A MULTI-AGENT SYSTEM FOR POWER DISTRIBUTION NETWORK PROTECTION AND RESTORATION: DESIGNING CONCEPTS AND AN APPLICATION PROTOTYPE

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ABSTRACT

In this paper an extended research based upon the potentials of implementing Distributed Artificial Intelligence (DAI) technology to achieve high degrees of independency in distribution network protection and restoration processes, is presented. The work that has already been done in the area of knowledge based applications and expert systems, is briefly reviewed. The authors justify the need to distribute activities in contradiction to the centralized methodologies. A model of the real environment is introduced in order to define the designing parameters of a Multi-Agent System (MAS). Its explicit goal is to autonomously perform effective fault management on Medium Voltage (MV) power distribution lines. The structure of a prototype MAS is then described. Some simulation results are evaluated. Finally, conclusive remarks regarding the perspectives of the proposed architecture are presented.

1. INTRODUCTION

Distribution system fault management and power restoration have been proved to be significant fields of research and applications for Artificial Intelligence. Researchers have already associated available knowledge and experience of domain experts with computational systems dedicated to centralized control and protection. As a result, several rule-based expert systems have been proposed [1], [2], [3] utilizing knowledge and reasoning in order to formulate logical, problem-solving procedures.

Expert systems have also been applied to the general concept of power system restoration, as shown in [4], [5] and [6]. Possessing an auxiliary role in decision making, Expert Systems require information concerning the topology of the network and the nature of the network's components, as well as remote metering of electrical values. Therefore, dedicated communication channels are postulated, including fiber optics or copper-wire telecommunications as well as wireless technologies such as GSM and TETRA [7]. However, issues regarding time and computational resources, costs and physical aspects of the problems restrain the operability of the above systems.

Power Distribution Network is a physically distributed system that depends on the proper functionality and interoperability of several heterogeneous components. Even technically advanced protection solutions will fail to encounter effectively a common distribution line fault without the supervision and interference of humans. As a result, time delays, which yield cost raisings, are introduced. Moreover the coordination of a large number of protective devices, even Intelligent Electronic Devices (IEDs) with programmable protection logic, distributed throughout the electrical network, is obviously unattainable. The need for protection and control systems which exhibit self-organizing, self-coordinating and collaborative behaviors is imperative.

Towards the common goals of rapid and effective fault identification and isolation, prevention from extensive outages and restoration of power to customers in minimum time intervals, decisions and actions should focus on local environments. Distributed Artificial Intelligence technology introduces the conceptual principles of Multi-Agent Systems, which are software/hardware structures with the ability to handle the distributed nature of the problems at hand.

Implementing the agent technology and especially MAS for infrastructures like the power grid, seems to be quite promising [8], [9]. In the case of distribution system fault management, the decomposition of the problem is quite effective [10]. Approaching the complex problem of distribution grid management in a distributed way, is related to the significant areas of applications for MAS, namely distributed solving of problems and solving distributed problems [11].

Distributed generation projects will also benefit from multi-agent technology. Indeed, MAS may be implemented for designing the development of distribution systems, in order to acquire bidirectional power flow capabilities and deal with the connection and synchronization of the distributed power sources to the grid.

2. THE PROPOSED SYSTEM APPLICATION FIELD

The distribution network consists of both underground (residential, commercial and industrial customers) and overhead (industrial and agricultural customers) MV lines. Statistical data indicate that underground lines usually sustain permanent outages while overhead lines usually undergo temporary ones. Therefore the protection systems vary according to the types of faults considered (permanent or temporary). The system proposed in this work focuses on the underground network, with radial feeders and/or open loop structure.

The inspection of an underground cable and the detection of a possible fault is an obviously difficult task to carry out. A typical underground MV line, equipped with protective and switching devices, is shown in Fig.1.

Control centers are located at the 150/20 kV substations. Data concerning the MV line currents, voltages and apparent power, are available from SCADA systems. The state of the 20 kV breakers is controlled locally or/and remotely via dedicated communication copper lines and modems.

A line fault will cause the tripping of the 20 kV circuit breaker and as a result, the entire line will undergo a power outage. Control engineers hereupon have to perform a search over the line, in cooperation with the technical support crew. The crew, under the guidance of the control center, manually operate the load switches of the line locally, while control center is trying to locate the fault by operating the breaker and deciding by its behavior. This procedure may last up to several hours, because the crew have to move from one substation to the other, often during the city's rush hours.

Since it is currently unattainable to automate the cable repairing procedure, the authors propose techniques aiming at minimizing the time requirements of the fault localization, isolation and power restoration of the non-problematic network sectors. It should be noted that our research considers technically advanced distribution networks by means of the following assumptions:

1. All the 20 kV load switches, located at the 20/0.4 kV substations, are equipped with motorized mechanisms controlled by switching relays.

2. Intelligent Electronic Devices (IEDs) for data acquisition and operating command dispatching are necessary providing ordinary communication protocols [12]. The IEDs' role should be restricted to record the electrical parameters of the substation and to indicate local fault detection.

3. Inductive and/or capacitive couplers along with MV modems will enable Power Line Communications (PLC).

4. Simple industrial computer systems, powered by Uninterruptible Power Supplies (UPS), in order to accommodate the distributed MAS, should be installed at the 20/0.4 kV substations.

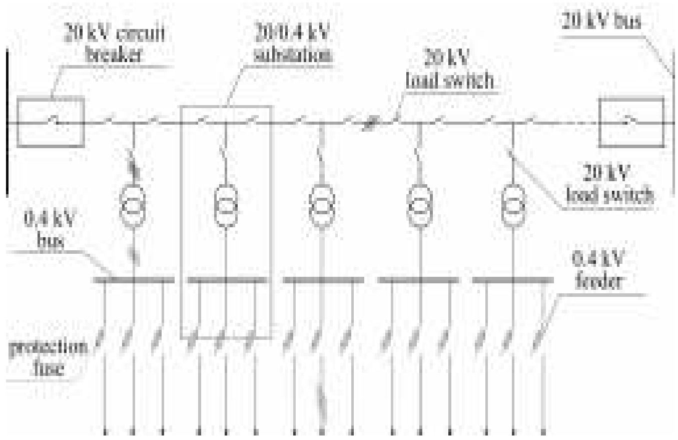

Fig. 1. Underground MV line (rated at 20 kV).

3. DESIGNING GUIDELINES – MAS ARCHITECTURE

Initially, the authors propose the distribution of a MAS throughout the physical environment of the distribution network. The proposed distribution defines the 20/0.4 kV distribution substations as local environments wherein the agents will live and act. The next step is to specify the properties of these environments that will finally determine the behavior of the agents.

A generalization [13] should be made in order to include both physical and relational aspects of the environments. An agent-entity cognizes the physical aspects as operational states of the local substation, such as values of electrical parameters, states of the load switches etc. The relational aspects concern the interactions with other agent-entities which co-exist in local and/or neighbored substations. According to this generalization, agents will cope with non-deterministic and partially inaccessible environments, if the metering devices fail to provide all required information due to hardware malfunctions, as well as if the interactions with other agents are unattainable due to communication problems. On the other hand, regarding the final actions for managing line faults, the agents' behavior is deterministic: the isolation of an identified fault and the restoration of power to customers require certain and absolutely defined switching actions.

The proposed architecture implements similar groups of collaborating software agents – agents communities in the environments specified above. Thus a distribution of the network management problem is being made as well as local activities are introduced, among the members of the agent communities.

In a multi-agent context, the agent communities are actually groups of software cooperatives and communicatives but independent agents, which are expected to join decisions and actions to achieve a common goal. The purpose of the common goal is to provide a glue to bind individuals' actions into a cohesive whole [14]. In the present work, the common goal is determined by the desirable system orientation. In order to comply with the requirements of the MAS principles, the authors developed the agent communities with JADE [15], a software development framework aimed at developing multi-agent systems and applications conforming to FIPA [16] standards for intelligent agents. The design of the system resulted in agent communities, each consisting of three software agents:

Agent Expert. It is a software agent that has been assigned the task to handle emerging situations. Equipped with the appropriate knowledge representation, beliefs about its environment and explicit goals, this agent combines data, assesses each situation separately and decides on the community's actions.

Agent Inter. It is a software entity responsible of providing Agent Expert all necessary connections with the physical environment. It possesses the appropriate knowledge to operate the programmable controllers and to decide on issues that affect the synchronization of the system.

Agent Com. An agent responsible for the communication issues among the agent communities. It initializes the communications between adjacent network nodes as well as between its substation and the *Terminal Agents*.

There are also *Terminal agents* which are pure reactive entities which operate the circuit breakers according to the messages they receive from *Agents Com*, inform the control engineers about the location of the isolated fault and send messages containing the state of the circuit breakers to the secondary substations.

Apart from the 3-agent structured communities, which are located at the 20/0.4 kV substations, individual agents are also introduced with explicit tasks:

- to operate the circuit breakers according to the messages they receive from *Agents Com*,
- to inform the control engineers about the location of the isolated fault and
- to send informative messages to the agent communities, containing the state and load conditions of the circuit breakers.

The specified location of those agents is the distribution line terminals, i.e. the 150/20 kV substations, therefore named *Terminal Agents*.

JADE framework provides the ability to build the necessary ontologies which cohesively describe the relations among the agents, the types and the forms of the messages to be exchanged, and finally determine the sender-receiver couples each time a communication procedure is initialized.

The 3-agent schema entailed the minimum number of activities that have to be performed in a distribution substation, without causing any operational defects: communications, switching device handling, decision making and supervision. A special care was taken regarding the versatility and the consistency of the agent communities. Different agents perform different and clearly distinct tasks without any overlapping phenomena. Moreover, the degree of intelligence of the agents is specified, according to the tasks and activities that had been assigned to each of them separately.

Agent Expert comprises a rule-based expert system and an agent software framework. Logical rules for decision making and action planning present its background knowledge. *Agent Expert* is able to identify a MV line fault and decide on the isolation actions in cooperation with the corresponding agents of the adjacent substations. In addition, *Agent Expert* may identify or even predict operational problems of the substation local environment. Dynamic predicates represent the alterable environment wherein the agent is expected to live and act. The expert system is programmed in PROLOG (PROgramming in LOGic) [17], which is a logic programming language allowing for the minimum semantic gap for knowledge representation. Along with a robust inference engine, the PROLOG logic-base is encapsulated in the agent framework.

Agent Inter and *Agent Com* demonstrate a lower level of intelligence, because they are supposed to act according to the decisions and orders induced by *Agent Expert*. However, *Agent Com* performs autonomous functions in terms of deciding upon the communication quality, while *Agent Inter* performs the data management and refinement. In this context *Agent Expert*'s expectations are fulfilled, as long as the appropriate data describing the environment are made available and the outcome commands are carried out. *Agent Com* and *Agent Inter* decide how and when they are going to accomplish their goals.

The above designing concept justifies the need for utilizing agents instead of objects for the scope of the system implementation. Agents are commonly regarded as autonomous entities, because they can watch out for their own set of internal responsibilities. Furthermore, agents are interactive entities that are capable of using rich forms of messages. These messages can support method invocation—as well as informing the agents of particular events, posing queries, or receiving a response to an earlier query. Since a key feature of agents is their autonomy, they are capable of initiating action, independently of any other entity [18].

4. KNOWLEDGE BASE—EXPERT REASONING

As already mentioned, *Agent Expert* masters the community's intelligence. Therefore, each time, *Agent Expert*, has to reason about:

1) the environment state, as determined by actions that have already taken place and
2) the environment conditions that change according to the substation's electrical parameters provided by *Agent Inter* as well as according to the messages received from adjacent substations.

The first kind of reasoning presupposes that *Agent Expert* is equipped with a knowledge base which thoroughly describes the environment state as well as logical relations among environment objects.

Three types of objects are defined in the knowledge base:

1) local objects,
2) neighbor objects and
3) global objects.

The MV load switches that belong to the local substation are objects of the first type. The adjacent substations, in terms of unique agent-community identifiers, are objects of the second type. Finally, the supplying circuit breakers are objects of the third type.

A kind of "intelligent" data structure has been selected in [19], in order to represent the environment objects in PROLOG, named *Frames*. Information about an object of the system is stored in a frame. The frame has multiple slots used to define the various attributes of the object. The slots can have multiple facets for holding the value for the attributes, or some default values or procedures which are called to calculate/update a value. A slightly different approach to *Frames* is being done in this paper: the frames are constructed like matrices of a relational database including key fields. The structure of the frames is best illustrated in Table I, Table II and Table III.

Table I

FRAME_NAME: Substation	
SLOTS	Name [String]
	Type [String]
	Switches [Integer]
	Power [Integer]
	Fault Position [Integer]
	Switch Action Position A [Integer]
	Switch Action Position B [Integer]

Slot 1: *Name* refers to the unique identifier of the agent-community that belongs to the substation.

Slot 2: *Type* refers to the type of a substation, namely: "local" or "neighbor".

Slot 3: *Switches* refers to the number of load switches of the substation.

Slot 4: *Power* refers to the actual load in [kVA] of the substation.

Slot 5: *Fault Position* refers to the position of the substation with respect to a fault. It is actually an integer used to enable control engineers to locate the isolated fault.

Slot 6: *Switch Action Position A* refers to the position of the substation with respect to a switching action of a different substation in the same MV line, taken place during the restoration procedure.

Slot 7: *Switch Action B* refers to the position of the substation that proceeded with a switching action, with respect to a preceding switching action of a different substation in the same MV line, during the restoration procedure.

Slots #6 and #7 are utilized by the crew in order to find which substations proceeded with switching actions for power restoration, reverse those actions and return system to normal condition.

Table II

FRAME_NAME: Switch	
SLOTS	Name [String]
	Substation [String]
	Power [Integer]
	State [Boolean]
	Fault Detection [Boolean]
	Voltage [Integer]
	Current [Integer]

Slot 1: *Name* refers to the identifier of the load switch

Slot 2: *Substation* refers to the identifier of an agent-community that belongs to a substation located at the side of the load switch.

Slot 3: *Power* refers to the apparent power in kVA of the switch.

Slot 4: *State* refers to the state of the load switch i.e. 1/0 for on/off

Slot 5: *Fault Detection* refers to the status of the switch fault indicator i.e. 1/0 for fault detected/not detected.

Slots 6 and 7: *Voltage*, *Current* refer to the corresponding electrical values of the switch.

Table III

FRAME_NAME: Breaker	
SLOTS	Name [String]
	Switch [String]
	Type [String]
	Power [Integer]
	Condition [String]
	State [Boolean]
	Remaining Power [Integer]
	Power Left [Integer]

Slot 1: *Name* refers to the identifier of the Circuit Breaker.

Slot 2: *Switch* refers to the identifier of the load switch that "sees" the Circuit Breaker.

Slot 3: *Type* refers to the type of the Circuit Breaker i.e. a supplying or an alternative supplying Circuit Breaker.

Slot 4: *Power* refers to the apparent power of the Circuit Breaker.

Slot 5: *Condition* refers to the condition of a Circuit Breaker i.e. available or unavailable during the restoration procedure.

Slot 6: *State* refers to the state of the Circuit Breaker i.e. 1/0 for on/off

Slot 7: *Remaining Power*: refers to the excessive loading capacity of a Circuit Breaker.

Slot 8: *Power Left*: refers to the remaining capacity of a circuit breaker after a switching action, during the restoration procedure.

At this point, the transition to the second kind of reasoning is being made. *Agent Expert* utilizes logical rules acquired by interviewing Control Experts during Knowledge Engineering phase of the system designing, in order to form its decisions concerning the local environment conditions and the actions of the agent-community, as shown in Section 6.

The *Frame* data structure that have been selected as well as the relational type of knowledge representation resulted in a relatively small number of logical rules used for fault localization, isolation and power restoration processes. Twenty rules for fault localization and isolation and sixty five rules for power restoration constitute *Agent Expert's* Expert System. The small number of rules improve speed and compactness in agent reasoning and thus accelerate the logic part of the community's operations by saving time for communications and switching actions.

The above knowledge representation enhances *Agent Expert* with capabilities to cognize a relative position of its substation in the grid, as well as the state and position of the adjacent substations. Moreover, by storing values of the electrical and switching parameters, *Agent Expert* keeps track of the local environment and uses this knowledge to reason about the environment conditions that change over time.

5. COMMUNICATIONS

Two types of communications occur during execution time, namely intra-community and inter-community. The communication procedures among the agents of the same community fall into the first category. They are specified by the FIPA standards and represent interactions of independent control threads occupied by agents living in the same environment.

The inter-community communications concern the corresponding procedures that take place between neighboring substations and among the substations and the control centers. Simple ACL (Agent Communication Language) messages are being exchanged among JADE agent-platforms while the necessary actions are performed mainly by *Agents Com*. The agents are aware of where to send a specific message and they know whether an incoming message is addressing them. Therefore all communications are secured.

The MV line serves as the physical communication channel. For the purpose of this research the amount of data is not a decisive issue, and in principle the CENELEC A-band (3-95 kHz available for utilities; European standard EN50065) allows a sufficient data transfer rate. The choice of utilizing the MV line for the communication needs results in several advantages regarding the autonomy of the system. The distribution network will rely on its own resources, whilst dependencies on extra telecommunication paths and networks will be avoided. The behavior of a medium voltage cable with respect to coupling schemes for Medium Voltage PLC is presented in [20]. In our work the results of the simulations are quite encouraging since the communications are mainly established between adjacent secondary substations, where the length of the medium voltage cable is less than 1 km. Therefore communication signals travel short distances along the cable conductors and more important: signal attenuation is low.

6. OPERATIONAL PROCEDURE

The proposed system does not require an overall synchronizing procedure. Agents may organize themselves, may keep up with their supervisor or may even obey the commands issued by other agents. They may demonstrate a variety of behaviors, from pure autonomous to pure dependent ones, depending on both internal (their own responsibilities) and external (environmental conditions) factors. *Agents Com* for example act autonomously when they communicate with each other, but may act in a dependent manner, when they send messages on behalf of *Agents Expert*. The ability to act by exhibiting a range of behaviors allows the system's entities to finally collaborate towards the common goal.

The operation of the MAS in a procedural way is as follows:

Step 1. Communication

a. Agents Com of adjacent agent communities exchange messages containing the load percentage of the substations and the state of the fault detectors. Depending on the time requirements for a message to arrive at its destination the agents may adjust their behavior accordingly.

b. Terminal agents broadcast the state of the circuit breakers.

c. Agent Inter collects data from the IEDs (currents, voltages, load switches states, local fault detectors states etc).

Step 2. Agents Com and *Inter* update the necessary inputs of Agent Expert's knowledge base and thus provide *Agent Expert* with the information to process.

Step 3. Agent Expert queries its expert system and as a result decides upon the local environment condition

The following steps won't be initiated, unless a fault isolation *and power restoration procedure is triggered:*

Step 4. Agent Expert forms the appropriate commands for line fault isolation; commands for MV load switch operating are forwarded to *Agent Inter*. Information about possible fault identification is forwarded to *Agent Com*.

Step 5. Agent Inter acknowledges and proceeds with the necessary actions. It informs *Agent Expert* whether the required actions have been taken.

Step 6. Agent Expert sends additional information for circuit breaker operation to *Agent Com*. *Agent Com* composes a message including all the available pieces of information and sends this message to the *Terminal agents*.

Step 7. Terminal agents proceed with the appropriate circuit breaker operations.

7. A CASE STUDY

The post-fault state of a MV underground line is shown in Fig.2. Prior to the fault, the breaker on the left was closed.

Fig.3 depicts the appropriate communications the agents perform according to steps 1 and 2. In this case the behavior of Agents Expert 1 and Agent Expert 2 is illustrated. They both trigger the logical rules that match the available data. Soon Agent Expert 1 realizes that the fault occurred on his right, while Agent Expert 2 realizes the same situation on his left (Step 3). It should be assumed that the fault did not cause the destruction of the physical continuity of the conductor. Agent Expert is nevertheless equipped with the appropriate rules to handle the rare case where substations will not establish contact with each other, due to the consequences of a powerful short-circuit or of a cable conductor discontinuity.

Steps 4, 5 and 6 are illustrated in Fig.4. The faulty part of the MV line has already been isolated, as a result of local switch operating actions guided by *Agents Inter1* and *Inter2*.

Agents Com1 and *Com2* inform *Terminals 1* and *2* respectively about the identified fault and the appropriate operating actions concerning Breakers 1 and 2. The operating actions finally lead to power restoration of the unharmed parts of the distribution line (Step 7). The restored MV line is shown in Fig.5.

The system is capable of localizing and isolating simultaneous or even cascading line faults. For n line faults (counting from the initially feeding bus side) the system will primarily detect and isolate the remotest (n^{th}) fault and then successively proceed with the rest of the faults.

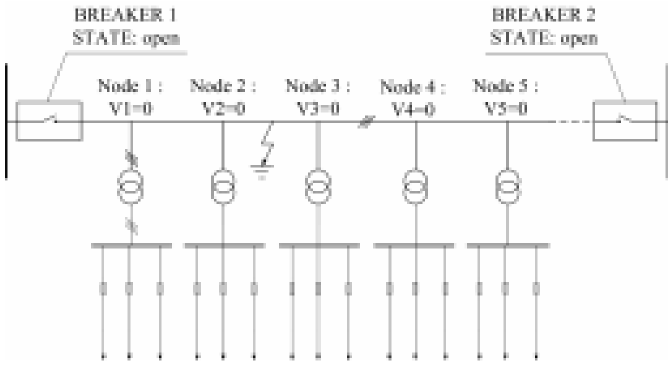

Fig. 2. MV underground line with a fault between substations 2 and 3: both breakers open.

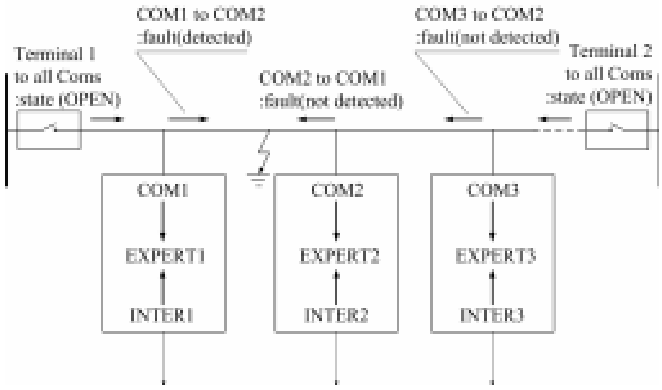

Fig. 3. Initialization of the fault localization procedure.

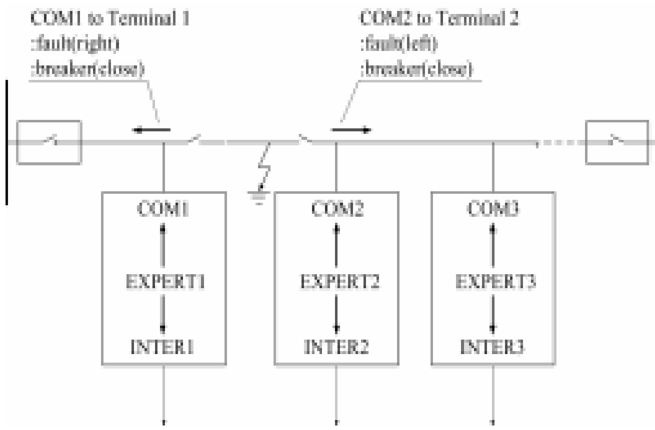

Fig. 4. Isolation of a line fault.

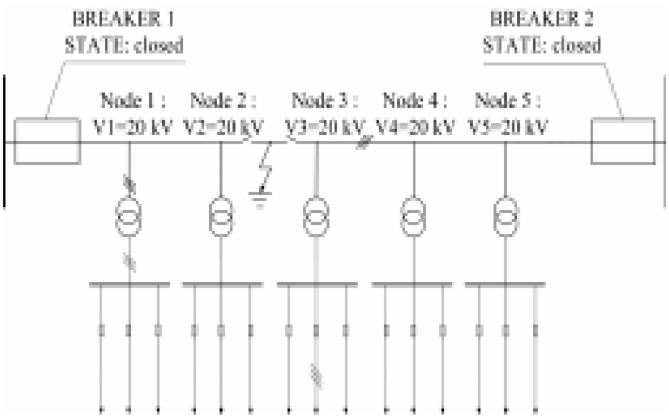

Fig. 5. Power restoration.

8. SYSTEM ROBUSTNESS

As already mentioned, *Agent Expert* demonstrates the highest intelligence level amongst the members of an agent community, by means of holding and manipulating a powerful rule-based Expert System. The intrinsic features of the Expert System, which define *Agent Expert* behavior, along with the collaborative relations among the agents, reinforce robust and stable deportment.

A hierarchical order of the rules constitute the Expert System. The rule hierarchy retains the system from unstable or insecure states. Rules that fire depending on the outcome of other more significant rules, also exist. The dynamic assertion and retraction of predicates during execution cycles enable *Agent Expert* and thus the entire community to cognize and keep intuitive track of the evolving environment.

The system is intended to work under real conditions. In order to sustain a coherent structure and to prevent the system from demonstrating undesirable behaviors, the core of the system's intelligence is equipped with the totality of the domain experts' knowledge and experience. According to the authors' point of view, this effort did not produce a simple reactive system but a powerful cognitive architecture that is capable of demonstrating complexed combinatorial functions to come up with the appropriate results.

9. DEVELOPMENT ENVIRONMENT

Experimenting with a fault management system that has been developed for distribution network infrastructure is actually a complicated procedure. A real testing scenario postulates the installation of the required equipment as well as the availability of a MV power line.

The prototype of the proposed MAS was developed and tested by numerous simulations, in order to conclude about the time and resources requirements of the system's operation, as well as about the system's stability. Three PCs connected via a 10 Mb/s TCP/IP Ethernet network have been used to simulate a 3-node schema. Each PC was accommodating a JADE platform with a 3-agent community. Two additional PCs corresponding to the 150/20 kV primary substations were also connected to the same network (Fig.6). Operational inputs were provided by input data files conforming to the COMTRADE [21] standard. Additional software objects simulating the IEDs were installed on laptops connected to the PC's via RS-232 serial ports. A variety of scenarios were tested by altering the data files (both in volume and quality).

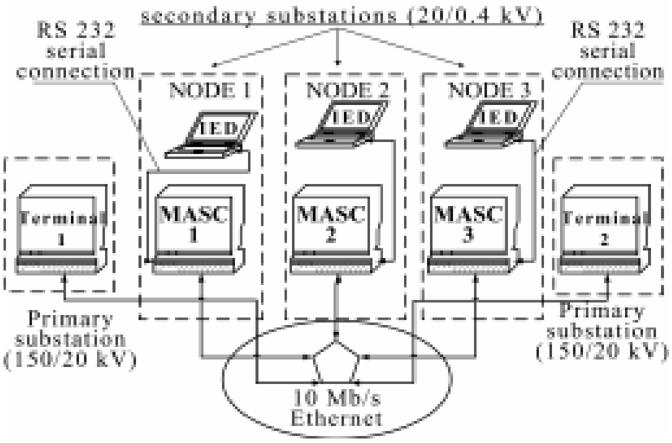

Fig. 6. Simulation topology.

10. RESULTS OF SIMULATIONS

Different simulations were performed which led to the following conclusions:

- The system responded to all testing scenarios in a flawless way entailing the completeness of the designing.
- The time response was exceptional. For input files of 300 records the agent-communities responded in approximately 180 sec. Since one overall execution cycle corresponds to one record of input data, the agent-communities are able of cognizing the local environment, processing, deciding and acting upon it, in less than 2 seconds.
- The system finally exhibited a highly adaptive behavior concerning its self-organizing ability. Once the agent communities established contact with each-other, the system resolved all the test cases despite of whether the execution cycles of the agent communities where synchronized or not. The system proceeded in virtual changes of the environment topology and the agent communities rearranged their activities in order to adapt to the topological changes.

An additional time delay, due to the PLC procedures and the operation of the switching devices, is expected in a real system. The corresponding expected times in the CENELEC A-band depend on the bandwidth provided by the PLC solutions available in the market, as well as on the maximum expected message size regarding the inter-community transactions. However the limited amount of exchanged data will not significantly affect the overall performance Therefore inter-community message transactions time, which in a 10-100 Mbps network is less than a second, is not expected to exceed one or two seconds in the CENELLEC A-band.

11. CONCLUSIONS

From the agent-technology aspect, the authors presented a concept of designing adaptive MAS which are application oriented; the system does not induce certain learning procedures regarding the fault management, since the experience provided by the domain experts is quite enough to enable the agents to identify and manage occurring faults. However, adaptive behavior is necessary since:

- the system ought not to become unstable when a network topological alternation takes place due to local activities of the agent communities,
- the system must maintain stability even if the actions of the agent communities are not synchronized, and
- the operation of the system must remain safe and must not oppose to human intervention.

The implementation of the proposed Multi-Agent architecture will provide a desirable autonomy in terms of self-management to the power distribution network. The entire network will become a living organism with self-healing capabilities. The power restoration procedures will become less time consuming

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