A Multi-Agent System for Restoration of an Electric Power Distribution Network with Local Generation

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***Abstract*-- This paper proposes a multi-agent system for restoration of an electric power distribution network that can perform an efficient and fast switching operation to isolate faults, restore power to the de-energized area, and secure critical loads. Local or distributed generation (DG) is present in the network but has a limited capability to serve the entire microgrid load. In this paper, the multi-agent system (MAS) is designed, developed and implemented in JAVA Agent Development Framework (JADE). Simulation results show that the proposed MAS is able to achieve a real-time restoration of the microgrid and secure critical loads upon the occurrence of an upstream fault.**

***Index Terms*—Power system reconfiguration, multi-agent system, JADE, microgrid, and distributed generation.**

I. Introduction

MICROGRID is a subset of a power distribution network that consists of small-scale power generating sources serving local loads [1]. A microgrid is capable of either operating in parallel with a utility grid or running autonomously in an islanded mode [2]. This feature makes it robust and resilient against unpredictable upstream outages. A microgrid can provide many advantages to a utility or its customers. These include, for example, reducing electricity delivery costs, and improving reliability and efficiency of electricity grids. Furthermore, in case of a fault or disturbance occurs in the utility grid, a microgrid is also able to detect, isolate, and restore power back to its critical loads by its internal generation. In such an emergency situation, a microgrid can perform load shedding in order to secure its critical loads and prevent power failure in a local area.

In a distribution power system, faults and outages are likely to occur. This is because distribution lines are not insulated and are exposed to the external environment such as tree branches. In order to improve reliability of a local power system, the process of fault detection, isolation and restoration is indispensable. In practice, once a fault occurs, it will be detected and isolated by overcurrent relays, in conjunction with reclosers or switches that experience the fault current. The follow-on step after the faulted section is isolated is to reconfigure the system to the desired post-fault topology. This is in order to re-energize power back to the unaffected areas as much as possible.

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Fundamentally, power system restoration comprises of two sequential steps [3]. The first step is to determine an optimal (sub-optimal) post-fault topology while subjected to the system constraints after fault such as power balance and lines limit. The second step is to determine a switching operation sequence after obtaining the post-fault target topology of the system from the first step. A complex decision-making process is indeed needed to determine an optimal (sub-optimal) post-fault topology of a microgrid as well as the corresponding operational switching sequence.

In recent years, there are many proposed approaches that deal with microgrid restoration, which can be broken down into 4 categories: heuristic [4]-[7], expert systems (ESs) [8]-[10], mathematical programming (MP) [9, 11], and soft computing [7, 10, 12, 13]. Heuristics and ESs have been used extensively, but they both have their own deficiencies with respect to the optimality of solutions. MP, on the other hand, is able to yield the optimal solution but it needs some engineering judgment in formulating restoration problems and requires long execution time [14]. Although soft computing methods are easy to implement, the optimal solution cannot be obtained in the true sense. Also, it needs long computation time to obtain an optimal solution.

A multi-agent system (MAS), consisting of multiple distributed intelligent agents [15], is one of the promising approaches in order to deal with power system restoration tasks. Multi-agent systems are adaptive, self-aware and semi-autonomous or autonomous that can respond to the external environment rapidly with or without human intervention. The MAS can provide a rapid and timely solution by using only a decentralized database. This paper proposes a multi-agent system-based restoration algorithm for an electric power distribution network with local generation. Agents are working, communicating and collaborating with each other to find a desired post-fault topology and its corresponding switching sequence. In this paper, the power system restoration framework, the MAS design, the MAS architecture and its implementation are discussed in details.

II. Power System Restoration Framework

The power system restoration framework presented in this paper restores power back to the microgrid by minimizing the amount of internal loads unserved after an occurrence of an upstream fault. The proposed framework comprises: the power system restoration algorithm and the agent negotiation process, which are further described below.

Four assumptions are made for this simulation study:

1. All circuit breakers are controllable and IP-enabled.

2. Communications among agents resided at buses, DGs, and loads are peer-to-peer based and can be facilitated by LAN or wireless LAN.
3. Line losses are excluded from the analysis.
4. A 3-phase fault occurs at a network branch resulting in a permanent upstream interruption.

A. Power System Restoration Algorithm

The proposed restoration algorithm is designed to maximize the amount of loads served.

$$max \sum_{i \in N} \alpha_i L_i \quad (1)$$

Where,

L_i : load at bus i
α_i : decision variable indicating restoration status ($\alpha_i = 1$: restored; $\alpha_i = 0$: not restored)
N : total number of load buses in the microgrid

The following constraints associated with the power system restoration model are taken into account.

1) Power balance between supply and demand at all load buses:

$$\sum_{k \in T_i} P_k - \sum_{k \in F_i} P_k - \alpha_i L_i = 0 \quad (i \in N) \quad (2)$$

Where,

ΣP_k : power flow from all branches attached to/ originated from bus i
T_i : total number of branches attached to bus i
F_i : total number of branches originating from bus i

2) Capacity limitation of available internal power sources for restoration:

$$\sum_{e \in F_q} P_e x_e \leq G_q \quad (q \in S) \quad (3)$$

Where,

P_e : power flow of directed branch e ($P_e \geq 0$)
x_e : decision variable of branch e ($x_e = 1$ if branch e, in the set F_q, is included in the restoration path, otherwise $x_e = 0$)
F_q : the set of branches with starting node q
G_q : available restoration power from energized bus q
S : the set of energized buses (i.e. buses with internal generation) in the microgrid

3) Limits on branch power flow:

$$|P_k| \leq U_k \quad (k \in B) \quad (4)$$

Where,

P_k : power flow of branch k
U_k : power flow limitation of branch k
B : total number of directed branches in the microgrid

B. Multi-Agent Negotiation Process

Typically, the power system restoration process consists of finding the post-fault target topology and the switching sequence. In order to obtain these targets, the proposed agents will communicate, negotiate and collaborate with each other.

In this paper, there are four types of agents: *facilitator agent (FA), bus agent (BA), load agent (LA), and distributed generator agent (DGA). FA* acts as a centralized agent residing in the main control center. *BA* contains *LA* and *DGA*.

Agents resided at every bus in the microgrid will follow the negotiation strategies described below.

1. If there are multiple branches that can fully energize a bus, the *BA* of that bus selects the branch with the highest availability of power for restoration.
2. If the amount of power available for restoration is insufficient, the corresponding *BA* tries to negotiate with its neighboring *BAs* to explore available DGs in the network.
3. With the availability of controllable DGs at its neighboring bus, *BA* tries to negotiate with its adjacent *BA* that has DGs to supply power to meet its demand.
4. In the case of insufficient power for restoration, load shedding scheme will be performed. *BA* will communicate and decide on load shedding schemes based on the preset load priority.

III. The MAS Architecture and Design

This section introduced the proposed MAS architecture, the agents' application design and behaviors design for power system reconfiguration applications in a microgrid.

A. Agent Architecture

The proposed MAS comprises of four types of agents. Their responsibilities are defined below.

1. *Facilitator Agent* (*FA*): A *FA* acts as a decision-making manager. It maps a microgrid topology by using agents' services, and is responsible for acquiring knowledge from other agents and its external environment. *FA* is designed to respond to an upstream fault, ensuring that the desired post-fault network configuration is met and the network switching sequence is performed correctly with respect to the network topology.

2. *Bus Agent* (*BA*): A *BA* overlays at each bus in the network. It acts as a coordinator between the facilitator agent (*FA*) and its corresponding load agent (*LA*). *BA* is designed to find a post-fault network configuration by interacting with its corresponding *LA*, distributed generator agent (*DGA*), and other *BAs*. *BA* monitors bus parameters, such as power flow to/from the bus, bus voltage, bus current, load power, and the status of circuit breakers connected to the bus. It also checks that all system constraints described in Section II(A) are not violated. During an outage, if the bus experiences a loss of voltage, the corresponding *BA* will start negotiating with its neighboring *BAs*. This is in order to restore power to the de-energized area.

3. *Load Agent* (LA): A *LA* resides at any bus that has connected load. *LA* monitors load parameters, such as voltage, current, and active power consumptions. Due to the fact that loads have different priorities, *LA* will need to know its own priority as well. During an outage, if there is not enough power available to serve all loads connected to system, *BAs* will send a control signal to *LAs* to secure critical loads by shedding non-critical loads.

4. *Distributed generator Agent* (*DGA*): A *DGA* monitors DG parameters, such as DG voltage and DG status. *DGA* provides its information to the corresponding *BA*, including maximum capacity of DG, type of DG and power generating by DG. During an outage, *BA* will negotiate with its corresponding *DGA* and see if there is enough power available from the DG to supply requested loads.

The proposed MAS architecture for power system restoration is depicted in Fig. 1

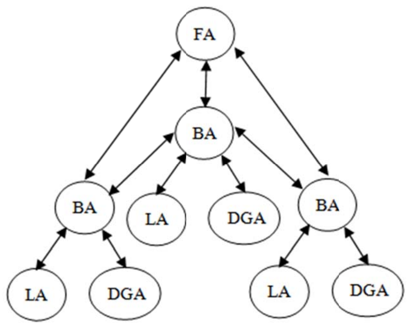

Fig. 1. The proposed MAS architecture for power system restoration.

B. Agent Application Design

The step of modeling knowledge for each type of agents is essential because different type of agents needs different data to process. In this section, the knowledge required for each type of agents is specified. The term “facts” is used to represent agent’s knowledge. Specifically, facts are statements that an agent believes to be true. Facts contain information either of the associated agent itself or the agent external environment.

Table I summarizes facts corresponding to each type of agents.

TABLE I.
AGENT’S FACTS

Facts	Value
Facts associated with *FA*	
- Bus status	Boolean
- System topology	Integer
Facts associated with *BA*	
- Bus status	Boolean
- Bus voltage	p.u.
- Bus current	A
- Circuit breaker status	Close/Open
- Status of DG	On/Off
- Status of Load	On/Off
- DG capacity	MW
- Load	MW
- Load priority	Integer
Facts associated with *LA*	
- Bus voltage	p.u.
- Load status	On/Off
- Load required power	MW
- Load priority	Integer
Facts associated with *DGA*	
- Bus voltage	p.u.
- DG status	On/Off
- DG capacity	MW
- Type of DG	String

C. Agent Behavior Design

Agent behaviors determine how agents should react to the system and their environment. Table II summarizes agents’ behaviors.

TABLE II.
AGENT BEHAVIORS

Agent	Behaviors	Description
FA	filterBehaviour	Receives message from its corresponding agents about MATLAB/Simulink environment data.
	busStatus	Monitors status of all buses in the microgrid. If the bus is energized then its corresponding flag is set to 0, otherwise it will be 1.The time which bus status change is also required.
	startToRestoreServer	Creates the target post-fault network configuration after *BAs* finish their negotiation process and controls the operational switching sequence from upstream to downstream.
BA	filterBehaviour	Receives message from its corresponding agents about MATLAB/Simulink environment data.
	requestPerformer	Negotiates with its neighboring *BA* to find the path for restoration and informs *FA* of the negotiation process.
	offerRequestServer	Receives a ‘call-for-proposal (CFP)’ message from other *BAs*, if its associated *BA* has available power to restore more than the required load power of the sending *BA*, then a ‘Proposal’ message is sent back to the sender.
	matchingServer	Receives an ‘Accept Proposal’ message from other BAs in case of those *BAs* accept the proposal sent by this *BA*.
	busCBAction	Sends OPEN/CLOSE signal to the physical circuit breaker residing in the MATLAB/ Simulink environment when the received message conversation ID is “Start Restore to *BA*”
	loadKnowledge	Acquires knowledge from *LA*: load status and load level. If the load is connected to the bus, flag is set to 1, otherwise 0.
	dgKnowledge	Acquires knowledge from *DGA*: dg status and dg power capacity. If the DG is connected to bus, flag is set to 1, otherwise 0.
LA	filterBehaviour	Receives message from its corresponding agents about the MATLAB/Simulink environment.
	loadStatus	Sends load status. If the load is connected to the bus, flag is set to 1, otherwise 0.
	loadStatus	Sends load power requirement.
DGA	filterBehaviour	Receives message from all corresponding agents about MATLAB/Simulink environment data.
	offerRequestServer	Receives CFP message from *BA*, if DG has available power to restore more than the required load power of the sending *BA*, then a ‘Proposal’ message is sent back to the sender.
	matchingServer	Receives an ‘Accept Proposal’ message from *BA* in case *BA* accepts the proposal sent by this *DGA*.
	dgStatus	Sends DG status. If the load is connected to the bus, flag is set to 1, otherwise 0.
	dgCapacityReport	Sends DG capacity power.

IV. IMPLEMENTATION OF THE DEVELOPED MULTI-AGENT SYSTEM

The simulated distribution network (microgrid) and the MAS reside in two different software environments. The microgrid is simulated in the MATLAB/Simulink environment whereas the proposed MAS is developed in Eclipse Helio [20]. In order to exchange messages between these two software environments residing in the same workstation, they are connected together using a middleware called MACSimJX [21]. It is the software that enables greater modeling capability for designing MAS and allowing the microgrid network developed in MATLAB/Simulink to be controlled by the agents operated in an external program. MACSimJX provides a pathway to MATLAB/Simulink to access the Java Agent Development Framework (JADE) as shown in Fig.2.

Fig. 2. Communications between JADE and MATLAB/Simulink via MACSimJX.

JADE [22] is selected as an agent platform for developing MAS due to its strong support from the industrial sector, and its open-source status. JADE complies with the Foundation for Intelligent Physical Agent (FIPA) [23] which provides the agent's communication language called FIPA ACL. This is the language that agents use in order to communicate, negotiate and collaborate with each other. Prime features of FIPA ACL are its ability to use different content languages and predefined interaction protocols, which help manage agents' conversations and ensure coherence of agents. JADE is also considered to be the leading and promising FIPA-compliant open-source agent framework [24].

V. Integration of MAS in a 4-buses test system

This section discusses and illustrates the process and method involving integration of the proposed MAS into the microgrid. The objective of this simulation is to demonstrate that the MAS can perform and facilitate power system restoration in an intelligent microgrid upon the occurrence of an upstream fault. The case study, communication and negotiation process among agents, and the simulation results are discussed below.

A. Case Study Description – Pre-fault Configuration

In order to demonstrate the effectiveness of the proposed MAS, it has been applied to a model microgrid network which consists of two substations (As/s-Bs/s) and 4 buses as shown in Fig. 3. Here each distribution substation has capacity of 8 MW and denoted by "Sub". There are two sets of 5MW load, each of which is connected to each substation bus – denoted as Bus 1 and Bus 2. In this microgrid, there are two sets of 2 MW load, each of which is connected to Bus 3 and Bus 4.

A label on a branch shows line flow capacity: 8MW capacity for lines that connects Buses 1-3, 2-4, and 3-4. Bus 3 and Bus 4 are connected together by a tie-line. The status of each circuit breaker is shown as NO (Normally open) or NC (Normally close). Each circuit breaker in the system is numbered by its connected bus following by its number. For example, CB31 means that this circuit breaker is connected to Bus 3 and its corresponding number is 1. In this study, there is a 1.2 MW DG connected to Bus 3 to supply power to the microgrid in case of an emergency. This DG will be available to partially serve the 2-MW critical load connect to Bus 4.

Before the 3-phase fault occurs between Bus 1 and Bus 3 at t = 0.2 second, the system conditions are as followings:

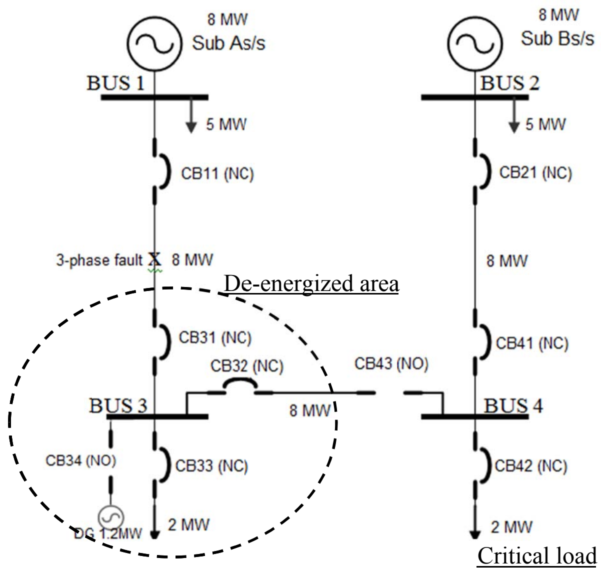

Fig. 3. 4-bus test system.

1. Buses 1 and 2 have power capacity of 8 MW. They are supplying power to their 5MW connected loads. Therefore, there is 3 MW available to distribute to their downstream buses.
2. Bus 3 has the connected load of 2 MW.
3. Bus 4 has the connected load of 2 MW.
4. DG is not connected to the system – the circuit breaker CB34 is normally open. It is assumed that DG has to supply power of 0.2 MW to its internal connected load while in operation.
5. There is no power flowing through the tie-line between Bus 3 and Bus 4 as the circuit breaker CB43 is normally open.

It can be seen that during a normal operating condition, the total power from the main grid is 16 MW (i.e., 8MW from Sub As/s and 8MW from Sub Bs/s). The total load connected to this microgrid is 14 MW (i.e., two sets of 5MW load connected to Buses 1 and 2; and two sets of 2MW load connected to Buses 3 and 4).

It is assumed that a 3-phase permanent fault occurs at the point shown by x in Fig. 3. The fault occurs at t = 0.2 second. Then, the fault is detected by the over-current relay in the network and isolated by the circuit breakers CB11 and CB31 between Bus 1 and Bus 3. The circled Bus 3 and its connected load are de-energized.

B. Topology Mapping and Agent Discovery Process

In order to integrate MAS with the physical entities in a microgrid, the designed agents are overlaid into the physical devices in the microgrid: *FA* resides in a microgrid control center; *BAs* reside in all buses throughout a microgrid; *LAs* and *DGA* reside in loads and DGs connected to each bus in a microgrid. The agents corresponding to physical devices in a microgrid are depicted in Fig. 4.

After agents' initialization, all agents will register their services to the Directory Facilitator (*DF*). *DF* provides the yellow pages service by allowing agents to publish their services to other agents. Therefore, available agent services are readily and easily for other agents to discover and exploit. This is in order to create a network topology of the simulated circuit. Then, the topology is mapped into the *FA* agent. The *DF* services designed for this particular power system restoration application are summarized in Table III.

TABLE III.
AGENTS SERVICES FOR POWER SYSTEM RECONFIGURATION APPLICATION

Agent	Service	Description
FA	Agent	a mandated agent service in JADE platform
	FA	declares FA service to *DF*
BA1	Agent	a mandated agent service in JADE platform
	BA	declares BA service to *DF*
	B11E31L	circuit breaker number 1 of bus 1 is connecting with circuit breaker number 1 of bus 3. Bus 1 energizes bus 3. Therefore bus 1 is an upstream bus and bus 3 is a downstream bus.
BA2	Agent	a mandated agent service in JADE platform
	BA	declares BA service to *DF*
	B21E41L	circuit breaker number 1 of bus 2 is connecting with circuit breaker number 1 of bus 4. Bus 2 energizes bus 4. Therefore bus 2 is an upstream bus and bus 4 is a downstream bus.
BA3	Agent	a mandated agent service in JADE platform
	BA	declares BA service to *DF*
	B11E31L	circuit breaker number 1 of bus 1 is connecting with circuit breaker number 1 of bus 3. Bus 1 energizes bus 3. Therefore bus 1 is an upstream bus and bus 3 is a downstream bus.
	B32T42T	circuit breaker number 2 of bus 3 can be connected with circuit breaker number 2 of bus 4. Therefore, there is a transfer line between bus 3 and bus 4
	CLA1	this service tells that *LA1* is connected to bus 3
	CDGA1	this service tells that there is DG available to connect to bus 3
BA4	Agent	a mandated agent service in JADE platform
	BA	declares BA service to *DF*
	B21E41L	circuit breaker number 1 of bus 2 is connecting with circuit breaker number 1 of bus 4. Bus 2 energizes bus 4. Therefore bus 2 is an upstream bus and bus 4 is a downstream bus.
	B32T42T	circuit breaker number 2 of bus 3 can be connected with circuit breaker number 2 of bus 4. Therefore, there is a transfer line between bus 3 and bus 4
	CLA2	this service tells that *LA2* is connected to bus 4
LA1	Agent	a mandated agent service in JADE platform
	LA	declares LA service to *DF*
	CBA3	this service tells that LA1 is connected to bus 3
LA2	Agent	a mandated agent service in JADE platform
	LA	declares LA service to *DF*
	CBA4	this service tells that *LA2* is connected to bus 4
DGA	Agent	a mandated agent service in JADE platform
	DGA	declares DGA service to *DF*
	CBA3	this service tells that *LA1* is connected to bus 3

C. Agents' Communication and Negotiation Process during the Restoration

The MAS monitors the system condition and acts corresponding to data received from physical devices in the microgrid. Fig. 4 illustrates the integration of the proposed agents into the microgrid. The arrows represent the messages exchanged between agents as well as the control signals sent to the circuit breakers.

The followings are the steps for fault detection, isolation and power restoration in the microgrid.

Step 1: *FA* maps the system topology to determine the switching sequences.

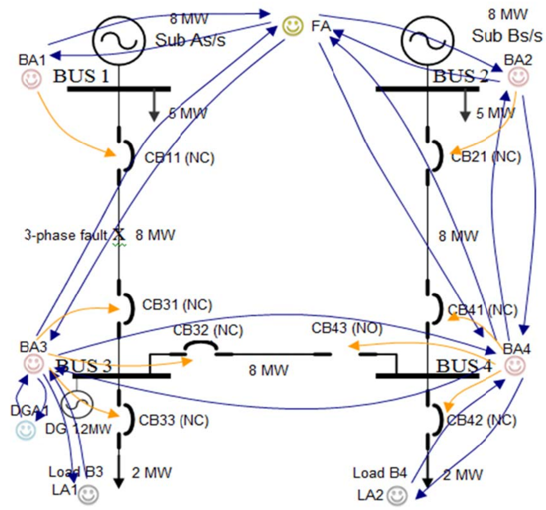

Fig. 4. Messages exchanged between agents and control signals.

Step 2: Fault detection and isolation are performed by the conventional over-current relay and existing protection system available in the microgrid.

Step 3: *BA* reports it status change to *FA*.

Step 4: The *BA* associated with the de-energized bus (an initiated *BA*) as well as *BAs* at other buses acquire knowledge (FACTs) from their associated *LAs* and *DGA*.

Step 5: The initiated *BA*, then, sends the 'call-for-proposal (CFP)' message to its adjacent *BAs* (the participated *BAs*).

Step 6: The participated *BAs* acknowledge that message by sending 'Proposal' messages back to the initiated *BA*.

Step 7: Once the initiated *BA* receives the replied message, it will make a decision whether to accept or reject the proposal(s) based on the following criteria.

Case 1: If the available power from each proposal received is more than the power requested by the initiated *BA*, the *BA* sends an 'Accept_Proposal' message back to the *BA* which proposes the largest amount of available power to restore to the de-energized bus.

Case 2: Conversely, if the available power from the adjacent BA is less than the required power, then the initiated *BA* will determine whether the backup DG connected to its own bus or its adjacent buses is able to pick up that amount of loads. If the backup DG is capable of picking up the load requested by the initiated *BA*, then the *BA* sends 'Accept_Proposal' messages back to the *BA* which proposes largest amount of available power and the *BA* corresponding to the bus that DG is connected.

Step 8: After the proposal is accepted, the chosen *BA(s)* sends a 'Confirmation' message back to the initiated *BA* for confirmation.

Step 9: After finishing the negotiation process with the adjacent buses, If the backup DG is connected to the bus corresponding to the initiated *BA*, then the initiated *BA* starts to negotiate (sending 'CFP' message) with *DGA* at its own bus. Otherwise, the initiated *BA* starts to negotiate with another *BA* that has DG connected to. The *BA* at another bus will, then, pass the 'CFP' message to its *DGA*.

Step 10: *DGA* receives the 'CFP' message and sends a 'Proposal' message back.

Step 11: The initiated *BA* will make a decision whether to accept or reject the 'proposal' message from the *DGA*. This can be divided into two cases.

Case 1: If the proposed power from *DGA* is more than or equal the required power of loads, then the initiated *BA* sends an 'Accept_Proposal' message back to *DGA*. It means that the available power to restore from the main grid and *DGA* is capable of securing the critical loads and serving the non-critical loads.

Case 2: On the contrary, if the proposed power from *DGA* is less than the required power of loads, then the initiated *BA* sends a 'Reject Proposal' message back to the *DGA*. This means that the available power to restore from the main grid and *DGA* is not enough to supply to either the critical loads or the non-critical loads. For this case, load shedding scheme is needed to be applied according to the pre-defined loads priority.

Step 12: If the *DGA* receives the 'Accept_Proposal' message, *DGA* will send a 'Confirmation' message back.

Step 13: The initiated *BA* sends a 'Request' message to *FA,* indicating that its connected load can be energized by the connected DG in the system.

Step 14: *FA* will then update the system topology. So, the target post-fault network configuration is obtained.

Step 15: Switching sequences will be performed according to the system topology mapped in *FA*.

D. *Results and Discussions – Post-fault Configuration*

The circuit as shown in Fig. 4 is simulated for 3 second. In this case study, a 3-phase fault occurs at 0.2 second. The fault is then detected by the existing over-current relay and isolated by the circuit breakers between Bus 1 and Bus 3. Upon the occurrence of the permanent fault, Bus 1 is isolated from the system. Therefore, the downstream Bus 3 is de-energized and needed to be restored in a timely manner.

The post-fault system conditions at $t > 0.2$ before reconfiguration process occurred are as followings:

1. Bus 1 is isolated and not connected to the microgrid.
2. Bus 2 has capacity of 8 MW and supplies power to its 5 MW connected load.
3. Bus 3 is de-energized. There is a connected load of 2 MW.
4. Bus 4 has a connected load of 2 MW.
5. There a tie-line between Bus 3 and Bus 4 available to supply power to the de-energized Bus 3.
6. The total power which can be supplied to the microgrid is 8 MW.
7. The total load connected to the microgrid is 9 MW, including a 5MW load connected to Bus 2 and two sets of 2MW load connected to Buses 3 and 4.
8. There is not enough power from the substation Bs/s (8MW) to serve all microgrid loads (9MW).
9. DG has additional 1 MW power available to supply to the microgrid. This is a 1.2MW DG that needs to supply its auxiliary load of 0.2MW.
10. Bus 2 is supplying power of 7 MW to the 5MW load connected to its own bus and the 2MW load connected to downstream Bus 4. Therefore, there is 1 MW power available from Bus 2 to pick up the non-critical load at Bus 3.

Fig. 5 depicts the communication and negotiation process among agents.

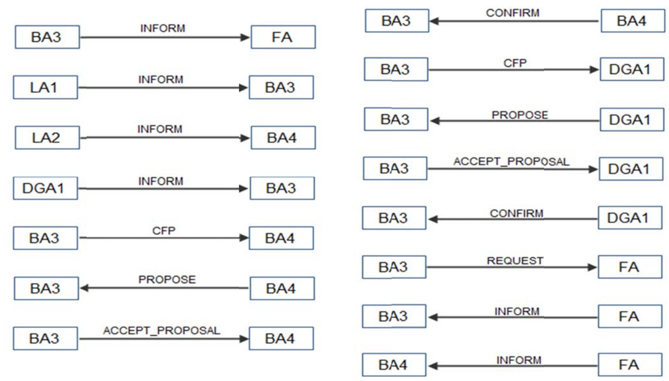

Fig. 5. Communication and negotiation process among agents

Initially, The *BA* associated with de-energized Bus 3 (*BA3*) monitors the voltage and current of its corresponding bus. At t=0.2 second, this agent detects the fault and the de-energized status at Bus 3. The *BA3* then starts to negotiate with its neighboring *BAs* and inform *FA* of its "de-energized" status. As soon as the *LA1* at Bus 3 detects that it has no supplied power, *LA1* sends message to inform *BA3* indicating that it requires 2MW to serve its load. *DGA1* at Bus 3 informs its status to *BA3* as well. *BA4* also acquires load level from its load agent (*LA2*) by getting the informed message from *LA2*.

BA3, then, sends the 'CFP' message, requesting for power of 2MW, to its adjacent *BA4* in order to find a restoration path. *BA4*, then, acknowledges and sends a 'Proposal' message of 1 MW power available to restore from its upstream Bus 2 back to *BA3*. However the proposed power from *BA4* is less than the required power by *BA3*. According to the Agent Discovery service, *BA3* knows that it can connect to the main grid only by connecting to Bus 4. Then, *BA3* sends the tentative 'Accept_Proposal' message to *BA4* and gets the 'Confirm' message back from *BA4*. *BA3*, then, needs to decide whether the connected DG is able to pick up that amount of load or not by communicating with *DGA1* at Bus 3. If this is not possible, *BA3* revokes all negotiation processes and tells *FA* that Bus 3 cannot be restored.

In this case, *BA3* also sends the 'CFP' message to *DGA1*. The *DGA1* sends 1MW power available in the 'Proposal' message back to BA3. At this moment, *BA3* knows that there is enough power to serve the load at Bus 3 for a total of 2MW, 1MW from *BA4* and 1MW from *DGA1*. Then *BA3* sends the 'Accept Proposal' message back to *DGA1*. *DGA1* sends the 'Confirmation' message back to *BA3*. Finally, *BA3* sends the 'Request' message to *FA* indicating that its connected load can be restored by Bus 4 and the DG connected to Bus 3. *FA* will then update the system topology and send an 'Inform' message to either *BA3* or *BA4* in order to perform system restoration. The post-fault target network configuration is obtained as shown in Fig. 6.

Switching sequence, depicted in Fig. 7 (only controllable switches are shown), is performed according to the system topology mapped in *FA*. In this case study, there is a requirement to energize Bus 3 before the DG available at Bus 3 can be synchronized to the system.

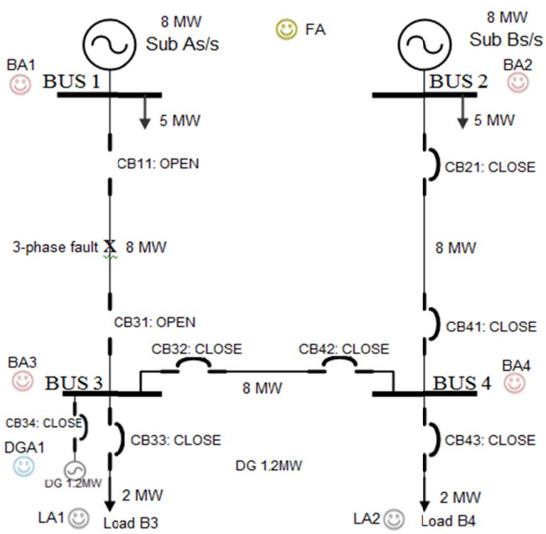

Fig. 6. The post-fault network configuration.

However, to energize Bus 3, a load shedding scheme needs to be implemented because during this step there is not enough power from the main grid to supply to both critical and non-critical loads. Therefore, non-critical load at Bus 3 is shed to secure the critical load at Bus 4. The switching sequence solution from simulation is also shown in Table IV.

Fig. 8 shows the simulation result of the simulated 4-bus test system. This figure illustrates the power, voltage and current at Bus 3 before and after the occurrence of the fault between Bus 1 and Bus 3. At t = 0.2 second, the voltage and current at Bus 3 are zero. The fault is then detected and isolated by the conventional protection system at t = 0.208 second. According to the switching sequence as shown in Fig. 7, at t = 0.308 second, the CB33 is opened in order to shed the non-critical load at Bus 3. At t = 0.408 second, CB42 is closed to energize Bus 3. Then CB34 connected DG to Bus 3 at t = 0.508 second. Finally, Bus 3 is re-energized at t = 0.608 second followed the operational sequence controlled by *FA*.

According to the power system restoration algorithm mentioned in section II(A), the simulation result shows that *FA* works in order to maximize the amount of loads served (14 MW); and that BAs ensure that all associated constraints are not violated. In this case study, the power balance constraint, the capacity limit constraint and the branch power flow constraint are met.

The sniffer agent GUI for this case study which monitors the communications and negotiation process among agents is also depicted in Fig. 9.

TABLE IV
THE SWITCHING SEQUENCE CORRESPONDING TO THE SYSTEM TOPOLOGY

No.	Line	Operational content	Time (second)
1	Bus 1 – Bus 3	CB11:OPEN, CB31:OPEN	0.208
2	Bus 3	CB33:OPEN	0.308
3	Bus 3 – Bus 4	CB42:CLOSE	0.408
4	Bus 3	CB34:CLOSE	0.508
5	Bus 3	CB33:CLOSE	0.608

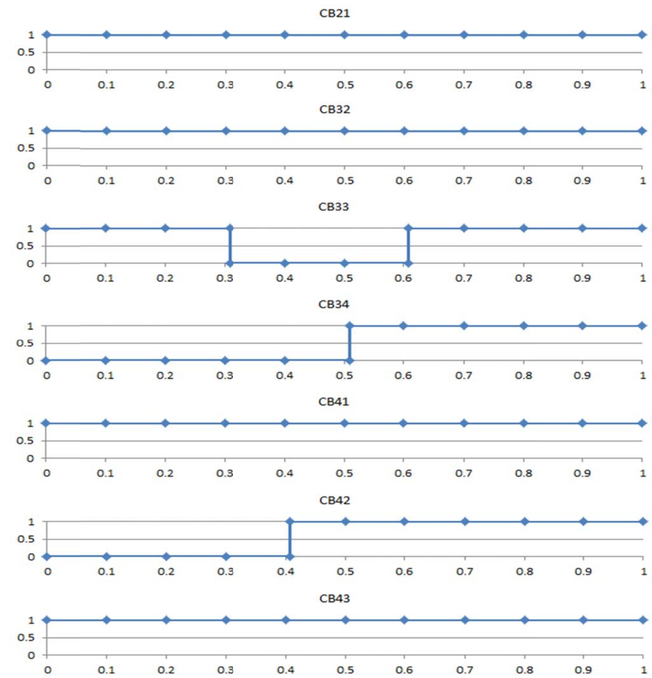

Fig. 7 The switching sequence obtained from the MAS (1=close, 0=open)

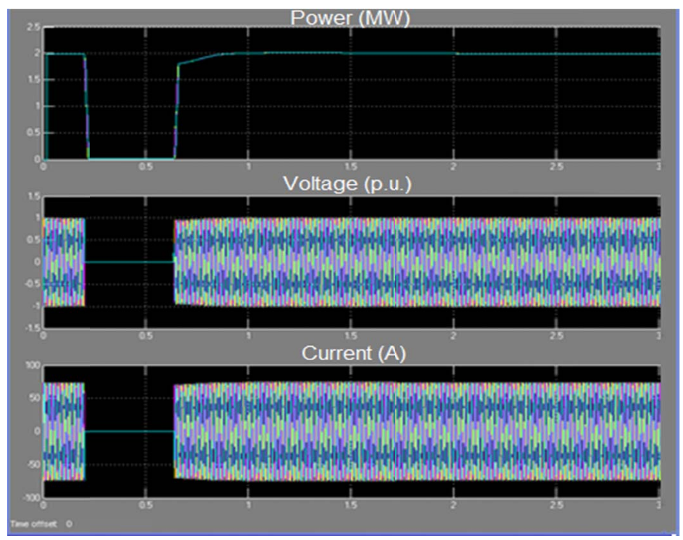

Fig. 8 Simulation result: power (MW), voltage(p.u.) and current(A) at bus 3

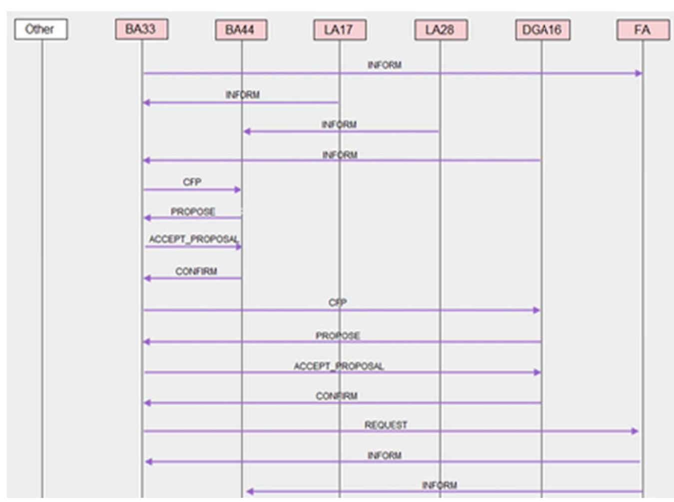

Fig. 9. The sniffer agent GUI of the simulation

VI. Conclusions

The simulation result shows that the proposed MAS can perform network reconfiguration and restore power to the de-energized area while satisfying the specified network constraints. The demonstration of the MAS includes both full restoration and path finding for restoration. The MAS is capable of securing critical loads, performing load shedding for non-critical loads, as well as controlling the use of DG. The simulation results indicate that the microgrid is reconfigured and restored within 0.4 sec after the fault which equivalent to 24 cycles (60Hz). This indicates that the proposed MAS can provide the post-fault network restoration service with a suitable switching operation in a timely manner, thus contributing to increasing the reliability and resiliency of a local electrical distribution network.

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VIII. Biographies

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