A Multi-Agent Based Power System Restoration Approach in Distributed Smart Grid

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***Abstract*--The objective of this paper is to design, develop and implement a multi-agent system (MAS) that provides intelligent and enables real-time management to a smart grid located at a distribution level (so called distributed smart grid). The MAS application development is discussed concerning suitable agent development framework, agent specification, agent architecture, and implementation of MAS. The paper illustrates MAS application in power systems. As faults and outages are inevitable and likely to occur in distribution systems, an efficient and fast switching operation scheme is required to detect the fault location, isolate the fault, and restore power to de-energized areas. The system under study consists of both physical (microgrid) and cyber elements (MAS). Finally, the simulation result indicates that the developed MAS for power system restoration applications can provide an effective and timely solution to manage microgrid given the existence of fault in the system.**

***Index Terms*—Power system restoration, multi-agent system, smart grid, microgrid, self-healing grid, feeder reconfiguration, optimization approach**

I. Introduction

SMART grid is the concept that enabling utility to delivery electricity by using two-way communication technology and computer processing. It provides substantial benefits to the utility as well as their customers such as reducing cost of delivery electricity, improving energy efficiency, reliability and transparency on the electric grid, and increasing the use of renewable energy. According to the National Energy Technology Laboratory (NETL) for the U.S. Department of Energy (DOE)'s A Systems View of The Modern Grid [1], a smart grid consists of five key technology areas: integrated communications, sensing and measurement, advanced components, advanced control methods, and improved interfaces and decision support. In the smart grid concept, these technologies are integrated in order to achieve the following modern grid principal characteristics:

- self – heals
- motivates and includes the consumer
- resists attack
- provides power quality for 21st century needs'
- accommodates all generation and storage options
- enables markets
- optimizes assets and operates efficiently

The advanced control methods (ACM), which can provide a truly safe, reliable and environmental friendly to the grid, are the focused technology area in this paper. ACM is referred to a devices and algorithms used to analyze, diagnose, and predict conditions in the microgrid as well as determine suitable corrective actions in order to eliminate mitigate and prevent faults, outages or any disturbances occur in power system.

Reliability is one of the key factors which have been concerned in recent years. Power system restoration is the process which is directly related to the increase reliability in the system. An effective and timely power system restoration can significantly improve the reliability of the system. Power system restoration consists of two sequential steps with switching operations excepted [18]. The first step is to determine an optimal configuration as a restoration target. The second step is to make up a sequence of switching operations (restoration procedure) to bring a faulted system into the target system obtained from the first step while maintaining a certain level of security. To obtain post-fault target network configuration and optimal operational sequence after service interruption is not without challenges. It is a complex decision-making and control problem for power system operator. So far, various approaches were proposed, which can be broken down into 4 categories: heuristic [12]-[14], Expert systems (ESs) [15]-[16], mathematical programming (MP) [16], and soft computing [17]. Heuristics and ESs have been used in industries extensively, but they both have their own deficiency with respect to the optimality of solutions. MP, on the other hand, is able to obtain the optimal solution after the formulation, but it needs some engineering judgment in formulating restoration problems due to its sheer difficulty. Also, its long execution time may sometimes make feel MP in practical considering the time constraints on site [18]. Although soft computing methods are easy to implement, they cannot obtain the optimal solutions in the true sense. Also, they need long computation time to obtain optimal solution.

A multi-agent based power system restoration is one of the promising approaches which based on the concept of distributed control system rather than the centralized control system named Supervisory Control and Data Acquisition (SCADA). Traditionally, SCADA is the centralized

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monitoring and control system consisting of hardware and specific software protocols. In order to make decision corresponding to the microgrid conditions, SCADA needs to collect and process huge amount of data acquiring from the system. Due to this fact, SCADA system cannot provide rapid and timely solution to power system restoration application of a wider scale of power system. Therefore, in order to confront the requirement of the future grid, relying on SCADA system for monitoring and controlling power system solely is not sufficient. The future trends of operation of power system are moving toward the use of software-based control algorithms such as distributed intelligent agents (or called multi-agent system).

In addition, deployment of the MAS for control of microgrid has recently been proposed to overcome the SCADA system drawback. The MAS offer various advantages over the SCADA system: first, the MAS development toolkits are available as open source software which makes them a superior choice rather than proprietary control protocols use in a SCADA system. Second, most toolkits are java based which makes them platform independent. Third, the developed MAS can be connected to any external physical machines or software entities allowing control of microgrid.

Multi-Agent System (MAS) is the system consisting of multiple agents working and communicating together to achieve the system target or their own targets. However, an agent might work alone as a single entity or work with other agents by communication, collaboration and negotiation processes in a system environment. The MAS consists of distributed agents that achieve an objective cooperatively. They can execute their tasks synchronously or asynchronously, and access decentralized database as needed [1]. The MAS is employed to deal with complex tasks, which cannot be solved by a single agent, by dividing system goal into smaller targets and giving them to each agent. Therefore the objective and goal are achieved by interoperating of agents. In the MAS, there are two ways which agents can interact with each others; direct and indirect interactions. For direct interaction, agents can communicate and negotiate to near-by agents or the agent which is specified to be a receiver of a sending message from the sender agent. For the indirect interaction, in an arbitrary system, agents need to react to their environment. By doing so, other agents are affected as well because the agents' environment has already changed.

Today's world, inundated with technological advancements, incorporates virtually limitless applications of multi-agent systems. Applications and possible uses of multi-agent systems cover a wide spectrum. In the context of power systems, there are various applications of the MAS such as power system restoration [18]-[23], power system condition monitoring [24], management of distributed energy resources (DERs) in microgrid [25]-[26], decision support to power system [27], and fault diagnosis [28].

This paper proposes a multi-agent system based power system restoration for a microgrid. The developed agents are capable of working and communicating together to obtain a post-fault network target configuration and a switching sequence corresponding to the topology of the system. The design, architecture and implementation of the MAS are also discussed.

II. Power System Restoration Framework

This paper considers a 3-phase fault at a network branch resulting in permanent interruption. There are four assumptions made for service restoration regarding the network configuration and simulation limitations:

1. All circuit breakers are controllable and IP enabled.
2. Communications between buses, DGs, loads, and all electronic devices are facilitated by LAN or wireless LAN.
3. Line losses in the system are excluded from the analysis.
4. Only one 3-phase fault occurs in the system.

A. Power System Restoration Model

The objective of the mathematical model of a power system restoration is to minimize the size of the un-served loads

$$\min \sum_{i \in N} \alpha_i L_i \tag{1}$$

Where L_i is the load at bus i, α_i is decision variable indicating restoration status ($\alpha_i = 1$: restored; $\alpha_i = 0$: not restored), and N denotes the set of loads in the microgrid.

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

1) Power balance between supply and demand

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

Where T_i is the set of branches incident to bus i, F_i is the set of branches with originating from bus i.

2) Limit on the capacity of available power sources (substation and DG) for restoration

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

Where P_e is power flow on the directed branch e (assume that $P_e \ge 0$), x_e is decision variable of branch e (if branch e, in the set F_q, is included in the restoration path, $x_e = 1$ otherwise $x_e = 0$) F_q is the set of branches with starting node q, G_q is the restoration power from energized bus q, and S is the set of energized buses that can be connected to de-energized area.

3) Limits on branch power flow

$$|P_k| - U_k \le 0 \quad (k \in B) \tag{4}$$

Where P_k denotes the power flow of branch k, U_k is the capacity of cable branch k, and B is the set of directed branches.

4) Constraint on radial configuration

This constraint means that an obtained target post-fault network configuration must be radial, and is used mandatory in the actual power system operations. To insure a radial configuration, the total number of branches incident to bus i must be unity.

$$\sum_{k \in T_i} x_k \leq 1 \quad (i \in N) \tag{5}$$

Where x_k is the number of branch adjacent to bus i.

B. Power System Restoration Strategy

The problem of power system restoration consists of finding both

1) A target post-fault configuration
2) Switching sequence

The proposed MAS are able to carry out these tasks by performing communications, negotiations, and collaborations among agents.

III. The Multi-Agent System Architecture

In this section, the MAS architecture and its design for power system restoration are introduced. MAS comprises multiple agents working and communicating together to achieve the system target or their own targets. The main objective of the process for designing and developing of the MAS architecture is providing autonomous and intelligent to distributed smart grid. In order to meet an objective without a human intervention, the autonomous and intelligent characteristics of smart grid can be provided by agents that possess learning and reasoning skills with the capability to adapt their acts corresponding to their perceived environment.

There are 4 types of agents proposed for power system restoration application:

1) Facilitator Agent (FA): there is a single FA available in the system acting as a manager for decision making. FA monitors bus status, which can be divided into energized and de-energized state, and maps system topology from upstream to downstream. FA also acts to ensure that the post-fault network configuration is met and network switching sequences are performed correctly with respect to system topology stored in FA.

2) Bus Agent (BA) resides in each bus in the network acting as a coordinator between FA and LA. BA is developed to decide a suboptimal target configuration after a fault occurrence by interacting with other BAs as well as LA connected to it. BA is designed to monitor real power flowing to or from the bus, bus voltage level, bus net current, load power requirement, and circuit breakers status. In emergency conditions, if the bus is de-energized from its upstream supply, then BA corresponding to that bus will start to negotiate with its neighboring BAs in order to restore power to the de-energized area by opening or closing circuit breakers connected to that bus.

3) Load Agent (LA): LA monitors load voltage, load current, active power consumptions at all critical and non-critical loads and control on/off status of loads. Regarding to the priorities of loads, LA keeps the assigned load priorities as well. In emergency conditions, if there is not enough power available to supply to all loads which are connected to system. BA will send a control signal to LA in order to secure the critical loads and shed the non-critical loads.

The architecture of MAS for the power system restoration application is depicted in Fig. 1.

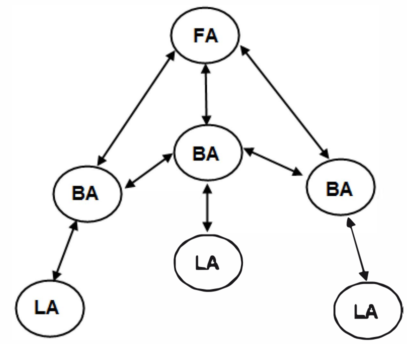

Fig. 1. Architecture of MAS for power system restoration application.

IV. The Multi-Agent System Implementation and Design

As stated earlier, communication and coordination between agents are essential components of MAS. In fact, agents should be capable of communicating with users, system resources and each other in order to collaborate, negotiate and cooperate to achieve their goals [2]. The Foundation for Intelligent Physical Agents (FIPA) [9] is selected as an agent platform for developing MAS. FIPA offers the communication language called FIPA ACL, which is currently the prevalent studied and used. The prime features of FIPA ACL are the feasibility of using different content languages and predefined interaction protocols which help to manage agents' conversations in order to ensure coherence of agents [2].

In order to implement the MAS, there are several commercial and open-source MAS building toolkits available. Some of them are Voyager [3], Zeus [4], Tracy [5], SPRINGS [6], and JADE [7]. JADE is selected for implementation of multi-agent system because of its strong support from industrial sectors, open source status and commonly used by existing users. Moreover, JADE is generally considered to be the leading and promising FIPA-compliant open source agent framework [8].

JADE stands for Java Agent Development Framework. It is an open source platform for development of peer-to-peer agent based applications [7]. In addition, JADE is claimed as the most widespread agent-oriented middleware in use today.

In this paper, the simulated system and multi-agent system reside in two different software environments. The test system is simulated in the MATLAB/Simulink environment whereas multi-agent system are developed using Eclipse Helio [11]. In order to exchange messages between them, the two have been connected together by middleware called MACSimJX [10]. MACSimJX is the software that enables greater modeling capability for designing MAS developed by Dr.Charles R. Robinson, University of York. In fact, it is an extension of MACSim, a project initially built to allow systems designed with MATLAB/Simulink to be controlled by agents that operate in an external program due to the unstable nature of MATLAB/Simulink when dealing with a multi-threading environment. MACSimJX provides MATLAB models developed in Simulink with an access to JADE. Fig. 2 shows communications between JADE and MATLAB/Simulink, which are facilitated by MACSimJX.

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

V. The Multi-Agent System Implementation in The 4-Buses Test System

The objective of this simulation is to demonstrate that the proposed MAS can facilitate the process of power system restoration after the occurrence of contingency in the system. The simulation setup, case study description, and simulation results are discussed below.

A. Case Study Description

In order to demonstrate the effectiveness of the MAS, it has been applied to a model network which consists of two substations (As/s-Bs/s) and 4 buses as shown in Fig. 3. Here each distribution substation has power capacity of 8 MW denoted by "Sub". The main utility grid voltage level is 22 kV. There is a 4 MW load connected to each substation bus (bus 1 and bus 2). In this microgrid, there are 2 MW loads connected at bus 3 and bus 4. The line flow capacity of each branch is 8 MW. NO (Normally open) or NC (Normally close) indicate the status of each circuit breaker. Bus 3 and Bus 4 are connected together by tie-line.

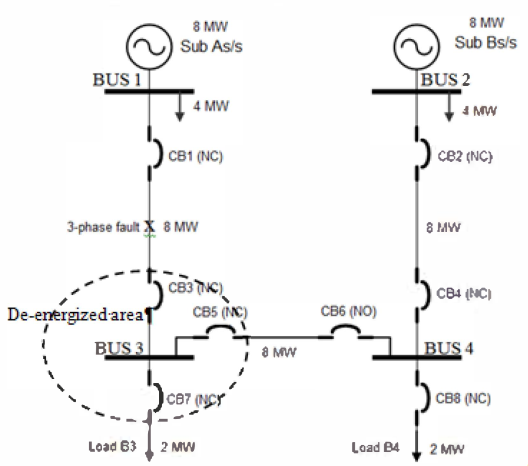

Fig. 3. 4-Bus test system.

Before the fault occurs at t = 0.2 second, the system conditions are as followings:

1) Bus 1 has the power capacity of 8 MW; it supplies power to the connected load 4 MW. Therefore, there is 4 MW power from bus 1 available to distribute to its downstream bus.

2) Bus 2 has capacity power of 8 MW, it supplies power to the load connected 4 MW. Therefore, there is 4 MW power from bus 2 available to distribute to its downstream bus.

3) Bus 3 has a load of 2 MW. Bus 1 is an upstream bus of bus 3.

4) Bus 4 has a load of 2 MW. Bus 2 is an upstream bus of bus 4.

5) There is no power flowing in tie-line between bus 3 and bus 4

6) The total power which can be supplied to this microgrid is 16 MW.

7) The total load connected to this microgrid is 12 MW.

It is assumed that a 3-phase fault occurs at the point shown by x in Figure 3.The circled buses and loads are de-energized. The fault occurs at 0.2 second, and then this fault is detected by over-current relay in the network and isolated by the circuit breakers between bus 1 and bus 3. Bus 3 is now de-energized. The developed MAS are capable of restoring power back to bus 3 by communication and negotiation processes among agents. The MAS monitors system conditions and acts corresponding to the data received. In this case, MAS is needed in order to re-energize bus 3 in timely manner. Fig. 4 depicts the integration of designed software agents into physical elements in the system, the possible messages exchanged among agents as well as control signals to the circuit breakers.

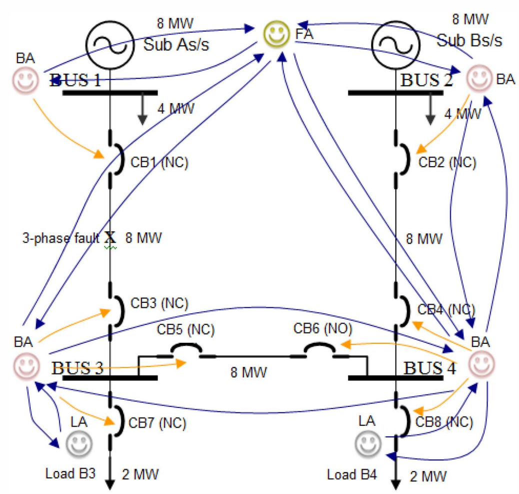

Fig. 4. Agents, message exchanged among agents and control signals.

B. Communication and Negotiation Process during Power System Restoration

Here are the steps for fault detection, fault isolation and system restoration. Fig. 5 illustrates negotiation process for this case study.

1) FA maps system topology for determining the switching sequences

2) Fault detection and isolation will be performed by the conventional over-current relay and protection system.

3) BA, associated with the de-energized bus, acquires knowledge from its associated LA.

4) BA, associated with the de-energized bus, reports it changed status to FA, and then sends "call for proposal" (CFP) message to its adjacent BA to find the path to re-energize itself.

5) Adjacent BAs acknowledge and send Proposal message back to the sending BA.

6) The sending BA will make a decision whether to accept or reject the proposed message.

7) If the sending BA sends the accept message to the receiving BA, then the receiving will send an inform message back to the sender. Conversely, if the sending sends a reject message back to the sender, then the sender will inform FA that it cannot be energized. It means that there is not enough power to supply to the load at the bus associated with the sending BA. Therefore, the sending BA will send message to LA to shed that corresponding load and the negotiation processes end.

8) Then, the sending BA sends inform message to FA that its associated bus can be energized via the receiving BA which proposed the proposal.

9) FA will then update the system topology. So, the target post-fault network configuration is obtained.

10) Switching sequences will be performed from upstream to downstream regarding to the system topology mapped in FA.

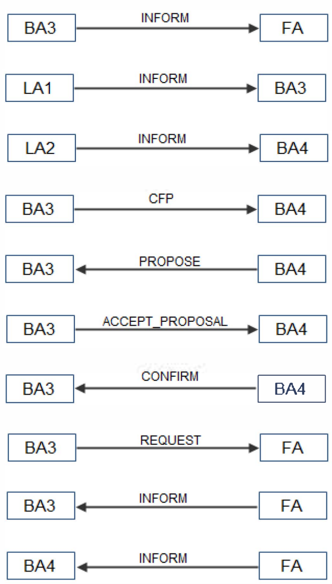

Fig. 5. Negotiation process during power system restoration.

C. Results and Discussions

The circuit in Fig. 3 is simulated for 0.45 second. In this case study, a 3-phase fault occurs at 0.2 second. The conventional protection system has been applied, and then fault is detected by over-current relay and isolated by circuit breakers between bus 1 and bus 3. After the occurrence of permanent fault between bus 1 and bus 3, bus 1 is isolated from the system. Therefore, the downstream bus 3 is de-energized and needed to be restored in timely manner.

The post-fault system conditions at $t > 0.2$ are as followings:

1) Bus 1 is isolated and not connected to the microgrid.

2) Bus 2 has capacity power of 8 MW, it supplies power to the load connected 4 MW. Therefore, there is 4 MW power from bus 2 available to distribute to its downstream bus.

3) Bus 3 is de-energized. There is a load demand of 2 MW connected to bus 3.

4) Bus 4 has a load demand of 2 MW connected to. Bus 2 is an upstream bus of bus 4.

5) There a tie-line between bus 3 and bus 4 available to supply power from 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 8 MW.

8) Bus 2 is supplying power of 6 MW to the load connected to its own bus and its downstream bus 4.

The BA3, associated with the de-energized bus 3, monitors the voltage and current of its corresponding bus. At t = 0.2 second, this agent detects the fault and bus 3 is de-energized. BA3, then, starts to negotiate with its neighboring agent and inform FA of its status that it is now de-energized with flag 0. As soon as LA1 detects that it is not connected to the grid, LA1 sends a message to inform BA3 that the amount of power to be restored is 2 MW. BA3, then, sends a CFP message 2 MW to its adjacent BA4 to find the path to re-energize itself. After receive the CFP message from BA3, BA4 acknowledges and sends the Propose message of 2 MW power left to restore from its upstream bus 2 back to the sending BA3. Due to the power proposed from bus 4 is equal to the power which BA3 call for proposal from BA4, the sending BA3 sends the Accept Proposal message back to BA4. BA4, then, sends the Inform message to confirm with BA3 that BA4 can energize BA3 via the tie-line between bus 3 and bus 4. Finally, the sending BA3 sends inform message to FA that BA3 can be energized via the receiving BA4 which proposed the proposal. FA will then update the system topology. So, the target post-fault network configuration is obtained as shown in Fig. 6. The switching sequences will be performed from upstream to downstream regarding to the system topology mapped in FA. The switching sequence is also shown in table 1.

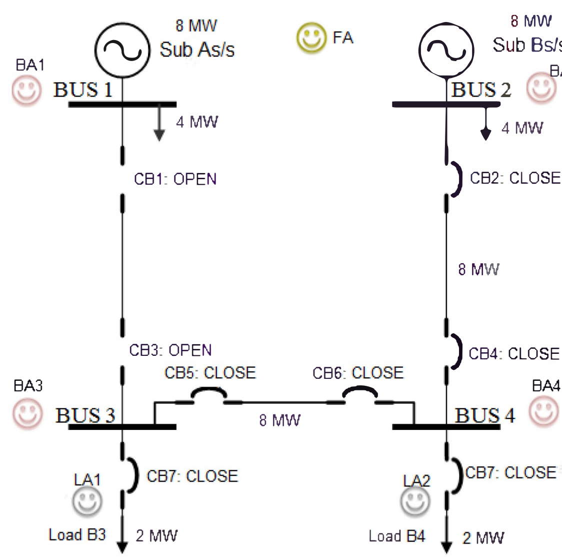

Fig. 6. The target post-fault network configuration.

TABLE I
THE SWITCHING SEQUENCE CORRESPONDING TO THE SYSTEM TOPOLOGY

No.	Line	Operational Content
1	Bus 1 – Bus 3	CB1:OPEN, CB3:OPEN
2	Bus 3 – Bus 4	CB6:CLOSE

Fig. 7 shows simulation result of the 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 of bus 3 are zero. After the conventional protection system between bus 1 and bus 3 detected and isolated the fault, then, bus 3 is re-energized at t = 0.4 second followed the operational sequence controlled by FA. Finally, the status of bus 3 is changed to “energized”. In order to verify the communication process of agents, Fig. 8 shows the sniffer agent GUI of the simulation.

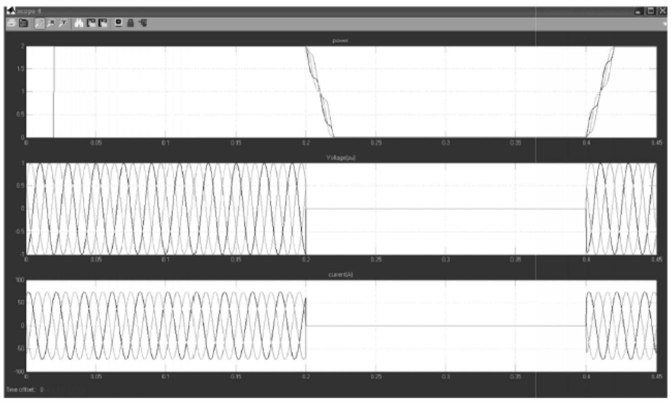

Fig. 7. Simulation result: power (MW), voltage (p.u.) and current (A) at bus 3.

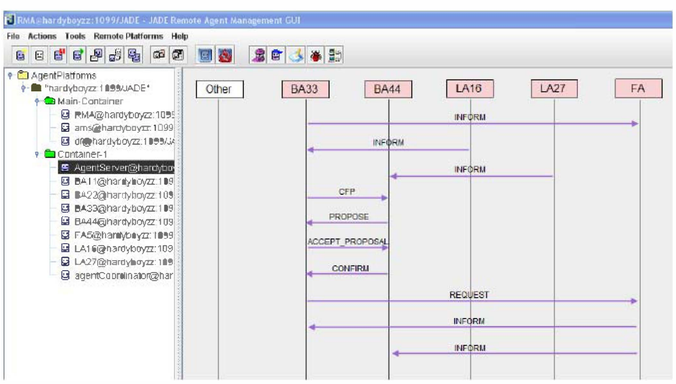

Fig. 8. The sniffer agent GUI of the simulation.

VI. CONCLUSIONS

This paper discusses the architecture, design and implementation of the MAS for power system restoration application. There are three types of proposed agents which are *Facilitator Agent* (FA), *Bus Agent* (BA), and *Load Agent* (LA). These agents work and collaborate together in order to achieve the target configuration and switching sequence after the occurrence of fault. The simulation result indicates that the developed MAS is capable of restoring power to the de-energized bus by communication and negotiation processes among agents in timely manner. The MAS features were demonstrated for full restoration and path finding for restoration. The MAS monitors system conditions and act corresponding to data received correctly. Moreover, the result point out that the MAS can provide a distributed solution for power system restoration strategies in distributed smart grid.

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