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Automatic restoration system for power distribution networks based on multi-agent systems

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Abstract: The advance on smart grid calls for the development and application of distributed intelligent control strategies based on open platforms that provides interoperability. The distributed control must be able to ensure reliable and secure operation of the power systems and enhance supply quality to consumers. The development of a multi-agent system for automatic restoration system (MARS) applied to a real power distribution network is presented. The agents of the MARS are embedded in external hardware to the intelligent electronic devices (IEDs) and communicate with each other via standard Foundation for Intelligent Physical Agents open protocols. To evaluate the MARS performance, a computer simulator was developed in Java to represent the distribution system. Experimental tests were performed in laboratory with the simulator integrated to the MARS via TCP/IP. The tests results have shown that the MARS was able to locate and isolate branches under permanent fault condition and restore healthy branches efficiently through a given switching sequence taking into account the system operational constraints. The proposed MARS has proved the effectiveness of distributed control scheme based on multi-agent system that runs independently of the current technologies of the IEDs of control and protection.

1 Introduction

In recent years, the electricity sector in many countries has experienced significant changes to become more efficient, reliable, cost-effective, competitive and environmentally sustainable. Many changes are driven by the smart grid concept that brings together technological solutions to infrastructure modernisation, control, automation and crescent incorporation of information and communication technologies [1, 2]. The main features of smart power grids are integration of different types of energy generation and storage resources, efficient use of grid assets, efficient operation of the power grid, automatic restoration, application of pervasive and active control, active participation of consumers and low environment impact [3].

With the development of smart grids, autonomous and intelligent distributed systems have been to a great extent pursued for application onto power systems [4, 5]. Multi-agent system is a suitable technique to that due to their important characteristics of autonomy, local views and distributed control [6, 7]. Various developments and implementations of multi-agent systems applied to smart power systems can be found in the literature [8]. The following are some application areas: reactive power dispatch [9], monitoring of service quality [10], adaptive protection [11], control of microgrid [12], state estimation [13], distribution transformer management [14] and automatic restoration systems [15–24].

Although there have been numerous advances, most restoration systems continue to require further advances in the domain of power systems. The goal of automatic restoration systems is to isolate the fault to reconfigure the grid and restore the power supply in a flexible and intelligent fashion based on real-time monitoring. Such system must prioritise safe restoration without violation of operational constraints, while minimising the affected portion of the system [20].

This paper aims to develop and evaluate a multi-agent-based automatic restoration system (MARS) for power distribution systems. A computer simulator with the power distribution network was developed in Java and the MARS in Java Agent Development Environment (JADE), an open architecture framework based on Foundation for Intelligent Physical Agents (FIPA) standard that enables the development of interoperable, flexible, expandable and fault tolerant agent systems. The MARS agents were distributed in four computers connected in WLAN via TCP/IP protocol to exchange information with the distribution network. Tests have shown that the MARS is able to exchange bidirectional information with the intelligent electronic devices (IEDs) based on the IEC 61.850 to restore the power distribution system.

The rest of the paper is organised as follows: Section 2 describes the strategies and techniques for the development of service restoration in power networks. The concepts of agent and multi-agent systems are presented in Section 3. Section 4 deals with the characteristics of the MARS. The simulator for testing and validating the MARS is described in Section 5. Sections 6 presents the workbench tests and discussion of the results. Finally, the main conclusions are given in Section 8.

2 Centralised and distributed approaches for restoration systems

In recent decades, researchers worldwide have been investigating different methods for the development and implementation of automatic restoration systems [25]. The main advantages of these systems are the support given to the system operators, the reduction of operation and maintenance costs, the outage curtailment and the improvement of power quality indices that involve the customers' satisfaction and the supply reliability [25].

Typically automatic restoration systems are based on different development models, notably: knowledge-based systems, heuristic search, fuzzy logic, optimisation, artificial intelligence, Petri net, genetic algorithm, ant colony search algorithm, tabu search, artificial neural network and hybrid models [25]. All these methods use centralised architecture. However, there is a great lacunae of work that relates to distributed architectures which are increasingly becoming commonplace.

Multi-agent systems have been pointed out as one of the most promising approaches for the achievement of automatic restoration function in a distributed architecture [15–24]. To accomplish this, each agent in a multi-agent network cooperates with each other to fulfil a common goal. The cooperation occurs in the form of coordinated control between the agents using the information from the network. Each agent may have limited resources, e.g. communication, sensing or storage capabilities. As a result, a centralised control algorithm is not feasible since not all the global information is available to each agent [26].

The international standard IEC 61.850 for substation automation, definitely breaks up the paradigm of automation functions for power networks, based solely on centralised control architecture. It establishes communication services for vertical communication (Client/Server mode), between IEDs and substation control unit, horizontal communication (Publisher–Subscriber mechanism) between IEDs and object oriented data model that provide interoperability between devices from different manufacturers [27]. The IEC 61.850 represents the trend to develop new generation of power system automation with distributed and smart functions at the various hierarchical levels of the automation system. These functions are able to solve local as well as systemic problems covering more than one electric plant [24].

However, the IEC 61.850 in itself presents limitations for the development of automatic restoration functions applied to power networks [14]. Much of the literature focuses on agents of automation restoration systems operating as an internal function of the IEDs [28, 29]. Due to the lack of suitable logical nodes for the multi-agent automation restoration system, [24] propose the revision of the standard with inclusion of new nodes.

Currently, the abstract data model as defined in IEC 61.850 can be mapped to Manufacturing Message Specification (Client/Server type), Generic Object Oriented Substation Event (GOOSE) (Publisher–Subscriber mode) and Sampled Measured Values (Publisher–Subscriber mode). These protocols can run over TCP/IP network using high-speed switched Ethernet to obtain the necessary response times <4 ms for protective relaying. GOOSE protocol is defined for fast transfer of event data for a peer-to-peer communication mode. However, it does not allow negotiation between agents, as does the ContractNet protocol established by FIPA. Further, there are many automation systems that use other protocols than those defined in IEC 61.850, as for instance DNP 3.0, which do not have features to make possible the development of distributed functions for troubleshooting sites, via communication between IED.

The main contribution of the proposed MARS includes the use of multi-agent along with the IEC 61850 or any other communication protocol that enables information exchange via TCP/IP. Such achievement indicates that the IEDs most usual communication protocols can be preserved and explored in innovative solutions to smart grids. A further contribution is the FIPA interoperable agents loaded in external hardware, making the MARS independent of the IEDs' current technologies and protocols.

Table 1 Description of the agents

Agents	Tasks performed by agents
Substation (AS)	Receives data from EA, sends message to EA to isolate the faulty section and sends message to FA to initiate the restoration process
Feeder (FA)	Performs negotiation of available power with other FA by sending or responding request messages; FA that initiated the conversation evaluates the received proposals and chooses the proposal of highest power; FA initiates conversation with the BA that is responsible for evaluating the operation constraints
Branch (BA)	Receives an authorisation message from FA; evaluates the impact of restoration as the branches overload condition and if the available power is enough to restore the branch. If restoration is possible, the BA sends message to the EA; otherwise, the FA is informed
Equipment (EA)	Receives fault-related data from the IEDs and reports them to the associated FA in order to initiate negotiation of power to restore de-energised but healthy branches

3 Multi-agent systems

This section provides a brief introduction on standards and terminology used by FIPA regarding multi-agent systems and the platform JADE that are used in the development of the proposed MARS. Further details on the topic can be found in [30–33].

Agents are hardware or software entities with high level of abstraction, resident in a given environment, with the ability to interpret data and run autonomous actions that change the environment state [28–31]. They have characteristics such as autonomy, reactivity, proactivity and sociability. These are intrinsic abilities of intelligent entities [31]. They are characterised by their behaviour and ontology. Ontology is a specification used for the purpose of enabling knowledge sharing and reuse by an agent or a community of agents.

FIPA is an IEEE Computer Society standard organisation, established in 1996, that promotes agent-based technology and the interoperability of its standards with other technologies [32]. The model protocol defined by FIPA is service-oriented, where the application layer has multiple sub-layers rather than only one as in the OSI or TCP/IP models. The agents can interact by using a set of FIPA defined iteration protocols, e.g. FIPA-Request Protocol, FIPA-ContractNet and FIPA-Subscribe [30]. These are the protocols used in this work. FIPA-Agent Communication Language (ACL) is a standard language for agent communications.

JADE is an open source platform used for implementing multi-agent systems through a middleware that conforms to the FIPA standard. JADE is implemented in the Java language for peer-to-peer agent-based applications [34]. Each platform has a special container that includes the Agent Management System (AMS) and the Directory Facilitator. The AMS is mandatory and provides white page service.

FIPA protocols are of fundamental importance for the cooperation and negotiation between agents. The main functionalities of the agents use message exchange service. In JADE, messages are objects that adhere to the ACL standard and have attributes such as content, protocol, message type and receiver(s).

In the MARS agent communication process, three FIPA protocols are used: FIPA-Request, FIPA-ContractNet and FIPA-Subscribe.

4 MARS

4.1 Multi-agent system architecture

Four classes of agents are defined: substation agent (SA), feeder agent (FA), branch agent (BA) and equipment agent (EA). Upon the occurrence of a permanent fault, the MARS performs the following tasks or functions: identifies the fault location, isolates the healthy branches affected by the fault, negotiates the reserve of power, analyses the operational constraints of the network and restores the healthy but de-energised branches, whenever is possible. The tasks of the agents are described in Table 1.

4.2 MARS formulation

As aforementioned, the developed MARS is capable of detecting faults, isolate healthy branches, reconfigure the network and restore supply safely according to priority criteria defined by utilities. To achieve a proper restoration, the MARS maximises an

Table 2 Data stored in XML file

Agents	Data/attributes
Substation	Name, status and equipment
Feeder	Name, status and equipment
Branch	Name, maximum loading, rated loading, number of customers, number of special customers and number of priority loads
Equipment	Name, code, status and communication port

objective function given as

$$\max \sum_{i \in A} W_i \qquad (1)$$

where $i \in A$ is the set of all system branches and W_i can be related to the number of customers, or the number of special customers at each branch i.

For a safe restoration, the MARS must examine the network conditions and perform the restoration without operational constraints violation. In this paper, the considered operational constraints are the transformers capacity limit at the power substations and the branches capacity limit of feeder cables, represented, respectively, by (2) and (3)

$$\sum_{j \in T} S_j < S_{\max,k} \qquad (2)$$

$$S_{j \in T} < S_{\max} \qquad (3)$$

$$I_i < I_{\max} \qquad (4)$$

$$I_{i \in A} < I_{\max} \qquad (5)$$

where $j \in T$ is the set of transformers of a substation, $i \in A$ is the set of system branches, S_j is the transformer capacity k,$S_{\max,k}$ is the total capacity of the power substation k. I_i is the current through a given branch i and $I_{\max}$ is the thermal limit of the branch.

The MARS checks if the transferred load due to the system reconfiguration does not cause overload in the substation responsible for the restoration and the increased load current through the feeder does not exceed the current capacity of the cables.

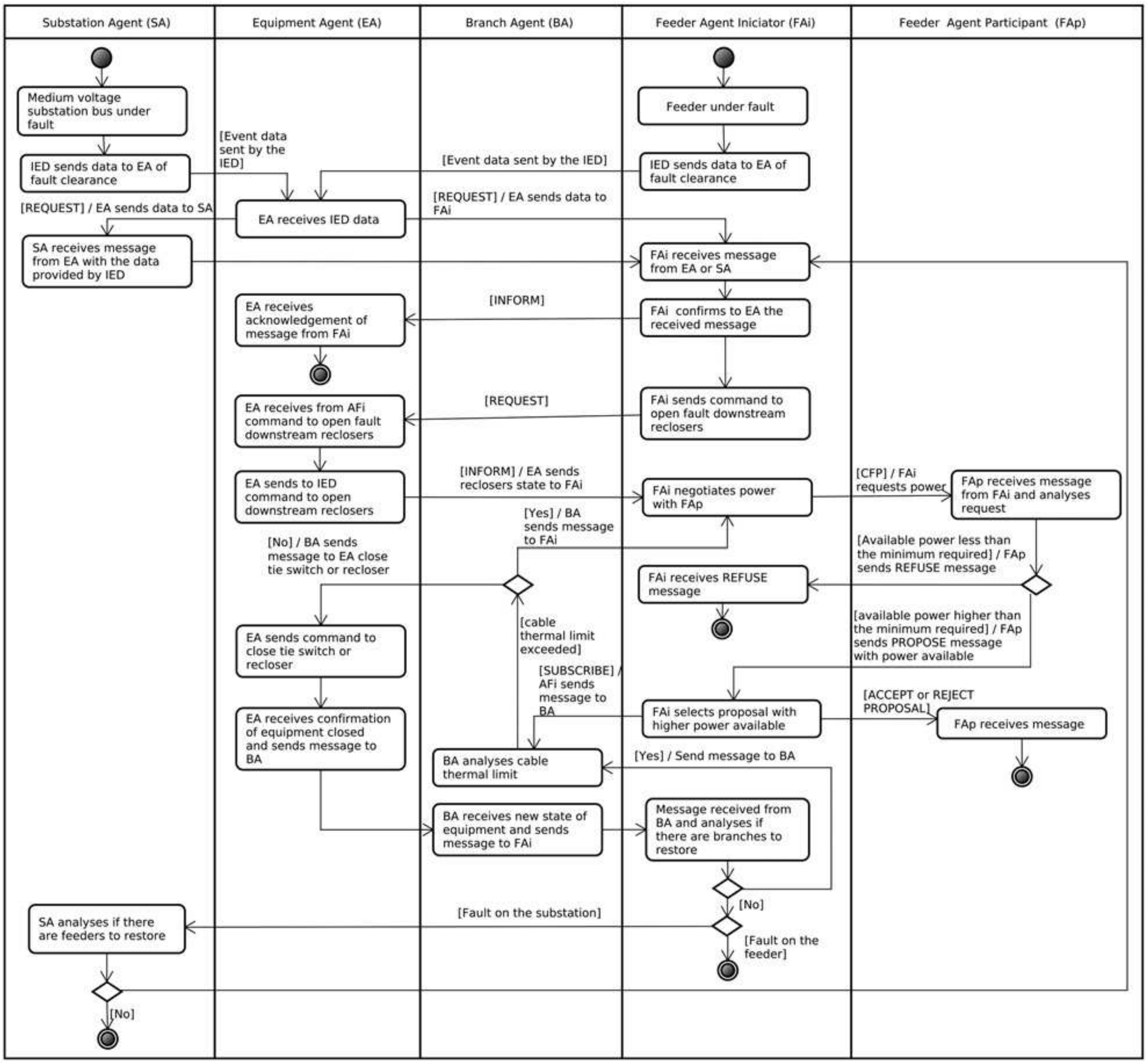

Fig. 1 *Modelling communication between agents for the restoration of the power network*

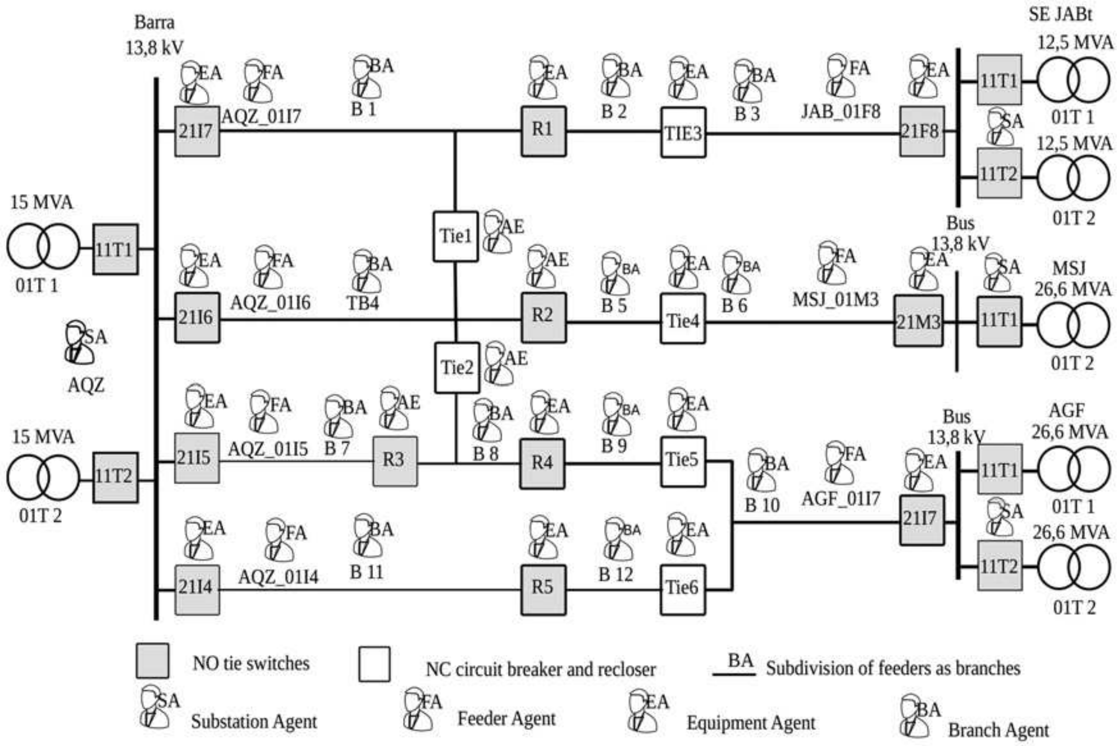

Fig. 2 *Distributed agents in the substations and the network*

4.3 MARS data model

eXtensible Markup Language (XML) is used for knowledge representation of all related restoration data. Table 2 presents the required data accessed by the FAs for the analysis and reconfiguration of the power distribution system.

4.4 Specification and modelling of MARS

From the implementation point of view, the MARS agents are software entities with intelligence embedded in hardware external to the IED (e.g. relays/control equipment).

The restoration system operates from information provided by IEDs and is not dependent on a centralised control system. Next, the MARS agents' behaviours are explained.

The SA manages the configuration of feeders affected by the loss of transformers in the substation. The FA negotiates power with other FAs and manages the recovery of each branch. The BA performs the restoration of branches by analysing the operational constraints of the power network. The EA represents the interface with the IED associated to the primary equipment (e.g. breakers, reclosers and switches). The IEDs provide data to the MARS via EA.

The EA uses the FIPA-Request protocol to send a message to FA following the occurrence of a fault. FA returns a message of the type INFORM confirming the receipt of the message.

The FA uses the FIPA-ContractNet protocol and sends message of the type Call for Proposes to all agents that can physically answer a request for solving a problem. It is used, for instance, when an initiator FA wishes to negotiate power with other neighbour FAs. The participant agents respond with a type PROPOSE or REFUSE message. When all messages are received, the initiator FA chooses the best proposal and then sends ACCEPT-PROPOSAL and REJECT-PROPOSAL, correspondingly. It is worth pointing out that the negotiation is made for each no restored branch individually; however, the command to restore power takes place once after completion of the analysis of all branches.

FIPA-Subscribe protocol is used for communication between FA and BA. When the branch restoration is possible, a message of the type AGREE is sent to the FA; otherwise, a message FAILURE is sent so that the negotiation for restoration of another branch is initiated.

The SA sends message to EA to isolate the faulty section and to FAs to initiate the restoration process. To perform the required negotiations, the FA uses the FIPA-Subscribe protocol.

The illustration of the modelling communication between the agents for the restoration of the power network is shown in Fig. 1.

Table 3 Branches data

Substation	Bay	Transformers nominal current, A	Transformers overload limit, A
AQZ	01T1	628	754
	01T2	628	754
JAB	01T1	524	629
	01T2	524	629
MSJ	01T1	1114	1337
AGF	01T1	1114	1337
	01T2	1114	1337

5 Power network simulator for MARS testing

This section presents the implementation of the MARS in a test workbench in the Power Systems Laboratory of the Federal University of Ceará, in Brazil.

5.1 Test system

A computer simulator was developed in Java to represent a real medium voltage distribution system for testing the MARS. Four power substations supply the 13.8 kV network: Aquiraz (AQZ), Jabuti (JAB), Messejana (MSJ) and Agua Fria (AGF). The substation AQZ has four output feeders (AQZ_01I4, AQZ_01I5, AQZ_01I6 and AQZ_01I7) while the others only one feeder, namely JAB_01F8, MSJ_01M3 and AGF_01I7. The medium voltage network has nine reclosers (21I4, 21I5, 21I6, 21I7, R1, R2, R3, R4 and R5) and six normally open (NO) tie switches (Tie1, Tie2, Tie3, Tie4, Tie5 and Tie6) for load transfer. The

Table 4 Branches data

Feeder	Branch	Load, A	Total current, A	Cable thermal limits, A	Number of consumers
AQZ_01I7	B1	12	244	475	300
	B2	232	232	475	250
AQZ_01I6	B4	33	183	438	350
	B5	150	150	232	400
AQZ_01I5	B7	54	331	475	350
	B8	120	277	475	300
	B9	157	157	242	250
AQZ_01I4	B11	164	203	475	200
	B12	39	39	438	300
JAB_01F4	B3	165	165	475	200
MSJ_21M2	B6	263	263	438	300
AGF_21I1	B10	343	343	525	350

reclosers and tie switches partition the network in 12 sectors or branches (B1–B12).

Fig. 2 shows the radial topology of the Aquiraz system, with the agents (SA, FA, BA and EA) distributed along the substations, feeders and equipment. Under normal operating conditions, the feeders (AQZ_01I4, AQZ_01I5, AQZ_01I6 and AQZ_01I7) are supplied by the substation Aquiraz (AQZ). The tie switches NO and the breakers normally closed are represented by rectangles in white and grey colours, respectively.

When a sustained fault occurs on the network, the MARS is executed to restore the power considering the network constraints to assure a safe restoration. The switching of the tie switches must maintain the radial configuration of the network.

After a sustained fault is cleared, the MARS agents interact, negotiate, cooperate and perform the automatic network restoration. In this process of cooperation and socialisation of information, the agents perform the following tasks/functions: locate and identify the fault, isolate the sectors affected by the fault, negotiate reserve power, evaluate the operating constraints and restore the sound branches.

Table 3 presents the nominal and overload current of the substation transformers. In case of a transformer outage, a limit of up to 120% of overload of the remaining transformer was admitted for 30 min utmost.

Table 4 presents data of the currents and the number of consumers in each branch of the distribution network.

These data are stored in an XML file and accessed by the MARS. The current measured corresponds to the load demand in each branch. The current in a sector equals to the total current measured at the beginning of the branch.

5.2 *Integration of simulator and MARS*

The simulator was provided for verifying the power distribution system integration on an external multi-agent-based restoration system. Communication between the MARS and the IEDs is performed using the proxy agent available in JADE platform for communication via TCP/IP between multi-agent systems and external devices/software.

When the user simulates a fault on the distribution network, data is sent via TCP/IP to the MARS application that runs on the JADE platform. The agents analyse the fault condition and take actions to isolate the fault and to restore the power network.

Fig. 3 illustrates the integration of the MARS in the JADE framework, the power system simulator and the XML data base. The XML data file is converted to Java object using the JDOM library and is sent as a message to other agents that need to access information from the database during the restoration process. The EA updates the database periodically. The FA checks and modifies the XML data file during negotiation for power and restoration of the power grid.

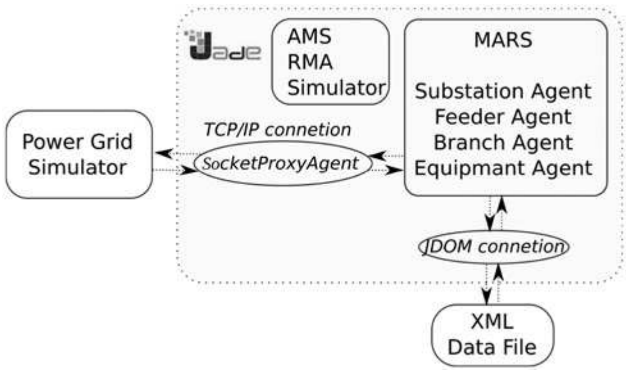

Fig. 3 *MARS integration to the simulator and the database*

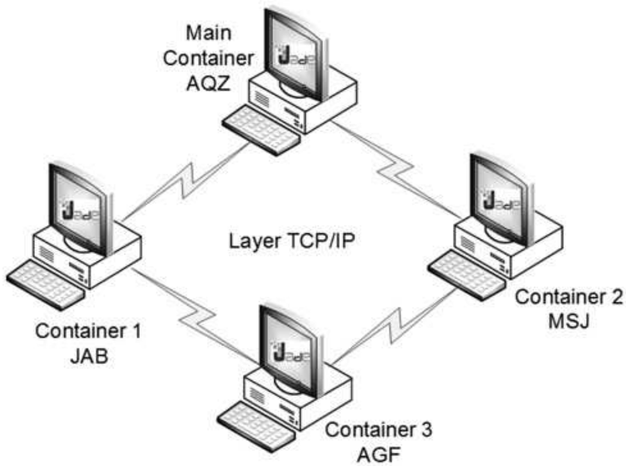

Fig. 4 *Test workbench of distributed multi-agent for automatic restoration*

5.3 *MARS topology*

MARS agents were distributed in four personal computers connected in a WLAN using TCP/IP protocol. Each computer has a container with agents related to a given substation of the test system. The computer with the AQZ substation hosts the main container that includes the AMS and the simulator. Fig. 4 depicts the test workbench topology.

It is worthy to mention that microcontrollers like Raspberry Pi or BeagleBone Black could be used instead of PCs to encapsulate the agents. The methodology adopted in the design of the proposed MARS takes into account the requirement of extensibility. Thus, the application tool can be easily applied to other power distribution networks.

5.4 *Case study*

Faults were simulated in all branches of the test system; however, as a matter of space, two case studies are presented: a fault on the transformer 01T1 in the AQZ substation and a fault on the B7 branch on peak demand condition.

5.5 *Case study 1*

For a fault on the 01T1 transformer, the transformer protection relays trip and the circuit breaker 11T1 opens to interrupt the circuit. Under maximum load condition, with the 01T1 transformer outage, the 01T2 transformer in parallel goes into overload and is taken out of service through the relay command associated to the 11T2 breaker. As shown in Fig. 5, both circuit breakers 11T1 and 11T2 are open and as a result, the 13.8 kV busbar of AQZ substation along with

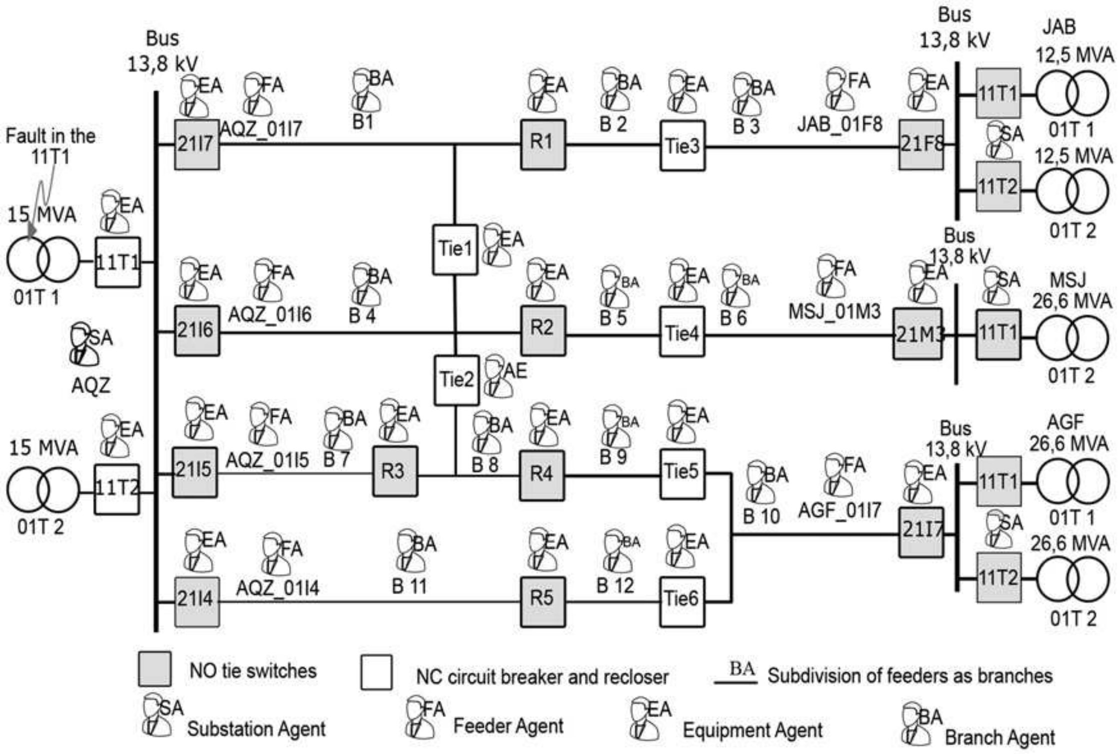

Fig. 5 *Fault on 01T1 transformer and breakers 11T1 and 11T2 opened by the protective relays*

the feeders AQZ_01I4, AQZ_01I5, AQZ_01I6 and AQZ_01I7 are all de-energised. Such scenario leads to ∼2650 customers without power supply.

Following the opening of the 11T1 and 11T2 circuit breakers, their corresponding IEDs send information to the EAs and the MARS initiates the automatic restoration of the feeders AQZ_01I4, AQZ_01I5, AQZ_01I6 and AQZ_01I7. The agents EA then send information to the SA AQZ that locates the outage transformer, identifies the overloaded transformer and sends the processed information to the FAs FA AQZ_21I4, FA AQZ_21I5, FA AQZ_21I6 and FA AQZ_21I7. These FAs analyse the received data and then they command the opening of the feeders' reclosers via the agents EA and the IEDs, isolating the 13.8 kV busbar, as illustrated in Fig. 6.

Once that the 13.8 kV AQZ busbar is de-energised, the agents FAs evaluate the data and make decisions based on the identification of the healthy equipment but disturbed by the faulty transformer, the analysis of 01T2 transformer capacity, the amount of load to be supplied and the number of costumers to be restored. From the analysis, the FAs send command message via EAs and IEDs for closing the circuit breaker 11T2, feeding the 13.8 kV AQZ busbar through the transformer 01T2, and closing of the 21I5, 21I6 and 21I7 autoreclosers in this sequential order. As can be seen in the one-line diagram in Fig. 7, the MARS decides not to close the recloser 21I4 to prevent the transformer 01T1 come to overload again. The AQZ_01I4 feeder has the smaller load and the fewer number of customers, and from this criterion the FA AQZ_01I4 has elected this feeder to be out of service.

The restoration of the AQZ_01I4 feeder is evaluated for each feeder branch. At first, the agent FA AQZ_01I4 sends a command message to open the recloser R5, isolating the branches B11 and B12, and evaluates the feasibility of supplying of the branch B11. However, the agent FA AQZ_01I4 attests that such measure would cause the output of the transformer 11T2 for overload once more. A negotiation between agents FA AQZ_01I4 and FA AGF_01I7 is then initiated for restoration of the two branches out of service. The agent FA 01I7_AGF returns message to agent FA 01I5_AQZ asserting availability to only supply of B12. The agent FA 01I4_AQZ grants the agent BA B12 of restoring the branch. The agent BA B12 does not identify any operational constraint violation and accredits the closing of the tie switch Tie6, restoring B12. Only the excerpt B11 is left without supply.

In this way, the MARS was able to restore safely the feeders AQZ_01I5, AQZ_01I6 and AQZ_01I7 through the substation AQZ, restore the branch B12 through the feeder AGF_01I7 from the substation AGF and no restore the branch B11 of the feeder AQZ_01I4 keeping the recloser 21I4 and R5 open. Fig. 7 shows the final configuration of the power distribution system following a fault in transformer 01T1 in the substation AQZ.

In this case study, 92% of the costumers affected by the outage in the transformer 01T1 were safely restored.

5.6 Case study 2

When a permanent fault occurs at the branch B7, the recloser 21I5 opens, and the MARS is initiated. The agent EA AQZ_21I5 receives information from the relay of the recloser AQZ_21I5 and then sends it to the agent FA AQZ_01I5. Next, the agent FA AQZ_01I5 sends command messages to the fault downstream EAs to open the reclosers R3 and R4. The agent FA AQZ_01I5 then initiates negotiation on power cooperation with the agents FA AQZ_01I6 and FA AGF_01I7 at substation AQZ and AGF, respectively, for restoration of the branches B8 and B9. The restoration is evaluated per branch, and the branch B8 is the first one to be assessed.

Fig. 8 shows the simulation results in which the reclosers R3 and R4 are open and the branches B7, B8 and B9 de-energised.

The first priority criterion set in the MARS is to transfer load between feeders of the same substation. Therefore, the agent FA AQZ_01I5 evaluates the proposal from FA AQZ_01I6. The agent BA B4 of the co-operator feeder evaluates the new upload condition of the branch B4 and yields no overload. The agent FA AQZ_01I5 accepts then the proposal from FA AQZ_01I6 to restore the branch B8.

The branch B9 is next evaluated. The proposal from the co-operator feeder FA AQZ_01I6 is also able to restore the branch B9. However, when the agent BA B4 evaluates the new upload

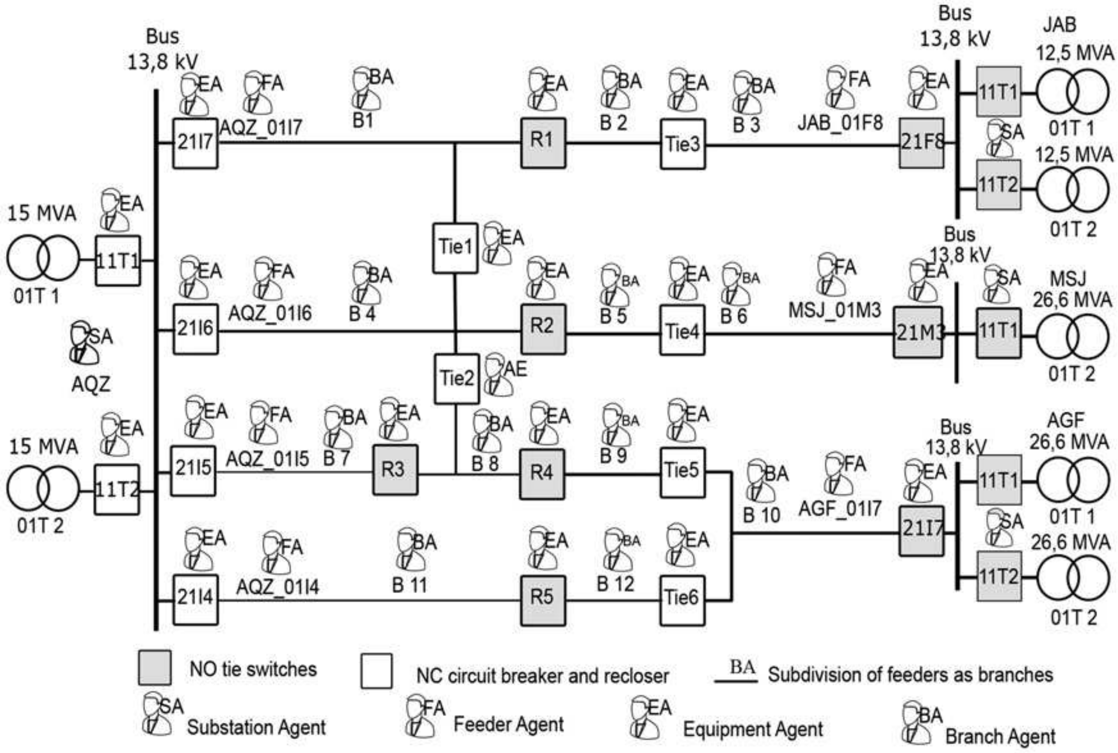

Fig. 6 *AQZ substation busbar de-energised*

condition of the branch, an overloading is found. The agent FA AQZ_01I6 informs to the initiator agent FA AQZ_01I5 and the proposal is rejected.

The agent FA AQZ_01I5 then evaluates the proposal from the FA AGF_01I7. The agent BA B10 evaluates the new upload condition and no violation is found. The agent FA AQZ_01I5 accepts then the proposal from the agent FA AGF_01I7.

The final step of the restoration process is switch on the reclosers and tie switches. The agents BA B8 and BA B9 send message to their respective EA to close the reclosers R2 and R3. Fig. 9 shows the final configuration of the distribution network. The restoration process ends up when there is no branch to restore.

As a matter of space, the sequence diagram illustrated in Fig. 10 is presented only to the test case 2. It describes the communication

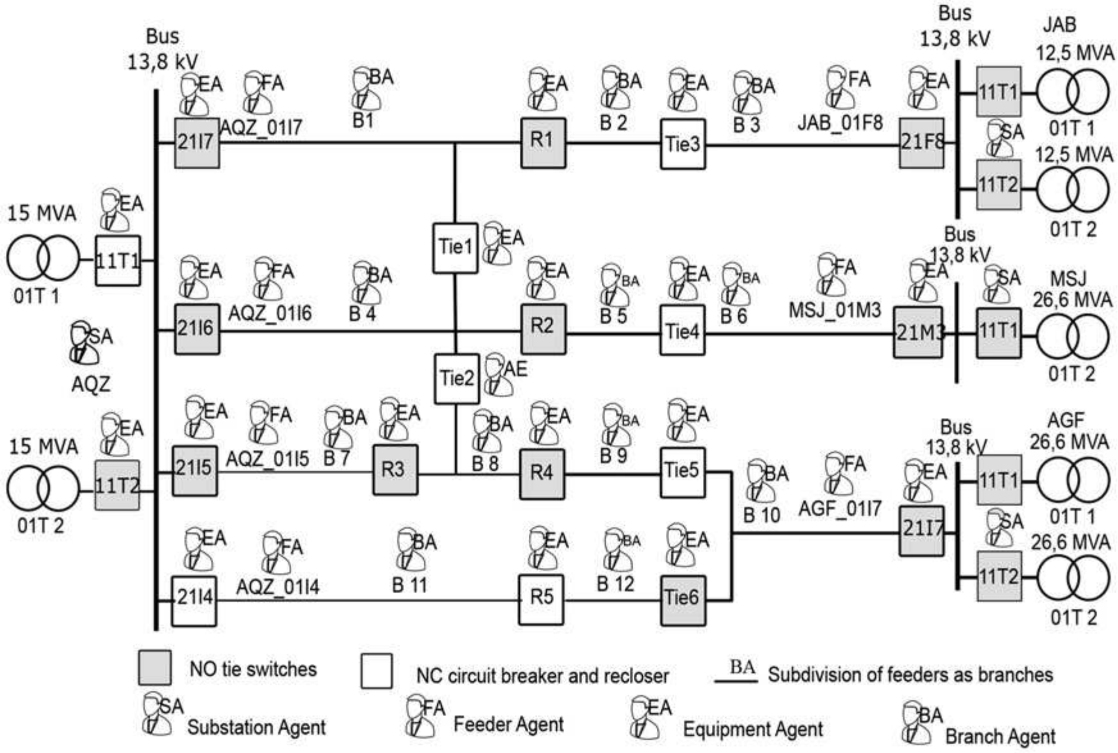

Fig. 7 *Restoration condition of the distribution system following a fault in 01T1 transformer*

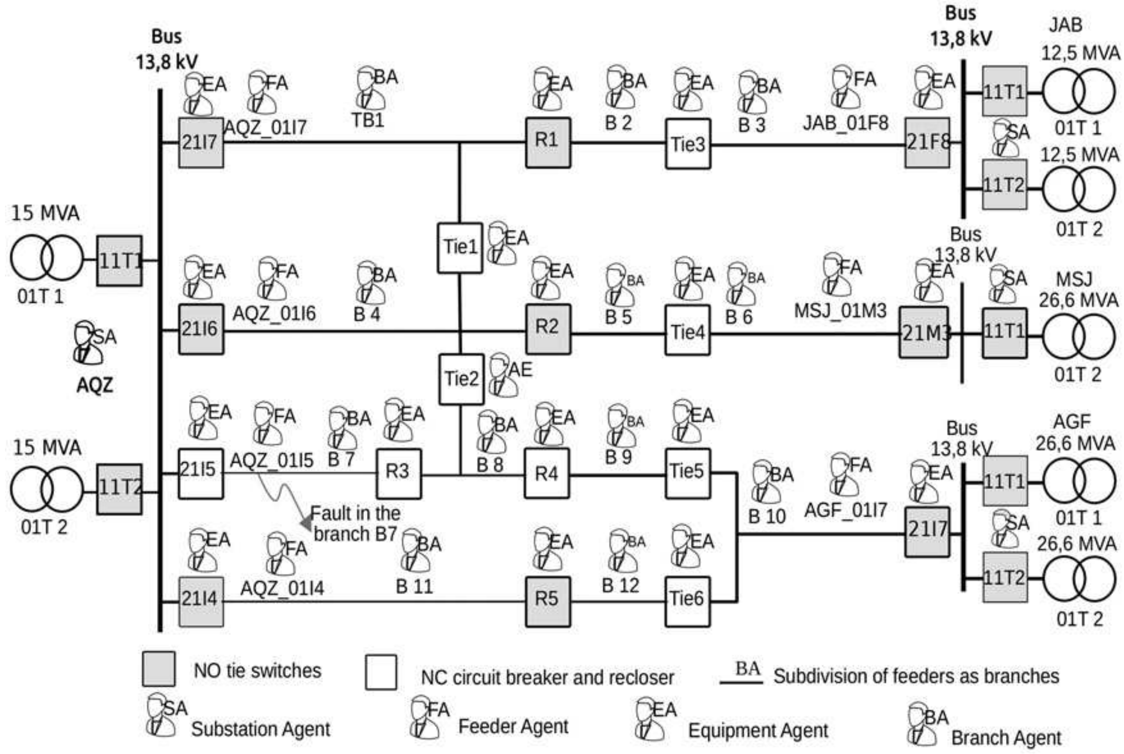

Fig. 8 *Distribution system configuration following a fault at branch B7 and the isolation of B7, B8 and B9*

between the MARS agents and the simulator when the distribution system goes through a fault in the branch B7. The diagram depicts the information exchange for restoration of the healthy branches B8 and B9 both of the feeder AQZ_01I5 through the feeder AQZ_01I6 from the substation AQZ and the feeder AGF_01I7 from the substation AGF, respectively. The diagram also highlights the protocols FIPA-ContractNet, FIPA-Subscribe and FIPA-Request, used for communication between agents during the recovery process of the power distribution network.

The communication between the simulator and the MARS is quite effective and the agents are able to interact, negotiate, cooperate and perform their tasks for the network restoration according to the criteria defined in the designed application. The proposed MARS is able to locate and isolate branches under permanent fault and

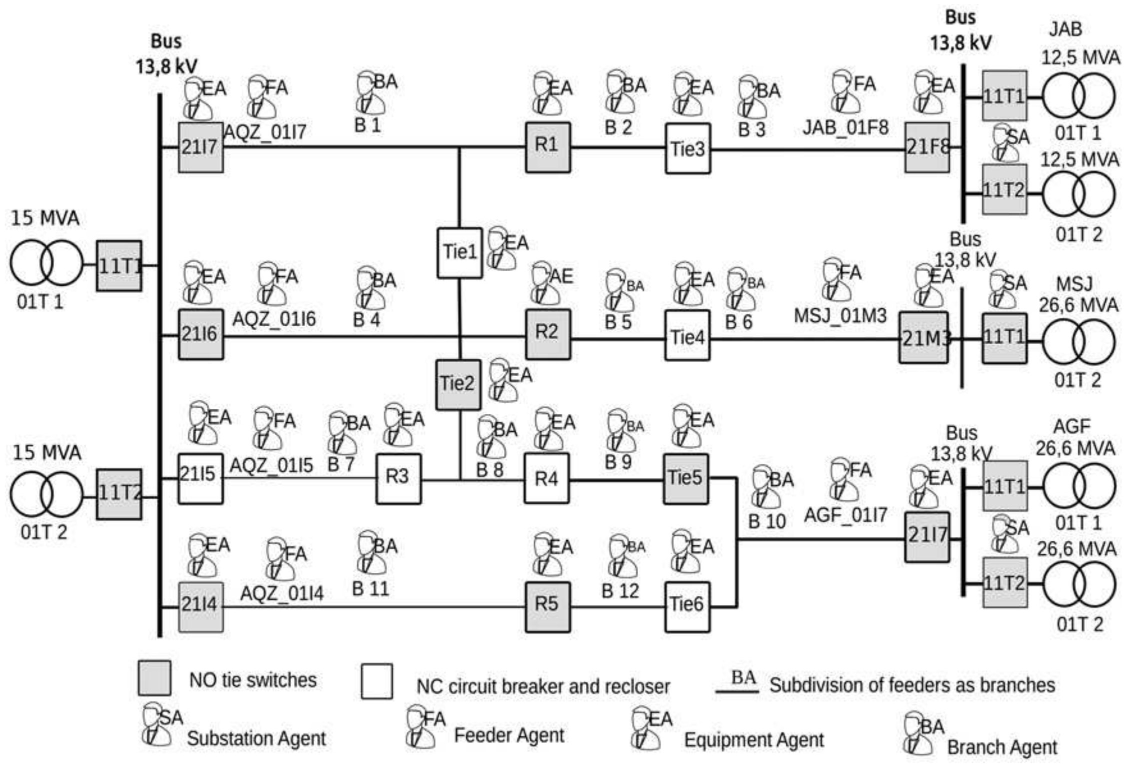

Fig. 9 *MARS isolates T7 branch and recompose the T8 and T9 branches*

IET Gener. Transm. Distrib., 2017, Vol. 11, Iss. 2, pp. 475–484

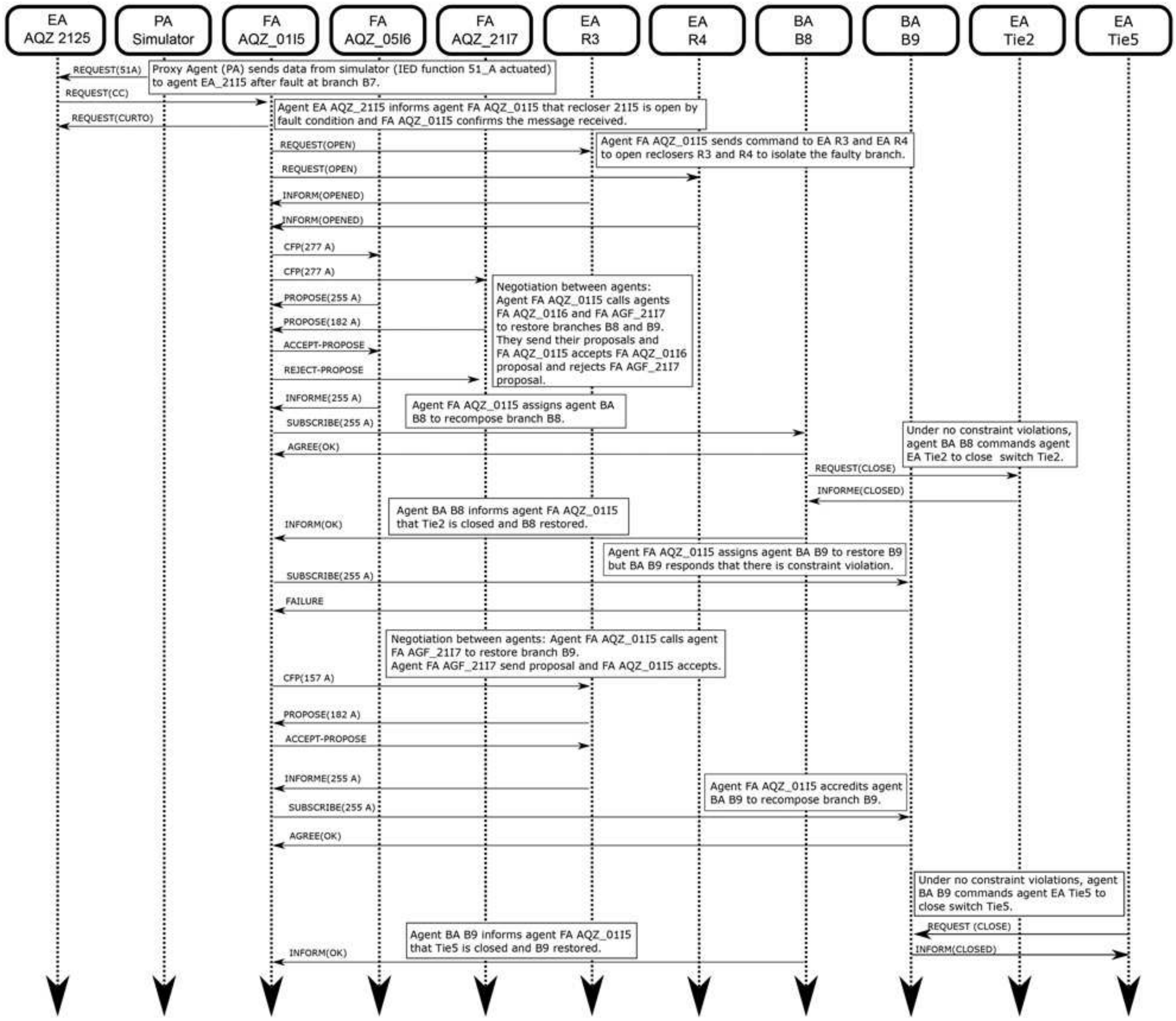

Fig. 10 *Graphical interface generated by JADE illustrating the exchange of messages during the process of restoration of the Aquiraz system*

restore power in safe and effective fashion, considering the operational constraints and defined priority criteria.

For the test case 2, the restoration took at most 3 s and a number of 550 customers got automatic supply restoration, what represented 61.1% of those affected by the fault.

6 Discussion of the results

A distinguishing point presented in this paper relies on using agents encapsulated in hardware other than on IEDs of control and protection. The agents are developed in JADE, an open architecture framework, based on FIPA standard, which enables the development of agent-based systems interoperable, flexible, expandable and fault tolerant [6].

The flexibility of MARS can be confirmed by its ability to evaluate several alternatives and priorities and choose the most appropriate recovery alternative. MARS is also extensible, allowing the updating of or the addition of new functionalities to the agents. MARS is likewise fault tolerant because it has the ability to negotiate and achieve the goals for which it was designed, even if part of the system fails.

Additionally, this paper explores the use of various features and expertise that corroborate to the advance of smart power networks, which are:

- The restoration system uses distributed control approach and multi-agent technology.
- Agents have local and distributed intelligence with the ability to analyse the data necessary for the restoration of complex power systems.
- Apart from the common client/server architecture, the approach uses peer-to-peer communication model.
- Agents use bidirectional peer-to-peer communication using TCP/IP protocol also adopted by IEC 61850.
- XML data file is used to create common information formats and share both the format and data over the Internet, which is also adopted by the standards IEC 61850 and Common Information Model.
- The power network simulator developed in Java for testing and validation of the MARS is an easy to use multiplatform, making the development of new features simpler.

7 Conclusion

This paper has presented a distributed multi-agent system for automatic restoration of power distribution systems. The MARS application developed in JADE platform and a power network simulator developed in Java were integrated through a WLAN using TCP/IP protocol. The multi-agents were embedded in external hardware, making the MARS system independent of the

IEDs' current technologies and protocols. The performance of the proposed MARS was evaluated in a test workbench. The test results have demonstrated the effective communication between JADE platform and the simulator, showing the ability of JADE application to real-time systems using peer-to-peer communication. Definitely, multi-agent systems have a great contribution for the control and management of the smart grids.

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9 References

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