Implementing Cooperative Agent-based Protection and Outage Management System for Power Distribution Network Control

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***Abstract*—In this paper, a wide research results upon the potentials of implementing Multi-Agent Systems (MAS) technology on Tehran-Iran power distribution network to gain high degrees of independency, is proposed. This work is in the area of agent-based and/or knowledge–based applications, distributed optimizations, distributed computing and expert systems. The proposed MAS is implemented using Java Agent DEvelopment Framework (JADE), which is fully accomplished in Java and compliant with Foundation of Intelligent Physical Agents (FIPA), also graph-theory-based expert systems implemented, which executed using PROgramming in LOGic (PROLOG), can be integrated with Java Integrated Development Environment (IDE). In order to power restoration decisions, Binary Knapsack Problem (KP) optimization algorithm is implemented with PROLOG. It is shown that, MAS technology's impact on outage management, upon medium-voltage (MV) power distribution lines, makes it be autonomously performing and effective cooperative. Since cooperation becomes more and more popular in software industry, the proposed MAS technology also offers modular, extensible, adaptable and versatile approach.**

***Index Terms*—Distributed Artificial Intelligence (DAI), Multi-Agent Systems (MAS), cooperative systems, power distribution network, protection and restoration**

I. Introduction

PROTECTION and outage management including fault management and power restoration as a common problem in the area of power generation, transmission and especially power distribution networks, has indicated to be an important field of research and applications of the artificial intelligence technology [1]. Many investigative approaches have been proposed in areas of centralized techniques by power engineers and researchers [2, 3]. The centralized paradigm is characterized by a complex and omniscient processing unit that is tailor made to solve the problem at hand. The process of substation automation can be defined as deployment of substation and feeder operating functions ranging from supervisory control and data acquisition (SCADA) and alarm processing in order to optimize the management of main assets and enhance operation and maintenance efficiencies with minimal human intervention [4].

There are main issues to change traditional approaches for future, especially because of increased penetration of Distributed Generation (DG) in power distribution networks [5]. A number of critical issues regarding DG units on one hand and their connection to network on the other hand, have to be considered. Moreover, more complexity in networks and complicated fault management, make traditional approaches not be appropriate.

In complex and extensive power distribution networks as the unit must gather the data from the whole system, its solution algorithms are necessarily complex and problem specific, and cannot easily cope with missing data.

Distributed Artificial Intelligence (DAI) is the study, construction, and application of *multi-agent systems (MAS)*, that is, systems in which several interacting, intelligent agents pursue some set of goals or perform some set of tasks. Behavioral flexibility and rationality are achieved by an agent on the basis of key processes such as problem solving, planning, decision making, and learning.

Implementing of MAS in recent years for control, management and protection of infrastructure [6], large-scale network, power grid and distribution network [7-10], and shipboard power system [11, 12], seems to be quite promising. Today these systems are not simply a research topic, but are also beginning to become an important subject of academic teaching and industrial and commercial application [13, 14].

Intelligent Electronic Devices (IEDs) are become standard by *IEC 61850*, in new or upgraded integrated substation protection [15, 16]. With the available microprocessor technology a single unit can perform several tasks like protective, control, and similar functions such as metering, event recording or built in fault analysis tools.

This works deals with a novel implementation of MAS in a real power distribution network (distribution network of Tehran, Iran) in order to perform protection and outage management with a Decentralized approach. The novel implementation also contains Binary Knapsack Problem (KP) optimization algorithm in order to perform power restoration, which is not presented in previous publications.

The rest of paper is organized as follows. The real power distribution network used in this research is introduced in section 2. MAS architecture is explained in section 3. Section 4 presents the restoration algorithm used in this paper as the novel implementation of MAS. Section 5 is devoted to case study and simulation results are presented in section 6 and conclusion is presented in section 7.

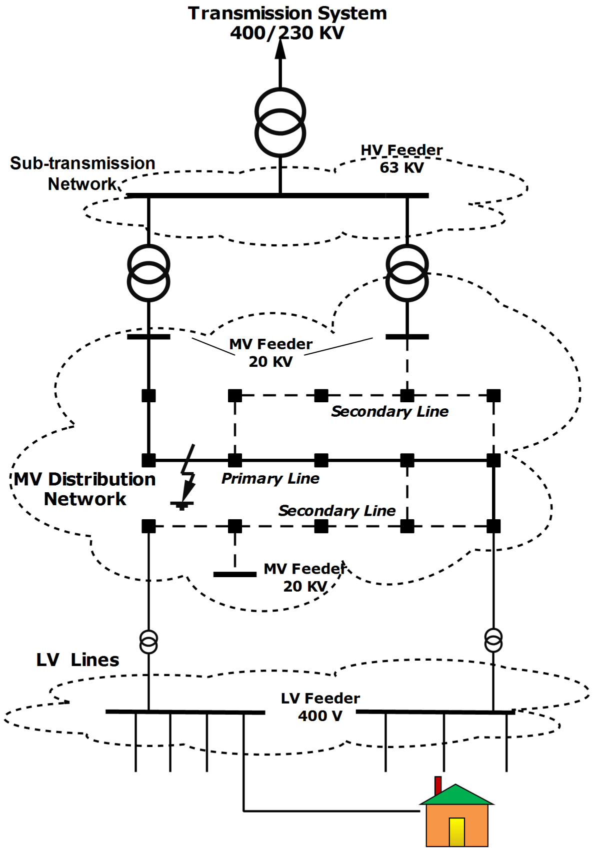

Fig. 1. Power distribution network simple layout, regarding to sub-transmission network and low-voltage distribution lines

II. Application Filed

This research focuses on an effective outage management system which is of major concern for fault localization, isolation and power restoration procedures. A power distribution system as in Fig. 1 can be viewed as a network of electric lines connected via power switches accommodated in 20-kV, represented by small squares in the figure, and fed via 20-kV circuit-breakers at terminal of lines, placed by 63/20-kV stations. They have two possible positions; either open or closed. Regarding to Fig. 1 there are several stages exist converting power from high to low voltage such as transmission, sub-transmission and distribution system for usage of electricity. Power distribution system is the final stage in the delivery of electricity to end users. Tehran power distribution network, which is used in this research, has a mesh-structured exploited radially and rated at 20 kV. Upon occurrence of fault, the circuit-breaker feeding of the faulty line opens in order to protect the rest of its feeder from damaging overloads. In order to isolate faulty lines and restore the rest of the network, the faulty ones shall be located and isolated, and then the network must be reconfigured. This has to be done within a short period of time with switching actions through substations and power switches.
The research is implemented by means of assumptions and definitions which are presented in Appendix A.

III. MAS Architecture

Various architectures have been proposed in the literature for MAS. These architectures have different types. (e.g. simple, complex, hybrid and layered models) based on the required flexibility [17]. In this research, since several rule-based expert systems have been developed for restoration and switching actions, layered architecture is the best choice.
The entity platform used by agents in the proposed MAS is provided by *Java Agent DEvelopment Framework (JADE)* [18, 19]. JADE is a *FIPA* standards compliant middleware, fully implemented in Java language which enables agents running, communicating with each other, immigrating from one device to another through network and many facilities with its great resources and libraries [20]. JADE messages adhere to *FIPA-ACL* standards [21]. One of differences between *Agent-Oriented Programming (AOP)* and *Object-Oriented Programming (OOP)* is agents has behaviors for doing main tasks and goals [22]. JADE has proposed several simple and complex behaviors for agents [18]. Agent behaviors will be discussed later in section 5 (Case study).
The agents compromise the rule-based expert systems programmed in *PROgramming in LOGic (PROLOG)* with useful Java interface software, called Amzi Prolog and Logic Server [23, 24]. Since this work is in the area of knowledge-based applications, PROLOG is used due to its robust search engine and ability to enable agents to act as an expert role.
Three layers are defined according to states of the agents for overall system structure as seen in Fig. 2. When the MAS is initiated, it goes to *Normally Steady (NS) State* directly, after doing some startup actions. This state is related with 1st Layer of MAS architecture. As soon as the occurrence of a fault the respective circuit-breaker opens and the state of the system is changed and goes to *Fault Isolation (FI) State*. At this time agents (SS and JS agents, see Appendix A) select 2nd Layer flexibly to perform locating and isolating the faulty line with some switching actions. After the fault is isolated with neighboring substations, they inform this action to whole modules respect to primary line and then the MAS prepare for *Power Restoration (PR) State.* As soon as the informs packet has propagated by substations near faulty line, the MAS state is changed to PRS and the 3rd Layer is playing critical rules to restore electric power to remaining substations of primary line.

A. 1st Layer - Normally Steady (NS) State

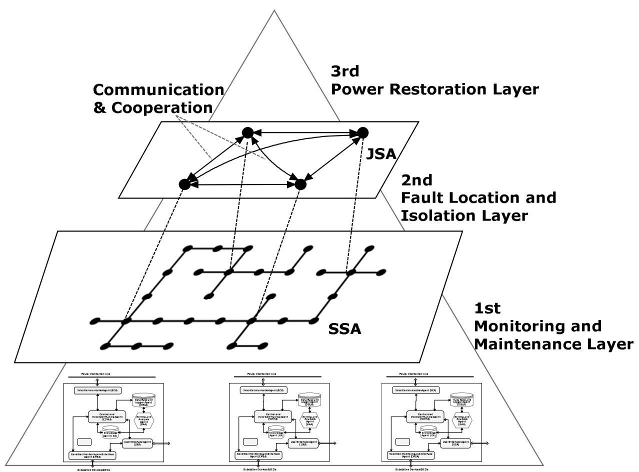

Fig. 2. Proposed 3-Layered architecture of MAS

First layer is for architecture of agents implementing in one substation include both SS and JS agents. This layer consists of all three elements of distribution line and not interfering in outage and protection managements. Since there are some critical devices placed in substations such as transformers, protection devices and power switches, which have equipped with IEDs to gather information, so protect and control of them perform multi-functionally.
According to Fig. 3, in this layer each substation module focuses on monitoring and maintenance until any event is occurred. InterCommunication Agent (ICA) also communicating among other modules which means, transmitting and/or receiving informative data from and/or to other substations and CBAs (see Appendix A). In order to local monitoring, management, control and decision making, there are several agents have been selected and implemented using JADE which hold with *JADE Container* (Fig. 3).

B. 2nd Layer - Fault Location and Isolation (FI) State

In this layer we assume each substations (SSAs and JSAs) act as independent modules that capable to automate its components and locate faulty line after tripping circuit-breaker and then isolate it and preparation network for later reconfiguration procedure. In this layer MV substations cooperate with each other to detect location of fault rapidly and isolate it by perform switching actions.
Distribution networks, unlike in transmission system may not be provided with protective devices or circuit-breakers in each branch of the feeder. For any fault in a feeder, a large part of the feeder may be isolated depending on the circuit breaker installation. For the purpose of speedy repair work and maintenance, it is important to find the exact fault location and type of fault.
We propose to way to solve this challenge in this paper. According to types of faults may occur in MV lines [25]. We proposed a strategy for detecting, locating and isolating fault. When the circuit-breaker of primary line was tripped, each substations start to send and/or receive information to and/or adjacent substations to retrieve neighboring conditions due to detect fault whether take its near place or not. If the fault resulted damaging or disconnecting the line, so it is easy to locate fast and isolate it quickly since communicating of adjacent substations had lost. In this situation when an agent try to send information to its adjacent, the InterCommunication Agent of substation return an exception that mean the communication channel deal with state of being broken. Other types of fault that occur on MV lines, detect with IED devices placed in substation so the adjacent substations of faulty line locating the fault.

C. 3rd Layer – Power Restoration (PR) State

As long as the faulty line is located and the fault is isolated from distribution lines, the state of MAS is changed to PR state. According to Fig. 5 (test case study) two sections are defined according to the fault location. Each section has its own strategy for restoration as follows:
Section A: As soon as the SSA beside the fault location at the side of primary circuit-breaker changes its state to PR state, send a request to CBA of the primary line to close the breaker (CBA 1, see Fig. 5) and restore power to *Section A* safely. The PR state finish as soon as electrical power is restored to this section. Upon modules sense voltage restored they change their internal state behavior and enter to NS State again until next event.

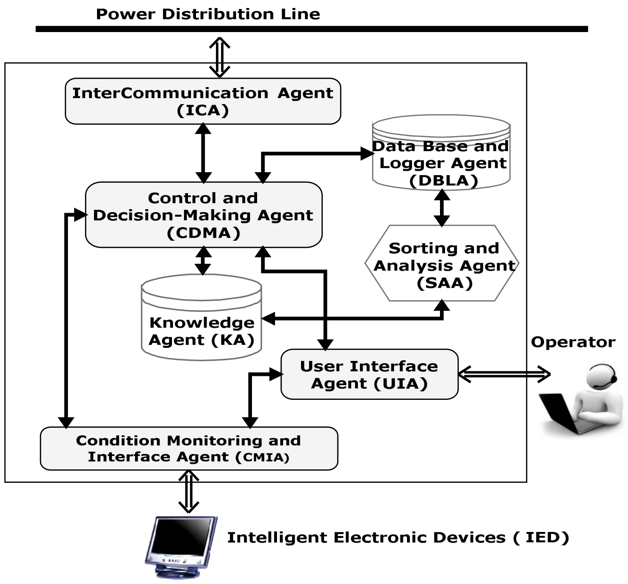

Fig. 3. JADE container of agents accommodate in substations

Section B: On the other hand after propagating fault isolation information from neighboring SSA agent to all other substations of primary line, all substations including SSAs and JSAs change their internal state behavior to PRS.
At this time all the modules perform restoration algorithm according to next section (Section 4).

IV. Restoration Algorithm

This proposed restoration algorithm concerning the isolated section of primary line that has no power i.e. Section B (see Fig. 5).
After the agents are entered to PR state, all primary line non-restored SSAs send restoration request packet include their attribute structure to adjacent agents at all sides (e.g. Fig. 5, SSA 1 sends to SSA 2 and 3), and then adjacents add their attribute structure to received information dynamically and send toward alternative direction(s) (Fig. 5, SSA 3 sends to JSA 1). Generally this propagation procedure stops at JSAs within a custom *restoration timeout* before make any decision. The JSAs collect attribute structures from other SSAs through gathering request packets of their zone within the timeout, after the timeout finish, JVMs won't accept any request from other SSAs. The restoration timeout may vary for each JVM due to its network topology zone and shall be defined by operator. In special case where propagating requests reaches a SSA with more than two neighbors (i.e. a grid junction), the SSA sends toward all directions that has JSA (e.g. Fig. , SSA 5 sends information of SSA 6 and 7 to JSA 1 and 2).
As soon as the time out is finished, each JVM start to construct mesh-structured model of its network zone from collected information.
Since each JSA gather information about its alternate CBAs capacity, in order to have better load flow and load management between JSAs, each JSA propagates its information to other JSAs via primary line and/or secondary line (if connected) and detecting whether any JSA exist with same alternative CBA or not. If there exist, the community of JSAs will be formed, and considered as one agent called *Augmented Junction Substation Agent (AJSA)* consists of 2 or more JSAs with same alternative power source through a

citcuit-breaker (e.g. Fig. 5, SSA 1 and 3 consider as a AJSA). In this case the first JSA of AJSA (i.e. JSA 1) gain control of the JSAs community (AJSA) as *master* and the other one will be *slaves*. The master JSA collect all information of sub-network and augment to its information from other ones. As a result the mesh-structured of sub-network become bigger sizeable and more complicated. Slave JSA(s) (i.e. SSA 3) won't interfere the power restoration procedure since now.

Now the JSAs and AJSAs start to implement following problem on their sub-networks and then finish PR state by perform switching action of results on SSAs.

A. Binary Knapsack Problem (KP)

The *knapsack problem* or *rucksack problem* is one of the most intensively studied discrete programming problems. KP has been studied through different approaches, according to the theoretical development of *Combinatorial Optimization* [26-29].

Given a set of *n items* and a *knapsack*, each item has a weight and a value, determine the number of each item to include in a collection so that the total weight is less than a given knapsack capacity and the total value is as large as possible.

p_j = *profit* of item *j*

w_j = *weight* of item *j*

c = *capacity* of the knapsack

Select a subset of the items so as to

$$maximize \quad z = \sum_{j=1}^{n} p_j x_j$$

$$subject\ to: \quad \sum_{j=1}^{n} w_j x_j \le c$$

$$x_j = 0 \ \text{ or } \ 1 \qquad j \in N = \{1, \cdots, n\}$$

$$where: \quad x_j = \begin{cases} 1 & \text{if item } j \text{ is selected} \\ 0 & \text{Otherwise} \end{cases}$$

B. Binary Knapsack Problem (KP) Representation

Here JSAs and/or Augmented JSAs (AJSAs) playing the knapsack roles. Capacity of knapsacks represents capacity of alternative power sources of each JSA. We assume each MV substation as items which will placed in knapsacks and each substation has known post-fault capacity (weight) and profit concern with neighboring JSA(s). The profit of SSA could determine the priority of restoring SSA in each step of PRS procedure.

The following factors may consider specifying the profit of SSAs:

1. Distance from substation to JSA
2. Number of JSA(s) that can support substation
3. Capacity of SSA
4. Number of adjacent substation near SSA

C. Power Restoration (PR) State Algorithm Procedure:

The JSA or AJSA at the first grid's junction (Fig. 5, JSA 1), decides which neighboring SSAs of its sub-network could be restored according to its capacity, SSA's capacity and SSA's profit.

In order to restoration procedure, each JSA implementing KP over its network zone sequentially.

The PR procedure continues until the last SSAs restored by JSAs and/or the JSAs remaining capacity is over. In this case the substations restored by perform switching actions and isolate SSAs from other part of network, and then JSAs close their switches in order to restore power.

V. CASE STUDY

In Large-scale systems centralized control such as SCADA may not be practical; in order to outage management and protection of local interventions where disturbance originates, distribution of intelligence and decision-support systems could be an alternative strategy [30].

Multiagent models are oriented toward autonomy, cooperation and planning. Proposed MAS 3-layered articeture depend on both agent environment and the coordinated process simulation.

In such cases the implementation are faced to the 1st Layer for substation simulation and the 2nd Layer for fault localization and isolation and the 3rd Layer for supervising and decision making in order to power restoration (see Fig. 2) with collaborations between JSA agents.

The MV distribution systems as depicted in Fig. 5, the distribution system has primary line where the fault occurred, and has some secondary lines are the alternative power sources for primary one.

In this section, a real scenario from Tehran power distribution network was selected which examine the performance of proposed MAS algorithm.

The first step of our implementation aimed at showing the ability of MAS and working agents together and illustrating communications between several agents.

Authors are developed MAS under *JADE* framework with *Agent-Oriented Programming (AOP)*. The important thing is selecting and implementing agent behavior. An agent can execute several behaviors concurrently. According to MAS architecture *Finite State Machine (FSM) behavior* is selected as main behavior (Fig. 4).

For each task of corresponding state sub-behaviors such as *One-shot* behavior for complete in one execution phase tasks, *Cyclic* behavior for never complete tasks, *Ticker* behavior for repetitively tasks in specific period of time, *Composite* behavior include *Sequential* behavior and *Parallel* behavior for doing complex tasks.

VI. SIMULATION RESULT

In this section, the MV distribution system of Fig. 6 has been simulated in order to illustrate conclusions related to implementation of the cooperative system. The simulation concerning Primary Line which powered by CBA 1 and the fault between Section A and Section B (i.e. SSA 1 and 16). Secondary Lines are alternative power sources which have also several SSAs and have limited power capacity. The simulated distribution system has 16 SSAs (Fig. 5, small black squares) on primary line which 15 of them placed in Section B.

There are 3 JSAs on primary line which JSA 1 and 3 as a AJSA and have same alternative power source (CBA 2) regarding to Secondary Line 1. JSA 2 has different alternative power source (CBA 3).

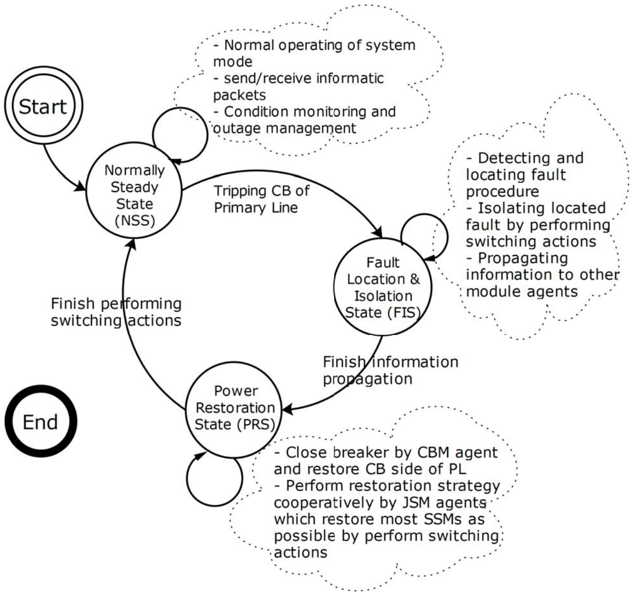

Fig. 4. Finite State Machine (FSM) diagram of proposed agents behavior

A. Premises

The Secondary Line 1 regarding to CBA 1 excessive loading capability may restore 1200 kVA power. The Secondary Line 2 which has CBA 3 has 650 kVA excessive loading capacity.

The fault occurred between Section A and Section B, located near SSA 1 at the side of CBA 1.

In order to implementing Binary Knapsack Problem recurrently, the profit of each SSA regarding to each JSA and pre-fault capacity of each SSA, shown in Table. II (Appendix B).

B. Results

The simulation focuses on the Sect. B power restoration which needs to implement complicated algorithm. The other section (Section A) will be restored as soon as the fault isolated.

VII. Conclusion

The implementation of the presented MAS technology in this work offer acting independently with desirable autonomy, in term of self outage management and protection of Tehran power distribution network. This technology also brings advantages over centralized control systems such as flexibility, reliability, adaptability, scalability and extensibility over future extensions like connecting Distributed Generations (DGs) to network.

The proposed 3-layered MAS architecture provides a reliable system and regarding to working state of system, switching between layers adaptively. Moreover according to the designation and determined agents behaviors, MAS is permitted to perform coordinated action without collision among agents and their tasks; thus robustness as a result of it.

In this approach new application in JAVA with PROLOG interface was developed, provide us novel representing power restoration problem as Binary Knapsack Problem (KP) and making decision with expert system by cooperatively solving among community of Junction Substation (JSA) agents.

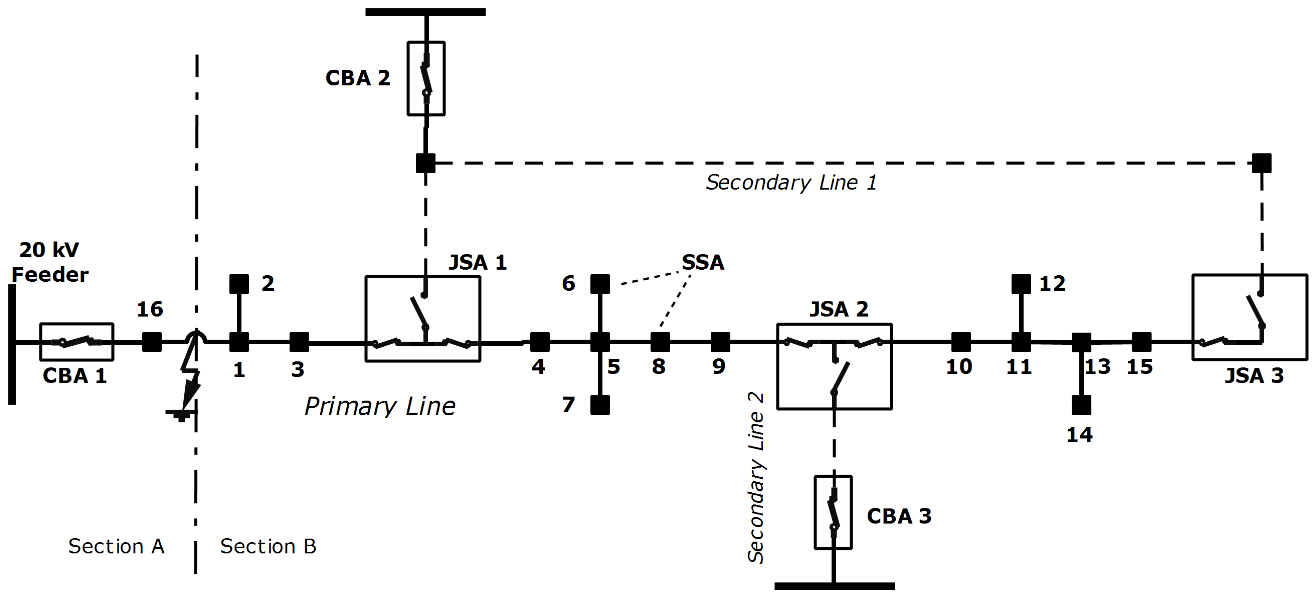

Fig. 5. Test case network topology (part of simplified Tehran MV power distribution network)

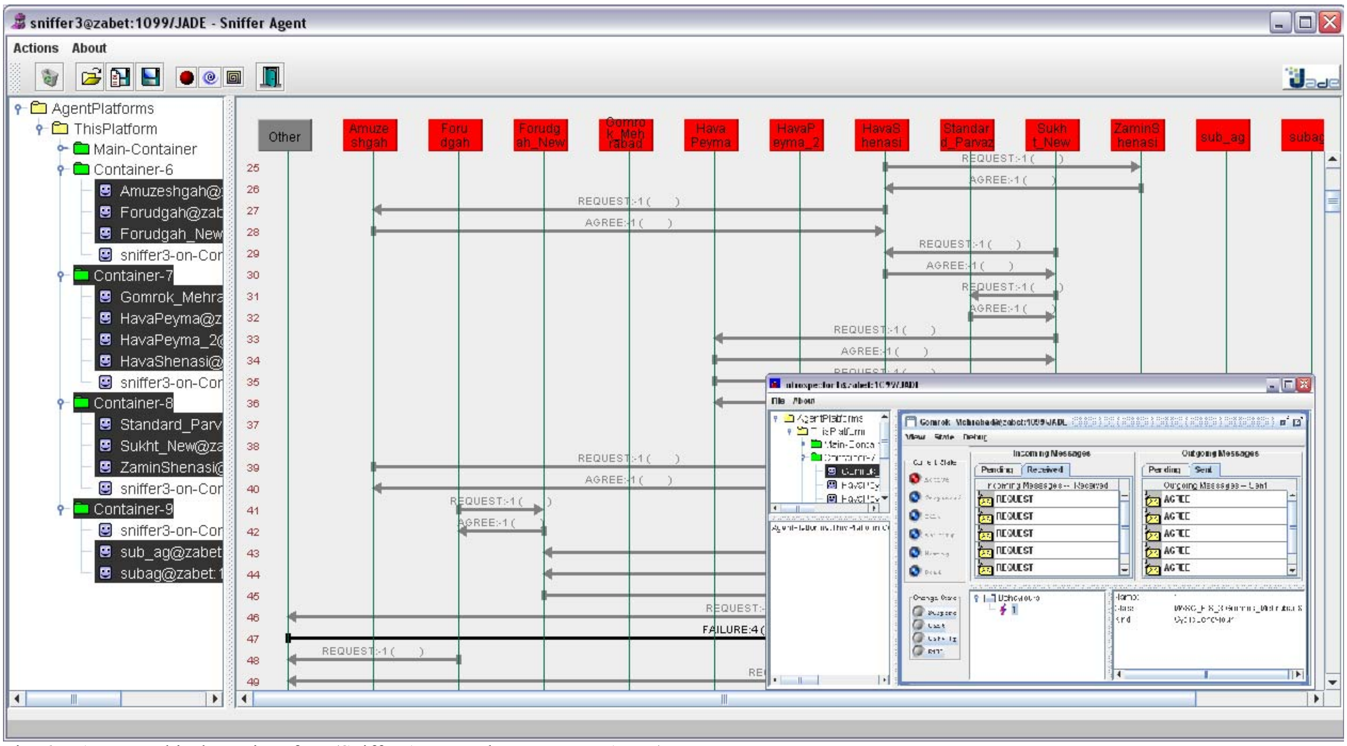

Fig. 6. JADE graphical user interface (Sniffer Agent and Introspector Agent)

In same time in spite of the fact that above efficiencies of distribution with MAS technology, some deficiencies like increasing communication between agents, increasing complication of system exist.

APPENDIX A

Each substation is equipped with backup power supplies, motorized switches mechanisms and IEDs for data acquisition, record electrical parameter and fault detection [9]. *Power-Line Communication (PLC)* with MV modems is considered for enable a communication channel for agent's communication.

As depicted in Fig. 1 we defined *primary line* which refers to the line of circuit-breaker that fault will occurred in it and *secondary lines* which supporting primary lines with other circuit-breakers and alternative power sources, have been isolated with normally open switches.

There are 3 types of distribution network element considered:

1) *Circuit-Breaker Agent (CBA):* This module accommodated at the terminals of lines near MV circuit-breakers. They monitor and maintain circuit-breakers conditions, transmit remaining capacity of circuit-breaker to adjacent substations of their primary line and receive from adjacent substations of lines.

2) *Simple Substation Agent (SSA):* This module of distribution network refers to substation that fed uni- or bi-directionally in both radial or ring network structure.

3) *Junction Substation Agent (JSA):* This module refers to 20-kV substations that placed on the distribution line junctions and should feed by two or more 20-kV feeders. Since these agents make power restoration decisions, they should be more critical.

Another communicating way such as wireless communication among JSAs is recommended but not imperative.

These three agents operate individual tasks and make decisions intelligently depend on the MAS states and layers, we called them individual *agents* according to its layer and task. SS, JS and CB agents have to cooperate and collaborate with each other and finally make best decision

TABLE I
RESULTS OF POWER RESTORATION ALGORITHM

	JSA 1&3				JSA 2			
		Restoration				Restoration		
	SSA	Power*	Profit	R.C**	SSA	Power	Profit	R.C
Step 1	3, 4, 15	370	300	830	9, 10	250	190	400
Step 2	1, 5, 13	300	260	530	8, 11	230	165	170
Step 3	2, 6, 7, 14	480	265	50	12	120	70	50
Total		1150	825			600	425	

1750 kVA power restored (94.59 %), and 1250 profit gained

*Power restored in kVA
**R.C = Remaining Capacity

with respect to their states and layers as discuss later.

APPENDIX B

Table 1 contains of premises about capacity and profit of each SSA. We noted that since SSA 1, 2 and 3 aren't neighbor of JSA 2, those profit concern as zero relate to JSA 2.

TABLE II
PREMISES CAPACITY AND PROFIT* OF SSAS**

	Capacity (kVA)	Profit w.r.t. JSA*** 1 & 3	Profit w.r.t. JSA 2
1	100	80	0
2	80	70	0
3	150	100	0
4	100	100	40
5	120	90	70
6	100	60	45
7	120	65	50
8	150	50	90
9	150	30	100
10	100	20	90
11	80	45	75
12	120	25	70
13	80	90	65
14	100	70	50
15	120	100	40
Total	1670	995	785

*Profit numbers are normalized and shown in percent
**SSA = Simple Substation Agent
***JSA = Junction Substation Agent

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