

Modeling of Communication Latency in Smart Grid

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Abstract—The goal of this paper is to model the communication latency among distributed intelligent agents because latency 1) is not zero, 2) is not constant, and 3) can have a significant impact on the higher-level capabilities of a smart grid installation, in particular any protection or coordination functions. Communication latency is considered an inherent parameter which affects the performance of the communication network -- the backbone of the multi-agent system. Due to many stochastic factors in a communication environment, communication latency will be best modeled as a random parameter with a probability density function. The latency of sending/receiving messages among distributed intelligent agents is randomly generated based on user input data. In the numerical studies, two abnormal events occurring in the modified IEEE 34 node test feeder will be simulated to validate the proposed methodology. The simulation will measure how fast the smart grid responds to the disturbances when considering fixed latency, as well as random latency.

Index Terms—Smart grid, multi-agent systems, communication latency.

I. INTRODUCTION

MULTI-AGENT SYSTEMS have recently emerged as a competitive technology for the advanced distribution automation requirements of smart grid, which is an advanced grid that makes use of distributed intelligence to fulfill its duties of self-healing, high reliability, high quality, and demand response [1]. In fact the application of a multi-agent system (MAS) to solve power engineering problems is not new. These problems include power system disturbance diagnosis [5], [7], [11]; distributed control [12], [13]; and modeling and simulation [6], [14], [15].

Communication networks have long been engaged with electric power systems, playing a vital part in the monitoring, operation and control functions of the system. One can find communication gear in virtually all stages of electric power systems, starting with power generation, up to transmission, down to distribution, and increasingly at customer sites. Previously, in the conventional power system, the communication system was mostly seen in the transmission network, where it served as the backbone for real-time monitoring, centralized control and protection. Recently, with the introduction of smart grid technology, communication systems are being deployed in distribution networks, where they are needed by the distributed intelligence platforms, such as MAS.

A multi-agent system is basically a distributed intelligence system which is formed by two or more intelligent agents that must have social ability and therefore must be capable of communicating with each other. While much research has been done on designing intelligent agents to solve power system problems, little attention has been paid to the impacts

of the communication network on smart grid performance. In a multi-agent system, agents usually communicate with each other via sending/receiving messages through meshed radio networks, fiber optic networks and wire/wireless modems. The two most important inherent properties of these networks are bandwidth and latency. In this research it is assumed that the MAS system was designed such that the throughput is always less than the communication network bandwidth, i.e. the communication link between any two agents is capable of transferring all messages as requested. Instead, the focus is to examine the latency to answer the question: how would the inherent latency of the communication network affect the smart grid performance?

In telecommunication, latency is defined as the total time required for a signal to travel from one point to another, generally from a transmitter through a network to a receiver. In MAS communication, latency is understood as the amount of time it takes for a message to be passed from the sending agent and received at the receiving agent.

Note that this paper does not attempt to model the individual communication network devices in detail. Rather, the focus is on modeling the agent-to-agent message latency to better understand its impact on high-level smart grid functions. A secondary application of the latency model in this paper would be to establish upper bounds on message latency such that specific user-defined reliability targets, e.g., SAIFI, SAIDI, CAIDI, etc. could be met.

The paper is organized as follows: Section II provides an overview of the MAS and its application in power systems. In Section III, the modeling of the communication network is detailed. Case studies and numerical results are shown in Section IV and V. Finally conclusions in Section VI and future work in section VII are discussed.

II. MAS FOR AUTONOMOUS POWER SYSTEM OPERATION

A. Intelligent Agents

An intelligent agent is an autonomous, goal-oriented entity that can interact with its environment. For example, an intelligent agent could represent an embedded system controller for a piece of equipment or it could represent a piece of software without any visible appearance [10].

The multi-agent system presented in this paper is based on the “team” concept [2]. A team corresponds to a power line segment bounded by intelligent switching points, see Fig. 1. The agents within a team can communicate with each other, while a team can communicate with other teams next to it via common “teammate(s)”. The “teams” of agents usually communicate with each other to negotiate the most efficient and expeditious reconfiguration of the system in response to fault conditions and other circuit abnormalities. An intelligent

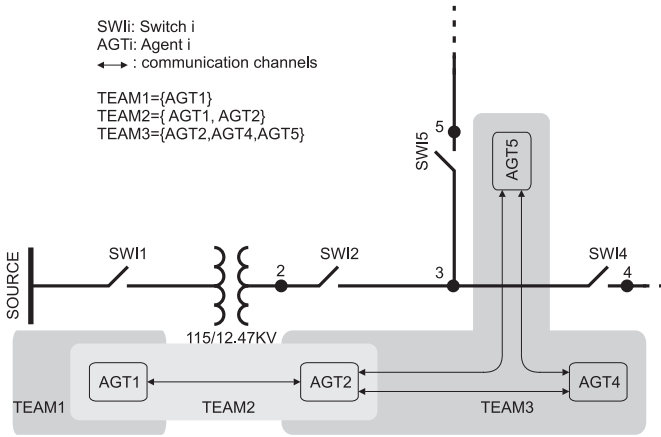


Fig. 1. Multi-Agent System and Power System Relationships

agent includes a conventional local controller, which receives the measurements from and sends control signals to its associated device in the power system. But an agent is different from the conventional controller in that it can work autonomously, proactively and socially.

B. Java Agent DEvelopment Framework (JADE)

Java Agent DEvelopment Framework (JADE) [9] is an open source platform for peer-to-peer agent based applications freely distributed by Telecom Italia. JADE is fully compliant with the FIPA-IEEE agent-based technology standard. Many research projects in power engineering have used JADE as a MAS framework [3], [4].

In a JADE platform, each agent is identified by a globally unique name (AID). JADE allows each agent to initiate communication with other agents at any time as well as receive incoming communication at any time. Agents communicate by asynchronous message passing, in which each agent has a sort of mailbox (the agent message queue) where the JADE runtime posts messages sent by other agents. Whenever a message is posted in the message queue, the receiving agent is notified. The receiving agent then can pick up the message from the queue to process it.

A message typically consists of the following fields:

- sender
- intended receivers
- communicative intention
- conversation ID
- content

C. Power System and Multi-Agent System Simulation

The idea of co-simulating a power system and a multi-agent system is illustrated in Fig. 2. The power system module is responsible for solving power flow while the multi-agent system module, which consists of many distributed intelligent agents, is in charge of working out the best configuration of the power network at any given time.

The co-simulation algorithm is described in the following steps:

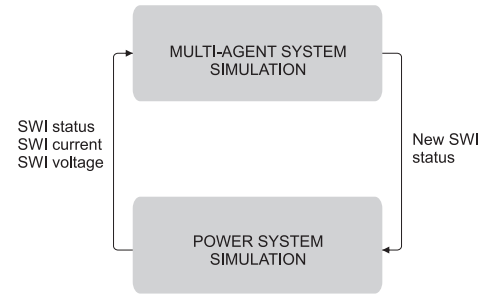


Fig. 2. Multi-Agent System and Power System Co-simulation

- 1) The user supplies power system data such as power sources, power network configuration, equipment settings, power demand; and multiagent system such as team, agent parameters, communication network configuration. In addition the user supplies a list of events such as fault and other abnormalities as input.
- 2) The simulation starts by setting time $t = 0$. The status of all intelligent switches are initialized to user input settings.
- 3) Given the status of all intelligent switches, the power system simulation module solves the three-phase power flow [8].
- 4) At each intelligent switch, measurements including present status, current and voltages at both sides are sampled every T_{samp} seconds and compared to user defined limits.
- 5) In the case of any local violation, an agent will initiate a conversation thread to communicate with other agents in the team. The conversation thread can propagate to neighboring teams, if needed, to resolve the violation in the most efficient way.
- 6) At the end of the conversation, each agent will decide a new switch status and send it back to its associated switch in the power system simulation module.
- 7) The power system module reconfigures the network based on the information received from the MAS and increments the simulation time $t = t + timestep$. Any event such as a short circuit or disturbance which is set to occur at the new time t is also included at this time.
- 8) If the event is set to end the simulation, then go to 9, else go back to step 3.
- 9) Exit simulation.

III. COMMUNICATION SYSTEM MODELING

A. Communication System

A multi-agent system is made up of two or more agents passing messages through a communication network. Two common types of communication technologies are used in power systems, namely traditional radio-based technology and fiber optic-based technology. Each technology has its pluses and minuses. Radio-based technology usually utilizes the unlicensed 900 MHz band frequencies, which has low cost, flexible infrastructure but usually has low throughput and long latency. Despite its shortcomings, the radio based technology is still applicable for large systems spreading over

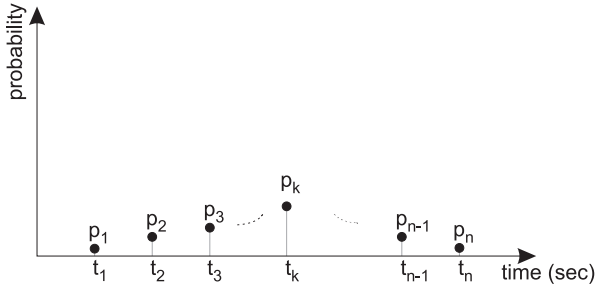


Fig. 3. Probability density function of the latency of the communication link from agent i to agent j

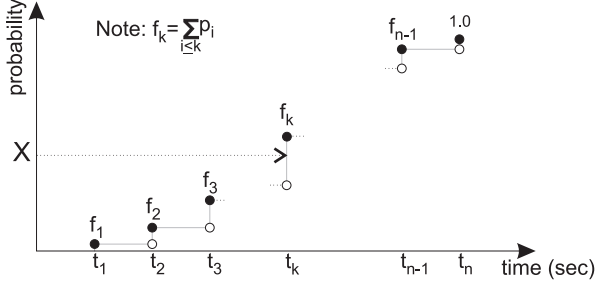


Fig. 4. Cumulative distribution function: at each jump the solid dot indicates the function value at the jump. For example, given a function value X , the latency corresponding to X is $t_{late} = t_k$

a wide geographic area. Fiber optic technology on the other hand often has much higher cost, but it offers a much higher throughput and minimal latency.

B. Communication Latency Model

Due to the inherent delays of existing communication technologies, latency must be incorporated into any realistic multi-agent system simulation. Communication latency is generally considered a stochastic quantity due to many random factors such as distance, repeater malfunction, density of the medium, electromagnetic interference, and ambient temperature. Therefore a random model is best suited to model the latency. For each directional communication link, the latency data can be obtained from

- 1) Field measurements of an existing communication network,
- 2) Manufacturer data of a proposed communication network, or
- 3) Repeated trials of user-defined latency statistics that yield desired smart grid behavior, i.e., meet certain reliability targets.

In the case of item 3, the user-defined latency statistics can be specified as upper bound latency profiles for use in designing a new communication network. Once statistical latency data is available, a discrete probability density function is easily created.

Fig. 3 shows a discrete probability density function of a communication path from agent i to agent j . The horizontal axis time value t_k shows the communication latency corresponds to a probability of p_k . Notice that the time sequence must be strictly increasing, i.e. $t_1 < t_2 < \dots < t_k < \dots < t_n$

TABLE I
NORMAL RANDOM DISTRIBUTION OF COMMUNICATION LATENCY

Point	1	2	3	4	5
Latency (s)	0.0333	0.0667	0.1000	0.1333	0.1667
Probability	0.0060	0.0120	0.0361	0.1265	0.6328
Point	6	7	8	9	10
Latency (s)	0.2000	0.2333	0.2667	0.3000	0.3333
Probability	0.1265	0.0361	0.0120	0.0060	0.0060

while the sum of probability values must precisely amount to 1.0, i.e. $p_1 + p_2 + \dots + p_k + \dots + p_n = 1.0$. For a particular communication link with a fixed latency value \bar{t} , meaning no randomness in communication, the probability of being at this latency while transmitting messages is always 1.0, therefore there would be only a single data point $(t_1, p_1) = (\bar{t}, 1.0)$ in Fig. 3.

Fig. 4 shows the cumulative distribution function of the random latency variable. The application of this cumulative distribution function is elaborated as follows:

- 1) Agent i sends agent j a message at time t_{sent}
- 2) The message is inserted in the message queue of agent j at time t_{sent}
- 3) Agent j picks up the message at time t_{sent}
- 4) A random generator is used to produce a random number $X \in [0, 1]$
- 5) A latency $t_{late} = t_k$ is found from Fig. 4
- 6) Agent j will process the message at time $t_{received} = t_{sent} + t_{late}$

IV. CASE STUDY

The system under study is a modified IEEE 34-node distribution system available at [16]. This is a very long unbalanced 24.9kV distribution system equipped with two in-line “step-type” voltage regulators, one in-line “step-down” transformer, and unbalanced “spot” loads as well as “distributed” loads.

More importantly, seven advanced switches have been added into the system, namely BRK_06, SCT_18, SWI_28, SWI_52, SCT_42, SWI_88, SCT_62, which are locally controlled by seven intelligent agents AGT_BRK_06, AGT_SCT_18, AGT_SWI_28, AGT_SWI_52, AGT_SCT_42, AGT_SWI_88, AGT_SCT_62 respectively, see Fig. 5. These agents, which are distributed along the feeder, form a multi-agent system of 8 teams:

- 1) Team 1 = {AGT_BRK_06}
- 2) Team 2 = {AGT_BRK_06, AGT_SCT_18, AGT_SWI_28}
- 3) Team 3 = {AGT_SCT_18}
- 4) Team 4 = {AGT_SWI_28, AGT_SWI_52}
- 5) Team 5 = {AGT_SWI_52, AGT_SCT_42, AGT_SWI_88, AGT_SCT_62}
- 6) Team 6 = {AGT_SCT_42}
- 7) Team 7 = {AGT_SWI_88}
- 8) Team 8 = {AGT_SCT_62}

Communication latency data must be given for each communication link. In general, the communication latency from agent i to agent j can be different than the latency from agent j to agent i . In this study, all communication links are assumed

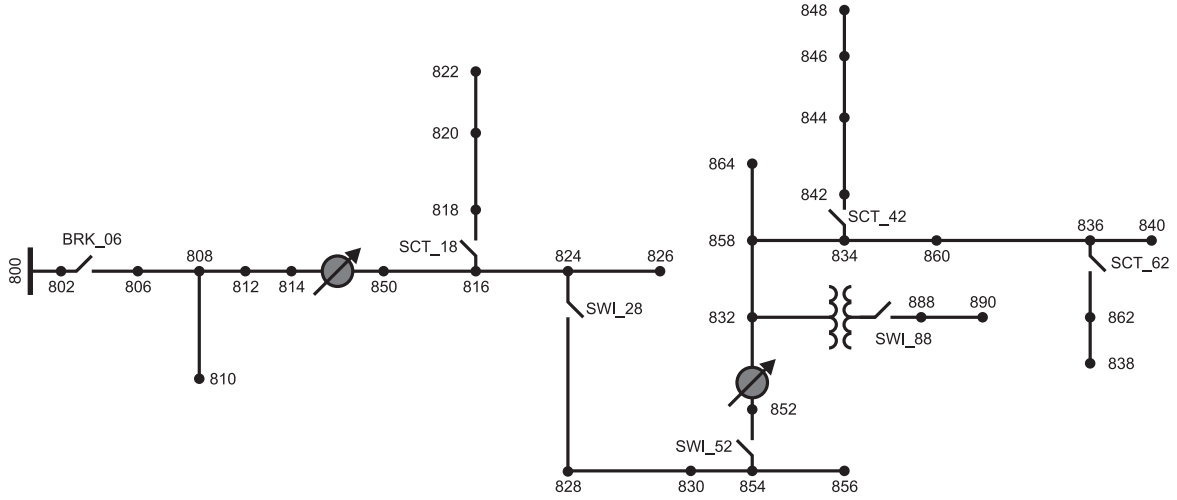


Fig. 5. Configuration of Modified IEEE 34 Node Test Feeder Equipped with Smart Switches

TABLE II
EVENT 1: FAULTED SYSTEM, FIXED COMMUNICATION LATENCY

time (s)	SWITCH							comment
	BRK_06	SCT_18	SWI_28	SWI_52	SCT_42	SWI_88	SCT_62	
0.000	1	1	1	1	1	1	1	normal
1.000	1	1	1	1	1	1	1	permanent fault on
1.033	1	1	0	0	1	0	1	fault isolated
1.100	1	1	0	0	0	0	0	SCT_42 opened & SCT_62 opened
2.200	1	1	1	0	0	0	0	team 4 restored
3.400	1	1	1	1	0	0	0	team 5 restored
4.583	1	1	1	1	1	0	0	team 6 restored
5.350	1	1	1	1	1	0	1	team 8 restored

TABLE IV
EVENT 2: DISTURBED SYSTEM, FIXED COMMUNICATION LATENCY

time (s)	SWITCH							comment
	BRK_06	SCT_18	SWI_28	SWI_52	SCT_42	SWI_88	SCT_62	
0.000	1	1	1	1	1	1	1	normal
1.000	0	1	1	1	1	1	1	temporary disturbance
1.067	0	0	0	0	0	0	0	feeder isolated
1.467	1	0	0	0	0	0	0	team 2 reenergized
1.917	1	1	0	0	0	0	0	team 3 reenergized
2.300	1	1	1	0	0	0	0	team 4 reenergized
3.500	1	1	1	1	0	0	0	team 5 reenergized
4.683	1	1	1	1	0	1	0	team 7 reenergized
5.450	1	1	1	1	1	1	0	team 6 reenergized
6.217	1	1	1	1	1	1	1	team 8 reenergized

TABLE III
EVENT 1: FAULTED SYSTEM, RANDOM COMMUNICATION LATENCY

time (s)	SWITCH							comment
	BRK_06	SCT_18	SWI_28	SWI_52	SCT_42	SWI_88	SCT_62	
0.000	1	1	1	1	1	1	1	normal
1.000	1	1	1	1	1	1	1	permanent fault on
1.033	1	1	0	0	1	0	1	fault isolated
1.100	1	1	0	0	0	0	0	SCT_42 opened & SCT_62 opened
2.000	1	1	1	0	0	0	0	team 4 restored
3.133	1	1	1	1	0	0	0	team 5 restored
4.283	1	1	1	1	1	0	0	team 6 restored
4.983	1	1	1	1	1	0	1	team 8 restored

TABLE V
EVENT 2: DISTURBED SYSTEM, RANDOM COMMUNICATION LATENCY

time (s)	SWITCH							comment
	BRK_06	SCT_18	SWI_28	SWI_52	SCT_42	SWI_88	SCT_62	
0.000	1	1	1	1	1	1	1	normal
1.000	0	1	1	1	1	1	1	temporary disturbance
1.067	0	0	0	0	0	0	0	feeder isolated
1.400	1	0	0	0	0	0	0	team 2 reenergized
1.917	1	1	0	0	0	0	0	team 3 reenergized
2.100	1	1	1	0	0	0	0	team 4 reenergized
3.100	1	1	1	1	0	0	0	team 5 reenergized
4.217	1	1	1	1	0	1	0	team 7 reenergized
4.950	1	1	1	1	1	1	0	team 6 reenergized
5.883	1	1	1	1	1	1	1	team 8 reenergized

to be based on radio technology, sharing the same latency distribution tabulated in Table I.

Two events are under study:

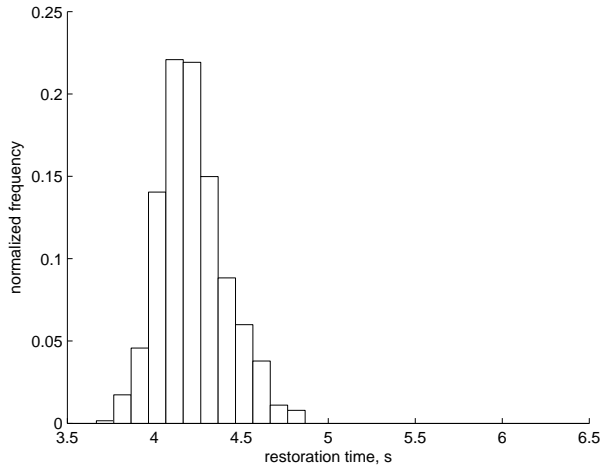
- 1) *Fault event* : simulation starts at time 0 then a permanent three phase to ground bolted short circuit happens at bus 888 at time 1.0 second
- 2) *Disturbance event*: simulation starts at time 0 then a temporary disturbance near the substation causes BRK_06 to open at time 1.0 second

V. SIMULATION RESULT

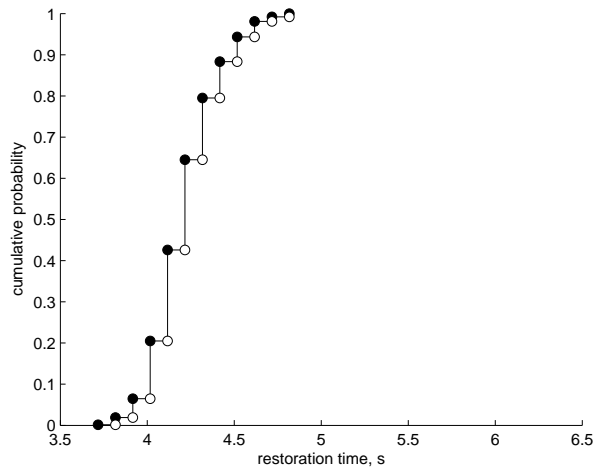
A. Simulating Events Considering Fixed Communication Latency

In this case, the events are simulated when latency is assumed to be fixed at the mean value of the distribution function in Table I, i.e. $\bar{t} = \sum p_i \times t_i = 0.168s$

The simulation results of event 1 are shown in Table II. At time 0 s, the system is at the normal state. When a fault happens at 1.0 s at node 888, an excessive amount of current



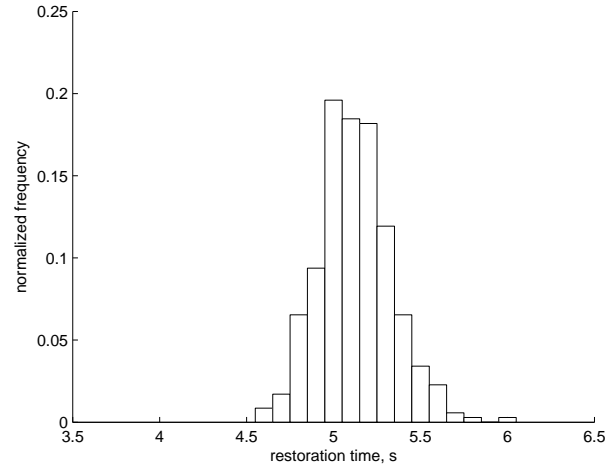
(a) Histogram



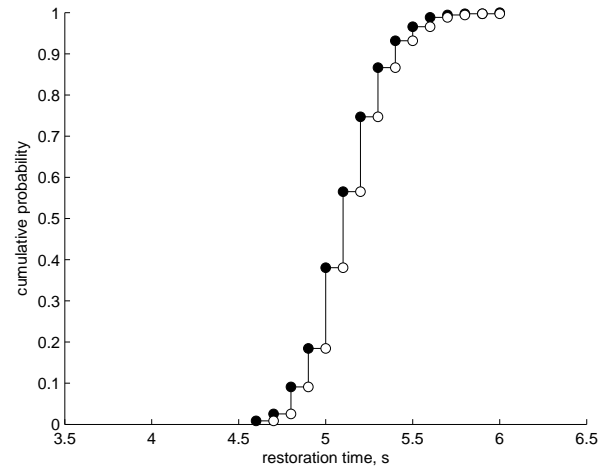
(b) Cumulative distribution

Fig. 6. Fault event

flows in the feeder. As a result, agents in teams 2, 4, and 5, upstream of node 888, sense the fault, causing the agents' fault timer to start counting. At 1.033 s the fault timers of AGT_SWI_28, AGT_SWI_52, and AGT_SWI_88 time out, and the associated switches open to isolate the faulted segment. Due to the isolation, AGT_SCT_42 and AGT_SCT_62 see voltage loss, until 1.100 s when they open their corresponding switches. The bulk of the feeder is islanded due to this serious fault. To restore lost load, the MAS queries the source to find out if it has sufficient capacity to pick up some load. If the source has capacity, then the MAS begins the restoration process starting from the outaged segment nearest to the source, then working its way down stream. From the team 2 segment, SWI_28 is closed at 2.200 s to reenergize the team 4 segment. SWI_52 is closed at 3.400 s to restore the team 5 segment. SCT_42 is closed at 4.583 s to reconnect team segment 6. Finally, SCT_62 is closed to bring the team 8 segment back in service. The team 7 segment is permanently faulted, therefore switch SWI_88 is locked out. The feeder is



(a) Histogram



(b) Cumulative distribution

Fig. 7. Disturbance event

partially restored. The total restoration time starting from the fault event is $5.350 - 1.000 = 4.350s$.

The simulation results of event 2 are shown in Table IV. At time 0 s, the system is at the normal state. A temporary disturbance, such as a tree contact or lightning strike, near the substation at 1.0 s causes switch BRK_06 to open, islanding the rest of the feeder. As the MAS realizes this problem, it orders all switches to open at 1.067 s, to prepare for any future restoration or reconfiguration. After that, the MAS starts querying the source to see if it is ready for restoration. As soon as the source is ready, the MAS begins the restoration process starting from the substation and working its way down stream. The result is teams 2, 3, 4, 5, 7, 6 and 8 are restored one by one. At 6.217 s, the feeder is fully restored. The total restoration time starting from the disturbance event is $6.217 - 1.000 = 5.217s$.

B. Simulating Events Considering Random Communication Latency

With random communication latency taken into account, the results are shown in Table III and Table V. It is easy to see that the sequence of actions is similar to those in subsection V-A, but notice the change in the time line. In event 1, the feeder is restored after 3.983 s while it is 4.883 s for event 2. In contrast to the fixed latency case mentioned before, the different restoration time while considering latency is due to the random latency in sending/receiving every single message among agents in the MAS to isolate the fault and the disturbance and to work out the best strategy to restore the load.

To better quantify the stochastic impact of the communication latency on the restoration time of the power system, 500 simulations were run for each event. The restoration time -- a period from the occurrence of fault/disturbance to the maximum restoration of load -- for each simulation was recorded and shown in Fig. 6 and Fig. 7. The histogram of the restoration time for the fault event is displayed in Fig. 6(a). The restoration time ranges from 3.711 s to 4.867 s, with an average around 4.220 s. While for the disturbance event, Fig. 7(a) shows that the restoration time varies between 4.550 s and 6.084 s, with an average of 5.114 s. It is observed that the shape of the two histograms are close to a normal distribution. In addition, cumulative distribution functions were constructed based on the histograms, see Fig. 6(b) and Fig. 7(b). These cumulative distribution functions are useful in that they show the probability of getting maximum load restoration in the power system within a given amount of time when a fault/disturbance occurs.

VI. CONCLUSION

This paper has presented a stochastic model to handle communication latency -- an inherent property in a physical communication network. The discrete communication latency data must be given as an input, from which a probability density function can be constructed. Any time a message is passed from one agent to another agent, a message latency is randomly generated based on the probability distribution. That creates a delay in processing message in the multi-agent system. Two abnormal events in an advanced three-phase unbalanced distribution system were simulated. Even though the simulation results showed a strong correlation between the latency in the communication network and the smart grid restoration time, that may not be true in general, especially under the heavy communication traffic conditions. Therefore it is important that communication latency be incorporated into multi-agent system simulations of realistic smart grid systems.

VII. FUTURE WORK

Latency is only one of the two key metrics of a communication system. The other metric -- bandwidth -- must also be considered. The other issue is the failure of the communication path between two sending/receiving agents. Analogous to the failure of a line/cable in a power network, when a communication path is subject to any fault/disturbance,

a multi-agent system must be able to detect and work out an efficient solution to overcome the problem. The research on these two issues has begun and once complete the results will be reported.

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