspective. While it is cumbersome to centralize these functions, this facilitates are the most complete information for decision-making. The second factor that may have discouraged development of capable distributed multi-agent systems is their difficulty. However, decentralizing decision-making has unique attributes that make it attractive from a resiliency perspective; chiefly because it can avoid the scenario where corruption or failure of the central supervisory node leads to total system collapse [17]. For any system, this definition is somewhat refined to include some constraints in terms of keeping the system stable following the restoration process. The following section explains these constraints with the suggested algorithm to restore the power for the connected loads using a MAS.

Mathematically, the restoration problem is formulated as an objective function satisfying the system constraints. Also, the fulfillment of the objective should not lead to violation of opening limits of the components as indicated in the following conditions:

- Power limit

$$P_{DG} \geq P_{Load} + P_{Loss} \tag{4}$$
$$Q_{DG} \geq Q_{Load} + Q_{Loss} \tag{5}$$

where P_{DG} and Q_{DG} are the generated active and reactive power of the DGs within the microgrid, $P_{Load}$and Q_{Load} are the load active and reactive power, and P_{Loss} and Q_{Loss} are the active and reactive power losses in lines. As shown in equations 4 and 5, generated active and reactive power must supply demand power [18].

- For power line current limits, the maximum current capacity of lines must be lower to prevent overloading [19].

$$I_i \leq I_{max} \tag{6}$$

where I (current) is the load current at node i

- Voltage limit

The system must always be within the allowed limits [20].

$$V_{min} \leq V_i \leq V_{\max} \tag{7}$$

- Frequency limit

The system frequency must always be within the allowed Limits [21].

$$f_{min} \leq f \leq f_{max} \tag{8}$$

V. Simulation Results

A. Fault Location, Identification and Isolation Case Study

A single line to ground fault is simulated on phase A, through a 0.5 Ω fault resistance at t = 1.5 seconds on the middle of section 13. The three phase current angle signals at the starting side (φ^a, φ^b, φ^c) and at the ending side ($\varphi^{a'}$, $\varphi^{b'}$, $\varphi^{c'}$) are measured at section 13 using PMU15 and PMU16.

The angle of phase A for each side of section 13 is offset by 120° (2π/3 Rad) from phase B and 240° (2π/3 Rad) from phase C as shown in Fig. 2(a), (b) and (c). Deviation phase angles for phases A, B and C for the distribution line at both sides of section 13 are shown in Fig. 2(d). It can be found that the deviation of phase angle A is greater than the threshold value that is 20°. On the other hand, the deviation phase angles of phases B and C are less than the threshold value. This means that the fault is a single line to ground fault and is located at section 13.

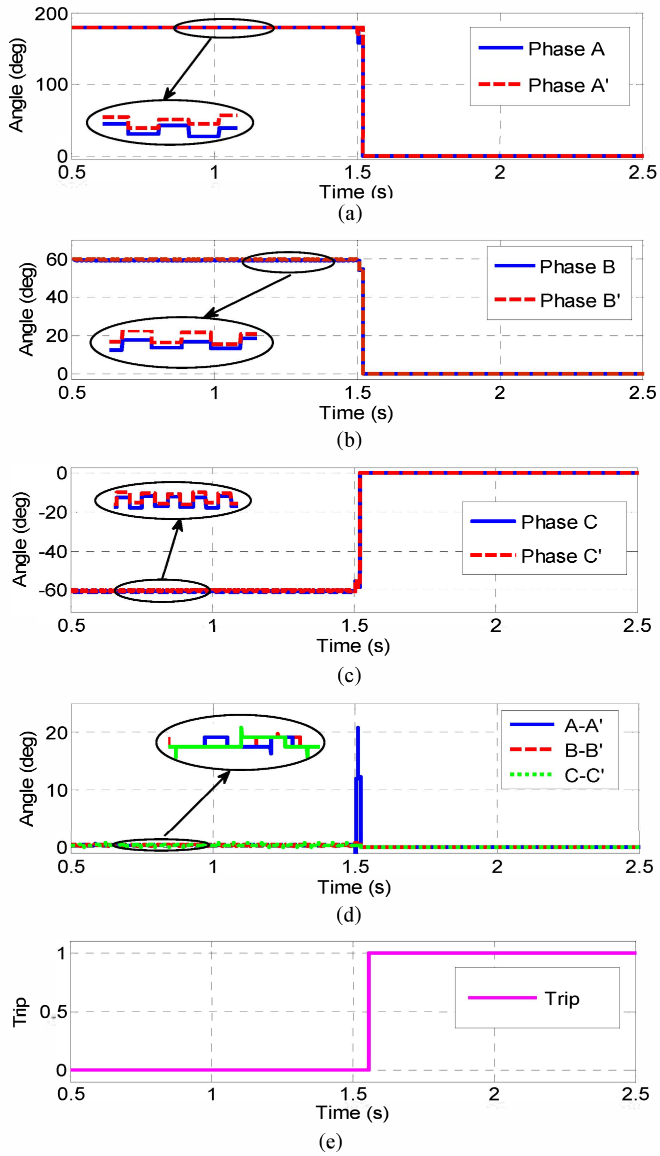

Fig. 2. Phase angles of starting and ending sides during single line to ground fault on phase A in the middle of section 13. (a) Angles of phases A, A', (b) Angles of phases B, B'. (c) Angles of phases C, C', (d) Deviation angles for phases A, B and C, (e) Tripping signal.

SA13 sends a trip signal to CB15 and CB16 that are connected at each end of section 13 to isolate the fault as shown in Fig. 2(e).

The three phase current angle signals are measured using PMU15 and PMU16 at both ends of section 13 for a double line to ground fault on phases B and C in the middle of this section. The phase angles at both sides of section 13 are determined as shown in Fig. 3(a), (b) and (c). The deviation phase angles for phases A, B and C are shown in Fig. 3(d). The deviation phase angles of Phases B and C are greater than the threshold value, which is 20°, while the deviation phase angle of phase A is less than threshold value. This means that the fault was a double line-to-ground fault and located in section 13. SA13 sends a trip signal to both CB15 and CB16 at both ends of section 13 as shown in Fig. 3(e).

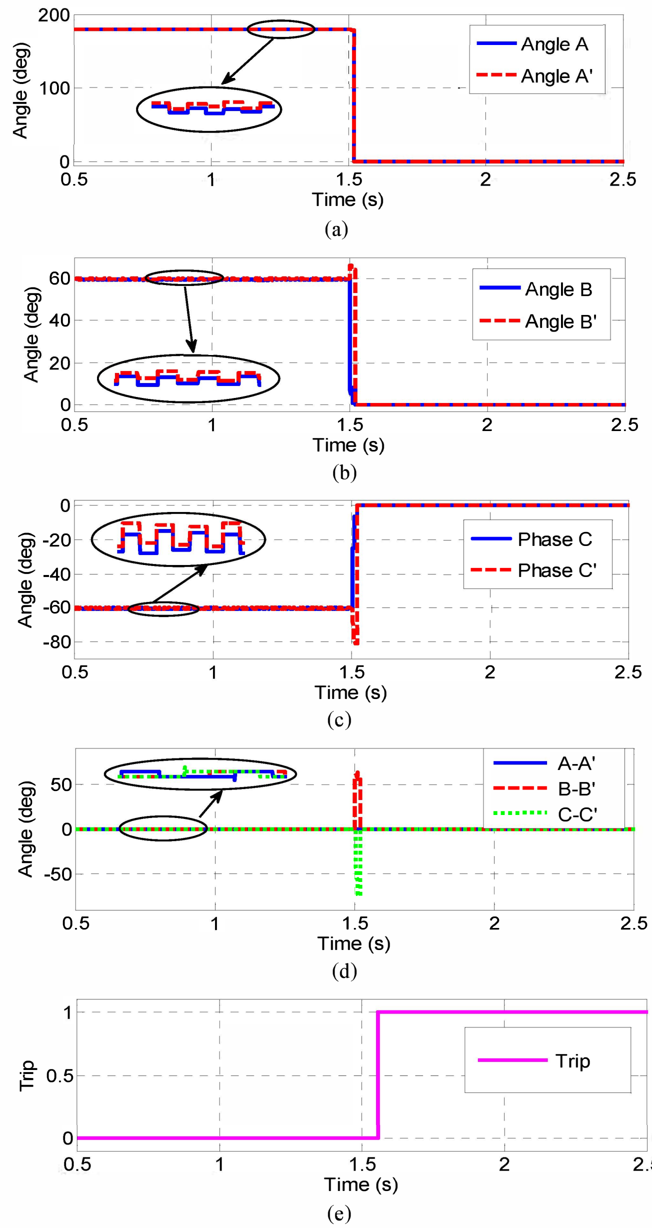

Fig. 3. Phase angles of starting and ending sides during double line to ground fault on phases B&C in the middle of section 13. (a) Angles of phases A, A', (b) Angles of phases B, B'. (c) Angles of phases C, C' (d) Deviation angles for phases A, B and C, (e) Tripping signal.

The phase angle of the three phase current signals are measured using PMU13 and PMU14 at both ends of section 12 during the three phase to ground fault in the middle of this section as shown in Fig. 4(a), (b) and (c).

The deviation of phase angles for phases A, B and C is greater than the threshold value that is 20°as shown in Fig. 4(d).

This means that the fault is a three phase to ground fault and located in section 2. SA12 sent trip signals to both CB13 and CB14 at both ends of section 12 as shown in Fig. 4(e).

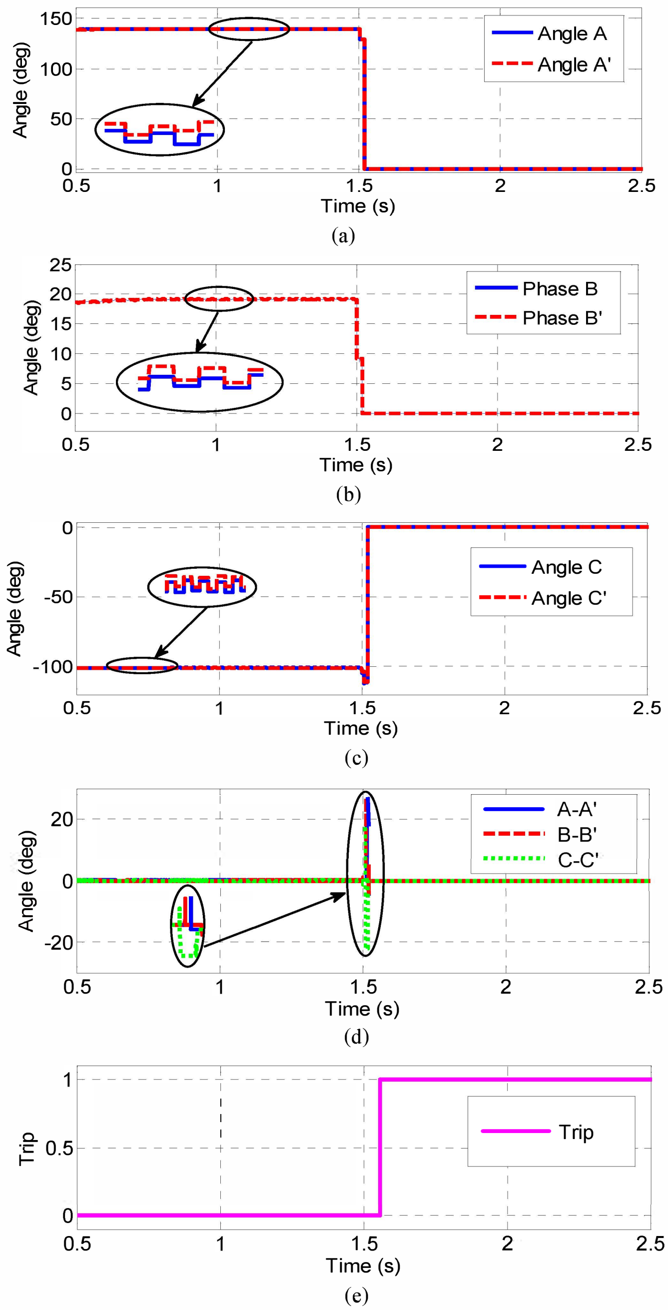

Fig. 4. Phase angles of starting and ending sides during three phase to ground fault in the middle of section 12. (a) Angles of phases A, A', (b) Angles of phases B, B'. (c) Angles of phases C, C' (d) Deviation angles for phases A, B and C, (e) Tripping signal.

B. Power Restoration Case Study

To demonstrate the capability of the suggested microgrid to restore all the loads, a single line to ground fault was applied in section 13. Using the communication between the SA13, PMU15 and PMU16, the fault can be detected and isolated as illustrated in Section V. Thus, DG2 gets disconnected from the network scheme by opening the circuit breakers at this section, which affects the required power supplied to loads 1 and 2 in this circuit. The following explanation is applied to restore power for the connected loads. L1 communicates with LA1 and sends the parameters [14.5, 60, 5200, 500] which represented [Load current 1, Frequency, Active power 1, Reactive power 1], respectively. Similar loading information is sent from [L2, L3, L4] to [LA2, LA3, LA4] as shown in messages 2, 3 and 4 in Fig.5. LA3 and LA4 forwarded the values of L3 and L4 which are [14.5, 14.5], respectively to RA1. Also, RA2 received messages from LA2 and LA1 with the pre fault information of L1, L2 as seen in messages 7 and 8. DG1 sent the value of its current which is 16 Ampere to RA1. The same messages are sent from DG2, DG3 and DG4 to GA2, GA3 and GA4 as indicated in messages 10, 11, and 12. RA1 communicated with GA3, GA4 to verify the status of DG3, DG4, which receives the data from GA1, GA2 to investigate about the available current of DG1, DG2 to supply L3 and L4 in case of disconnecting DG3 or DG4. Similar data is passed to RA2 from different generator agents as shown in messages 17, 18, 19 and 20. RA2 is informed that DG2 is disconnected, and the output capacity of DG1, DG3 and DG4, which are [16-15-15], that represented [Current of Distributed Generator 1- Current of Distributed Generator 3- Current of Distributed Generator 4], is enough to supply the connected loads 1, 2, 3 and 4. RA2 sends signals to DG1, DG2 and DG4 in order to supply the loads as shown in messages 21, 22, 23 and 24 as seen in Fig. 5. A similar decision is taken from RA1 in case of a disconnected DG3 or DG4.

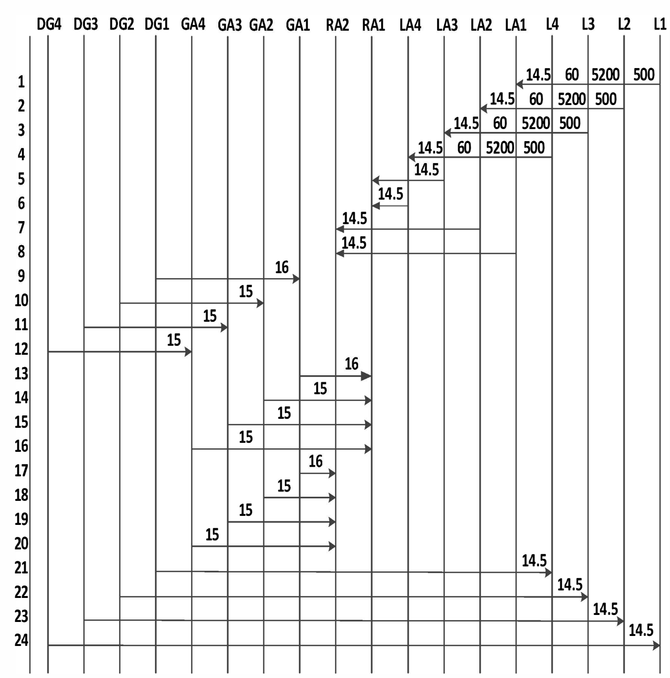

Fig. 5. Trace of messages between agents for full service restoration.

Fig. 6(a), (b), (c) and (d) shows the three phase currents of all DGs in the microgrid. It can be noted that the current signals of DG1 are increased from 16 A to 21 A. DG3, DG4 are increased from 15 A to 20 A in order to compensate the power losses of disconnecting DG2.

Upon comparison of Fig. 7(a), (b) with Fig. 7 (c), (d) which show the load currents of 1, 2 and 3, 4 respectively, a higher effect and a faster restoration time can be noted on the former.

After isolating the fault and disconnecting DG2 from the system, loads 1, 2 and 3, 4 were restored after 1.55s and 1.75s respectively.

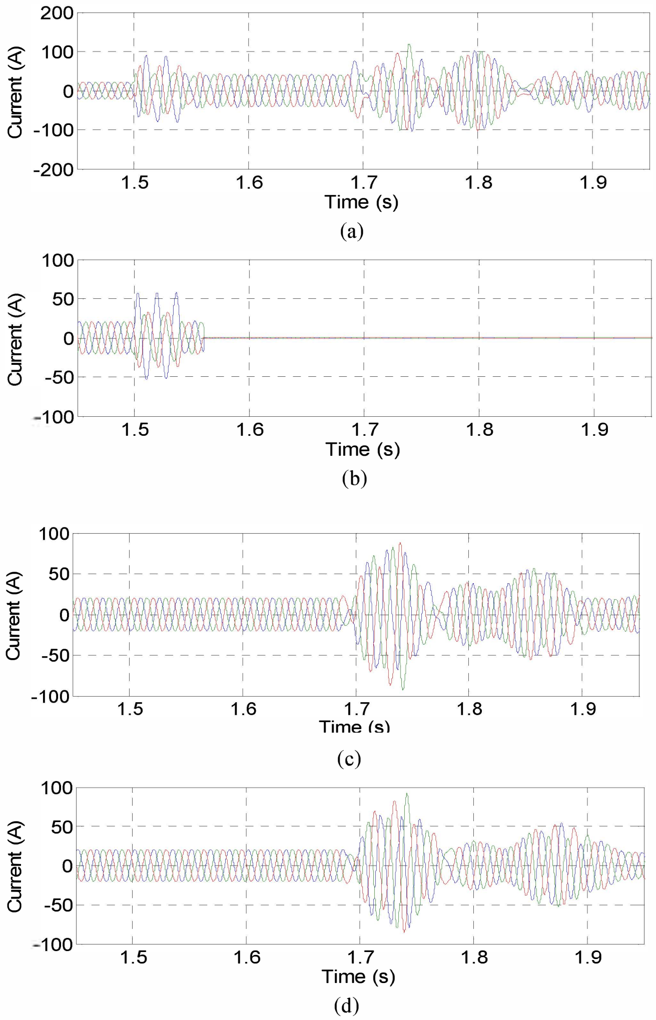

Fig. 6. The three phase current of DGs during single line to ground fault in the middle of section 13. (a) Current of DG1, (b) Current of DG2, (c) Current of DG3, (d) Current of DG4.

When a fault occurs in section 12, isolating it from the system using the communication between the SA12, PMU13 and PMU14. As explained in section V, for circuit one the loads 1 and 2 will be supplied by DGs 1 and 2 respectively. Generator 3 and 4 will be able to feed the loads 3 and 4 in circuit 2. In this case, we do not need to increase the current from generators, in such a way that the two circuits works independent from each other.

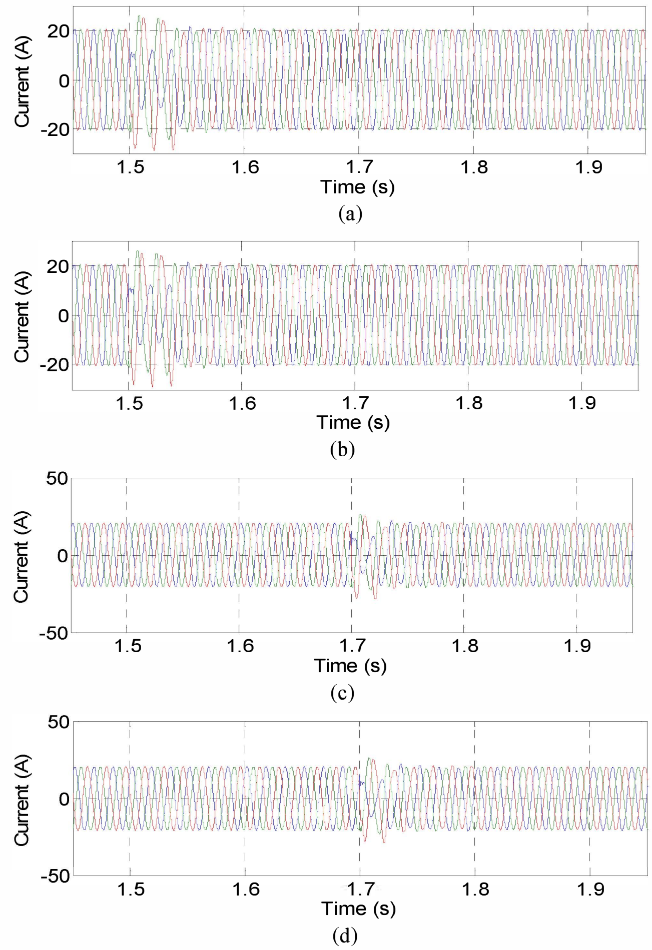

Fig. 7. The three phase current of the loads during single line to ground fault in the middle of section 13

VI. Experimental Results and Validation

This section introduces the real-time experiments to validate the proposed multi-agent framework. The proposed multi-agent framework is implemented in a reconfigurable small scale power system available at Florida International University, Smart Grid Test Bed as shown in Fig. 8 [22-23].

The platform consists of conventional and non-conventional generation units, transmission and load models, field sensors and actuators. Further information about the test bed can be obtained from the above references.

A. Fault Location and Isolation Operation

Fig. 9 shows the correspondences exchanged between the agents to perform the operations of fault location, isolation, and restoration in real-time. After applying a fault, PMUs at both sides of each section measure the three phase current angle signals and forward these signals to their corresponding SA. The SA of the faulted section sends trip signals to both circuit breakers that are located at the both sides of this section to isolate the fault from the system. The type of fault can be identified according to the current phase angle difference between phases A, B and C.

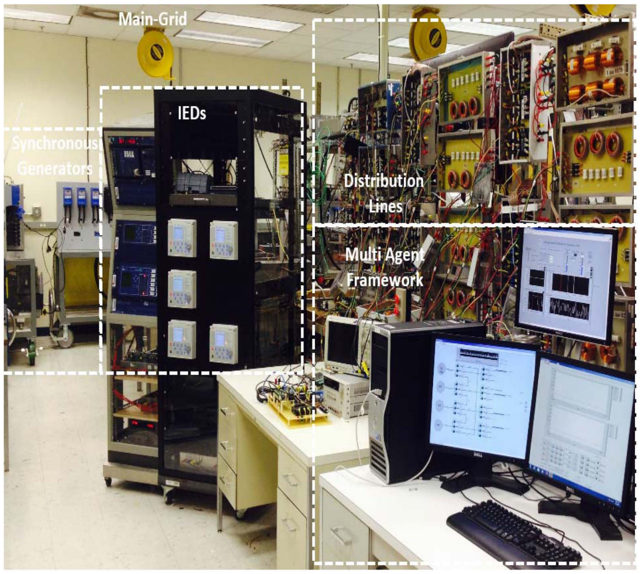

Fig.8. Agent platform and laboratory setup

Similar to section V, the location of the fault can be determined and the faulty section can be isolated from the system for all types of faults using current phase angle comparison technique. Fig. 10 shows the difference of the current phase angle between the phases, and it covers the operation before and during the fault. If we applied a single phase to ground fault at section 13, it can be seen from Fig. 10(a) that at the 131st second the phase angle deviation of (A-A') at both sides of this section is increased above the threshold value, which was adjusted to be 20° and the other deviation phases (B-B') and (C-C') are not changed. Additionally, for a double line to ground fault on phases B and C in the same section, the deviation of these phases increased above the threshold value. On the other hand, the deviation of phase A is not changed as shown in Fig. 10(b). Finally, a three phase to ground fault is applied to the last section in circuit one and the deviation phase angle of the three phases are increased above the threshold value as shown in Fig. 10(c).

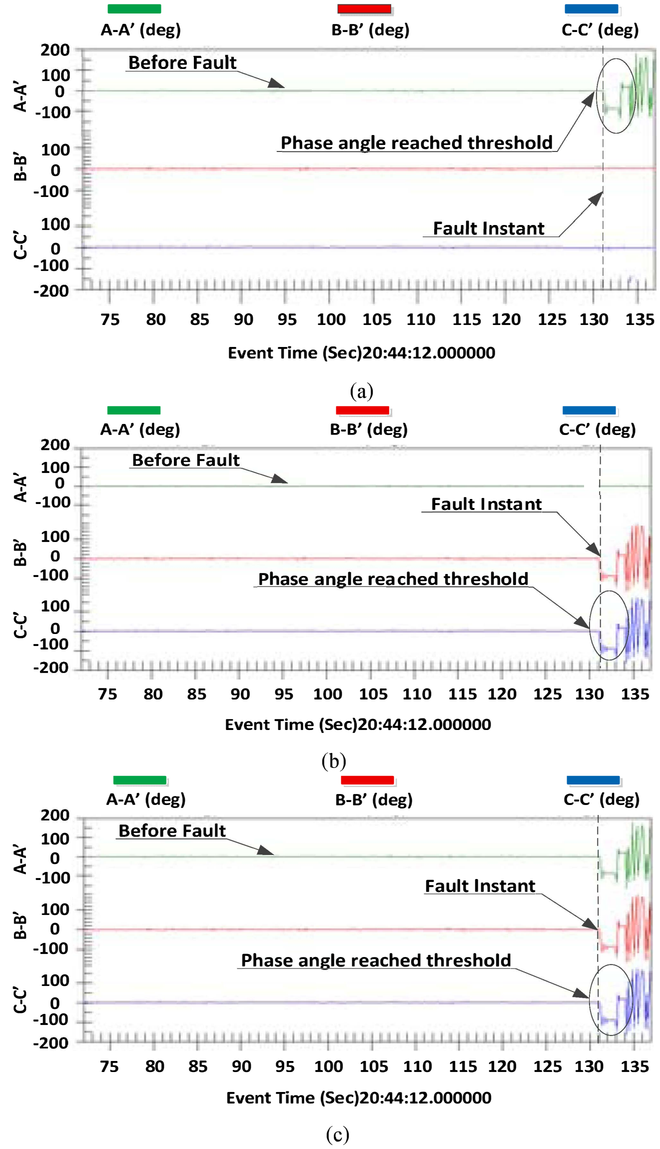

Fig. 10. Phase angle difference of starting and ending sides at section 13 during. (a) Single line to ground fault, (b) Double line to ground fault. (c) Three phase to ground fault.

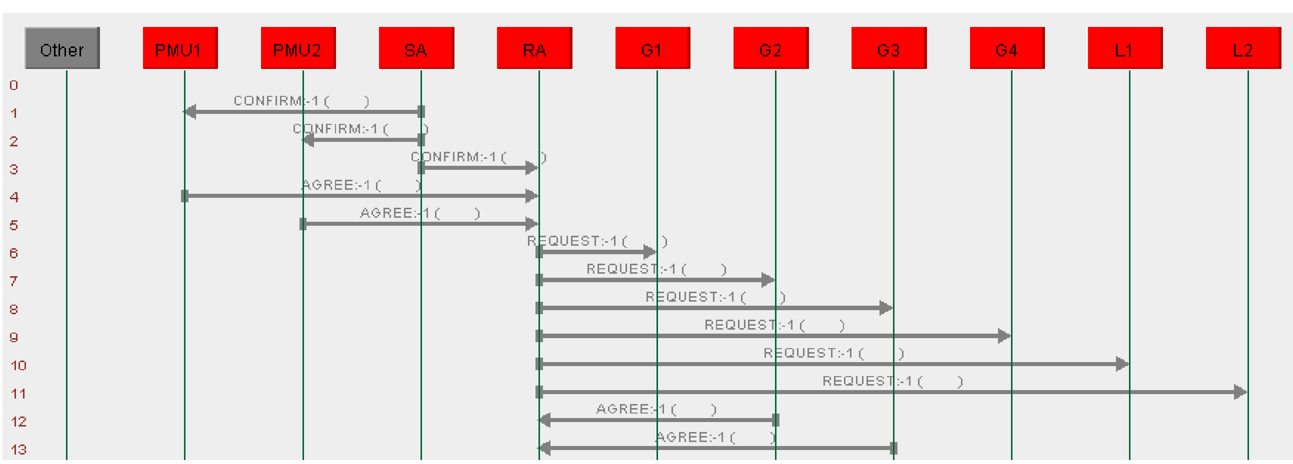

Fig. 9. Correspondence between multi-agent system.

B. Restoration Operation

As explained before in section VIII, RA is communicating with all the generators of the system. Once the fault occurred in section 13, which is located in circuit 1, RA2 requested from Generator 3 and Generator 4 to inject more power in order to compensate for power losses as a result of disconnecting Generator 2 from the system due to the fault. Fig. 11 shows the real power of each generator that is connected in the system. From the 70th to the 140th second, all the generators can feed the loads in the system during the normal operation. At the 131st second, the fault occurred and generator 2 is disconnected from the system. For generator 1, the output power is increased from 1200w to 1500w after isolating the fault from the system. Generators 3 and 4 can perform the lower restoration process in order to check the synchronization conditions are satisfied and increased their rating value from 900w to 1200w.

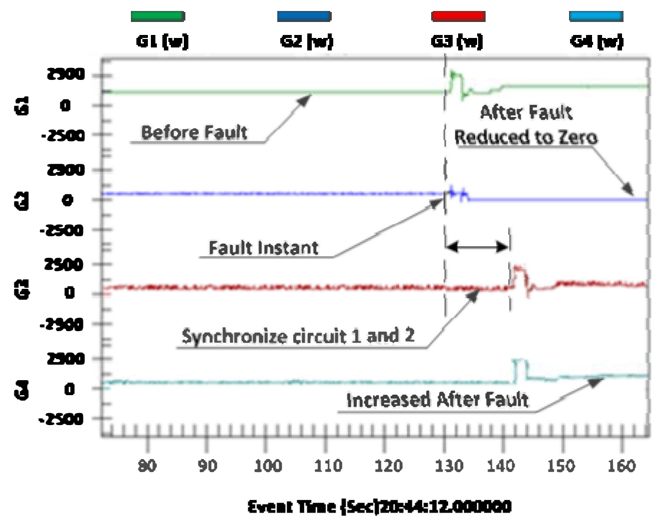

Fig. 11. The real power of each generator before and after fault at section 13.

VII. CONCLUSION

This paper proposed a new distribution line protection methodology utilizing contemporary communication technologies between multi-agents. This technique studies the variation of phase current at both ends of the distribution line to accurate identify and isolate the faulted section in the system. This method does not need voltage transformers and improves the pilot protection scheme. Communication between multi agents is used to restore power for different loads in the system by changing the configuration of the system to maintain its reliability. Experimental results strongly validated the effectiveness of the proposed protection scheme.

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