Agent-Based System Applied to Smart Distribution Grid Operation

D. Issicaba, M. A. Rosa, W. Franchin and J. A. Peças Lopes
Institute for Systems and Computer Engineering of Porto (INESC Porto)
Faculty of Engineering, University of Porto
Portugal

1. Introduction

The twenty-first century has been called software century by some software engineering researchers. The challenge for humanity is to improve the quality of life without making unsustainable demands on the environment. Agent-oriented software engineering is an important emerging technology that can cope with the ever-increasing software complexity of the technical world (Liu & Antsaklis, 2009).

This chapter presents an agent-based architecture which was developed to support the smooth modernization of the power distribution grids. This architecture copes with the smart grid paradigm (ETP, 2008) and leads to changes in the grid operation rules, control and protection, as well as grid infrastructure. The main target of the architecture is to distribute decisions related to smart grid operation and to improve service adequacy and security. Hence, a complex environment simulation is designed to emulate the distribution grid operation and evaluate the impact of agent's plans of action. The environment itself is modeled using a combined discrete-continuous simulation approach (Law, 2007) in which steady-state and dynamic aspects of the electrical behavior of distribution grids are represented in a detail way.

The simulation platform was designed according to the software engineering methodology Prometheus (Pagdgham & Winikoff, 2007). The resultant architecture follows a block-oriented paradigm in which the power distribution grid is divided into blocks for protection and control purposes. Such paradigm shows to be considerably convenient to support the transition from actual grids to smart grids. In addition, it allows software agents to be assigned to the management and control of blocks of the grid, given life to "block agents". Agents are also assigned to entities which are capable of affecting the distribution grid operation, such as distributed generators (DGs), special loads, and electric vehicles (EVs). All agents are modeled according to the Belief-Desire-Intention (BDI) paradigm (Bratman et al., 1988) and implemented using JASON (Bordini et al., 2007), the open source interpreter of an extended version of AgentSpeak. A didactic case study illustrates how service adequacy and security can be improved with the application of the proposed agent-based decision planning.

1.1 Problem statement

Electrical power grids are designed to provide electricity with a certain level of adequacy and security. Like most of the systems developed by the human beings, the electrical power grids evolve based on trends motivated by economical, environmental and societal drivers. Recently, such drivers have caused the advent of well-established initiatives especially concerned with these systems as the Modern Grid Initiative (NETL, 2007), the IntelliGrid Initiative (EPRI, 2005), and the European Smart Grids Technology Platform (ETP, 2008). In general terms, these initiatives try to foster on different extends the deployment of decentralized control and management solutions, the integration of renewable and distributed energy resources, as well as the modernization of the power grids. The deployment of decentralized control and management solutions has increased in the past few years. The integration of renewable and distributed energy resources has also increased, particulary in what concerns wind power in Europe. The modernization of the power grids is a gradual process which can be observed in countries with more economical power.

The technical challenges created by this context embrace several power engineering related fields of expertise as power electronics, communication, information technology, and software engineering. Additionally, the quoted drivers have been influencing power engineering itself in terms of its areas (long-term planning, mid-term planning, short-term or operational planning, operation, control and protection), as well as its structure/organization (generation, transmission, and distribution). In particular, the distribution grid operation and control might stand as one of the most promising to change areas. As a matter of fact, most of the interruptions in supply are caused by problems at the distribution grids which lacks monitoring and control devices in comparison with the transmission grids. Furthermore, distribution grids are the main locus for distributed energy resources (DERs) such as DGs, energy storage devices and controllable loads. At last, the proposed modernization along with the integration of DERs must guarantee service adequacy and security. Such target involves re-evaluating distribution grid operation and control under the presence of DERs.

Nowadays, the capability of DERs are yet not exploited at their most. In fact, traditionally distribution utilities employ the practice of tripping DGs after the occurrence of a fault. Hence, islanded operation is avoided both for sustaining the operation after a fault or for restorative purposes. Therefore, in order to profit from the benefits DERs can provide to the grid operation and to foster the large-scale integration of DERs, control strategies for the emergency operation of distribution grids with DERs must be developed. Furthermore, the impact of these control strategies in the distribution grid performance must be evaluated to foster the integration of such strategies into the operation procedures. Finally, these control strategies must be designed in order to make it possible their gradual implementation, without requiring great changes in the simple and cheap structure actual distributions grids are operated.

1.2 Motivation

Agent-based technology provides the most suitable paradigm to allow a smooth transition from the actual distribution grids to smart distribution grids. Such statement is justified by the followings.

1. The increase in complexity and size of the distribution grids bring up the need for *distributed intelligence* and *local solutions*, which fall into the scope of agent-based technology.

2. Smart/modern grid design concepts related with operation and communication can be tested through an agent-based modeling and simulation.

3. Decentralization, autonomy and active management are properties inherent of a system developed under the agent-oriented philosophies. Furthermore, an adequate agent-based modeling can produce flexible, extensible, and robust systems[1](McArthur et al., 2007). All these features are of most importance to a smooth modernization of distribution grids.

The tangible product of the work is an agent-based simulation platform where the smart grid operation and control solutions can be tested and evaluated. The target group of the work includes software engineering researchers and power engineers.

2. Brief discussion about the state of the art

Regarding applications related to this research, some works must be emphasized. In (Rehtanz, 2003), the application of autonomous systems concepts and intelligent agents theory for power systems operation and control is discussed. In (Amin, 2001), a conceptual framework for a power system self-healing infrastructure is envisaged. In (Nagata & Sasaki, 2002; Nagata et al., 2004; 2003a;b), the authors presented a multi-agent system designed for distribution systems restoration. This works abstracts network buses as agents, along with a so called facilitation agent who is responsible for aiding negotiation processes among bus agents. A more decentralized approach for distribution system restoration is shown in (Solanki et al., 2007), where switches, loads and upstream links are abstracted as agents. In (Hossack et al., 2003), the agent abstraction was utilized to integrate tools for post-fault diagnoses. In (Baxevanos & Labridis, 2007), a control and protection framework using agent-based technology is proposed. An autonomous regional active network management system is introduced and discussed in (Davidson & McArthur, 2007). This work provides an interesting discussion about requirements for practical active management of distribution grids. In (Dimeas & Hatziargyriou, 2005), entities related with the control of micro grids are abstracted as agents and their interactions modeled. Although in this work the agent-based modeling was utilized, the resultant control architecture maintain the hierarchical structure applied in the micro grid (and multi-micro grid) concept. A distributed electric power system simulator environment is presented in (Hopkinson et al., 2006). Finally, an intelligent agent-based environment to coordinate maintenance schedule discussions is introduced in (Rosa et al., 2009), and a modern computing environment for power system reliability assessment is presented in (Rosa et al., 2010).

In general, these works do not describe the deployment of a software engineering methodology. In addition, none of them provide one of the most important issue for the practical implementation and acceptance of agent-based technology in distribution grid applications: an environment which emulates the system operation to evaluate the agent-based solutions according to standardized (and regulated) distribution grid performance indices (see (Issicaba et al., 2011) for details). This work introduces such

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[1] Conceptually, flexibility is the ability to respond correctly to different (dynamic) situations. Extensibility connotes the ability of augmenting, upgrading or adding new functionality to a system. Finally, robustness stands for a degree of system fault tolerance.

a platform as well as discusses the physical/hardware implementation of the proposed solutions, how the environment is influenced by them in terms of modeling, and some agent interactions necessary to solve problems related to smart distribution grid operation.

3. Distribution grid automation

Grid, in the electrical engineering vocabulary, means the infrastructure used to deliver electric energy over an area. As a consequence, it connects the whole chain of the electricity business from the high voltage generation and transmission facilities up to houses and industries. Hence, large amounts of electric energy are produced in the generation facilities and transported through the transmission grid. By means of the distribution grid, these amounts of electric energy are partitioned and distributed to the customers over large coverage areas, usually under the concession of an electric distribution utility.

Distribution grid automation consists of a set of technologies that enable an electric distribution utility to remotely monitor, coordinate an operate distribution grid components, such as circuit breakers, reclosers, autosectionalizers, and so on, in a real-time mode from remote locations (Northcote-Green & Wilson, 2006). The main reason for the distribution grid automation may be sustained by the difficulties the utilities have in monitoring, coordinating and operating feeders everyday, manually. Usually, the remote controls are activated at a control room inside the electric distribution utility. It is interesting to notice the centralized concept behind this control principle which, in fact, is one of the automation measures adopted for reducing the utility man hour and man power.

One of the primary difficulties about managing a distribution grid starts with its extend. Usually, for each 1 km of transmission grid there are about 70 km of distribution grids, only considering an ordinary distribution utility around the world. Therefore, huge investments in distribution management system (DMS) including cooperation with other application systems such as network geographic information system, costumer information system and usually a large communication infrastructure are needed.

3.1 General aspects about the distribution grid automation

Before introducing any set of architectural solutions for the control and automation of distribution grids under the smart grid paradigm, it is important to highlight some others existing initiatives such as the GridWise Architecture Council (`http://www.gridwiseac.org/`), EPRI IntelliGrid (`http://intelligrid.epri.com/`) and Utility AMI (`http://www.utilityami.org/`). These initiatives along with the U.S. National Institute of Standards and Technology (`http://www.nist.gov/`) and other stakeholders have constructed a reference model for smart grid interoperability of energy technology and information technology operation with electric power system, end-use applications and load (IEEEP2030, 2011). Besides the goals and general directives, such model identify the logical information that can be interchanged between entities, communication interfaces, and data flow. Such information is of major interest to evaluate the complexity in operating power systems. As an instance, Fig. 1 shows the distribution grid domain, its entities and related communication interfaces of this model. Apart from these initiatives, some European projects can also be quoted such as the InovGrid Project, which proposes an hierarchical technical architecture focused on micro grids and multi-micro grid concepts (Cunha et al., 2008).

Henceforth, it is recommended that control and automation solutions should be compatible and/or as complementary as possible to the existing specifications, and also foster their decentralization and extensibility. In terms of distribution grid network management, as already mentioned, the current DMS platforms have evolved in order to integrate and/or cooperate with other systems, mainly focusing on the whole set of activities around the distribution grid operation. The evolution of the DMS into the electric distribution utilities is discussed. Fig. 2 highlights the typical pathways from which DMS have evolved around the world.

From the control and automation perspective, the distribution grid has been evolved from the substation automation to feeder automation. Fig. 3 shows the main distribution grid equipments involved in this evolution.
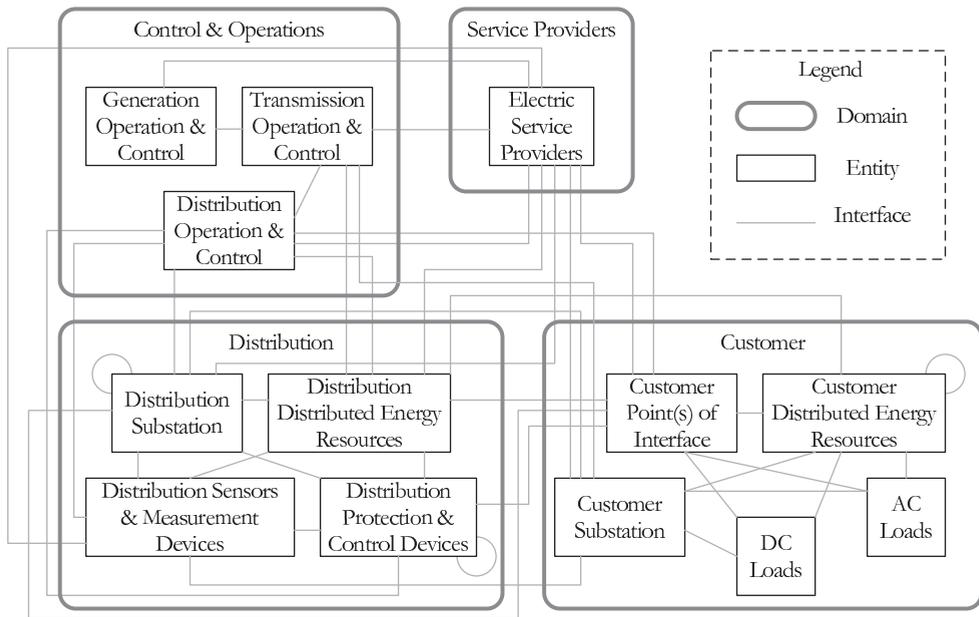

Fig. 1. Distribution grid interoperability perspective. Adapted from (IEEEP2030, 2011).

The target is to improve the grid performance, mitigate the impact of interruptions, diminish interruption times, reduce crew personnel and its operational costs, and so forth. Furthermore, the ongoing integration of DERs in the distribution grids have introduced challenges to distribution grid control and protection.

3.2 Towards a decentralized distribution grid automation

The distribution grid is subjected to random conditions linked to the environment such as weather behavior, presence of vegetation near the overhead network, interaction with human-being and so forth. From a centralized DMS perspective, the decision-making process involves directly at least one operator (human intervention) which should decide whether to change or not the operational status of a remote controlled device. Additionally, it requires
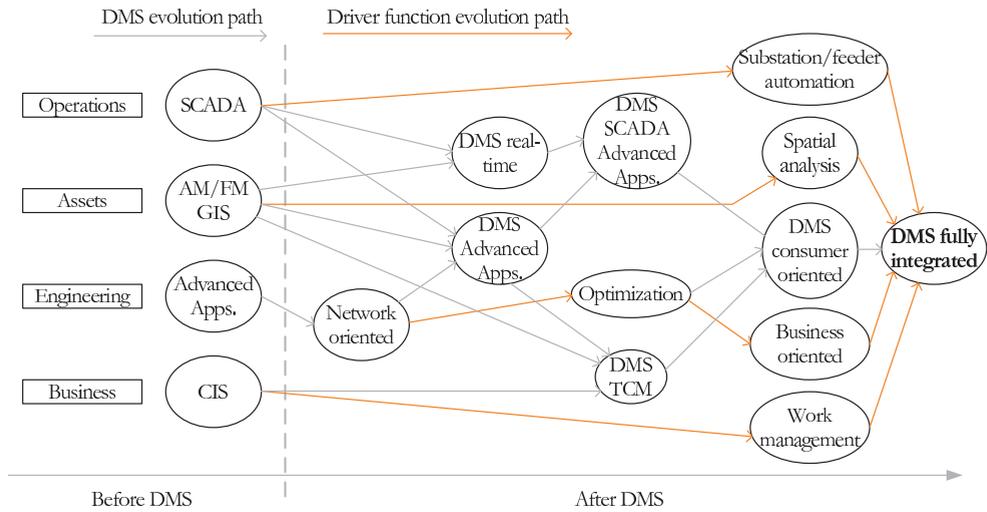
Fig. 2. Typical pathways of DMS evolution (Northcote-Green & Wilson, 2006).
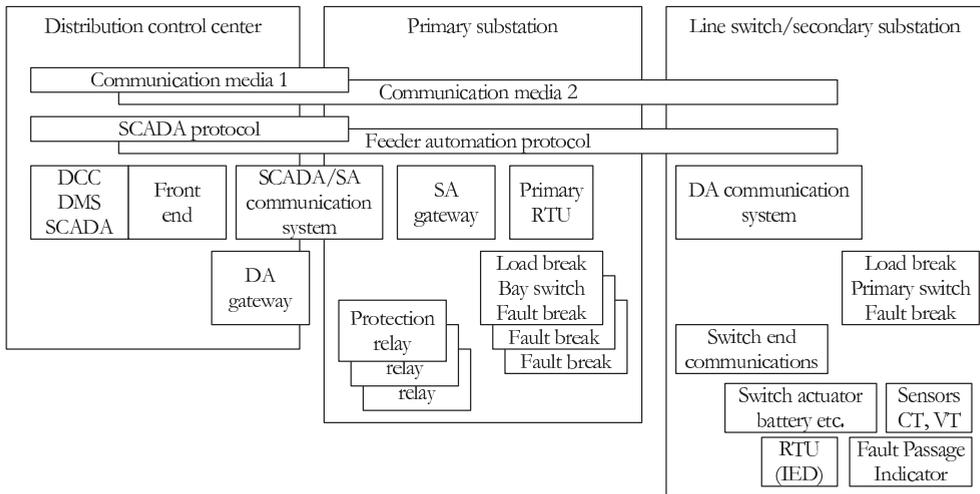

Fig. 3. Components of distribution grid control and automation (Northcote-Green & Wilson, 2006).

precise information that cover almost every possible equipment condition and surrounding environment variables necessary to preserve, not only the asset integrity, but also the safety of the utility staff. In general, a considerable number of field electricians trained to interact with the network components is needed.

Conversely to the centralized solution commonly applied in several utilities, the proposed solutions are based on a decentralized perspective, where the remote control actions are
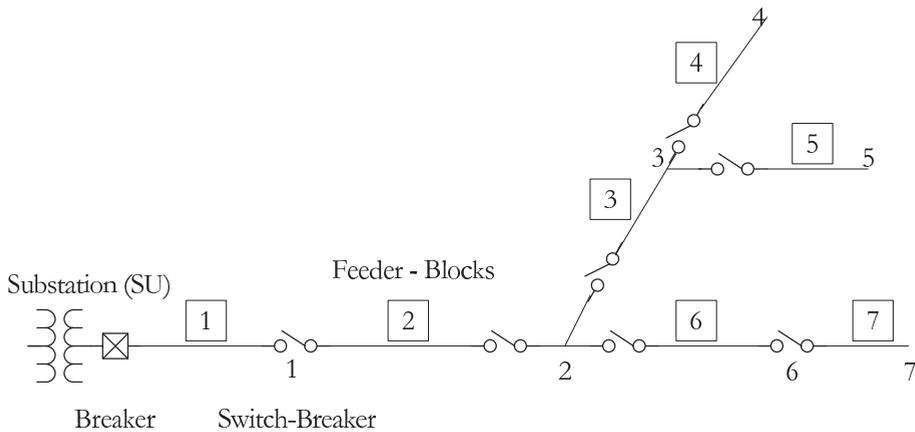
Fig. 4. Distribution feeder divided into blocks.

supported by an agent-based architecture. In fact, the automation decision tree introduced in (Northcote-Green & Wilson, 2006) revels that the current distribution grid automation infrastructure that allows a centralized control is entirely prepared for decentralized approaches. Therefore, the ordinary steps to the implementation of automation for any manual switch can be revisited in order to clarify the requirements for decentralized solutions under an agent-based paradigm.

Let us discuss some properties about the distribution feeders. From the construction point of view, it is mandatory to understand the design of a a distribution feeder, and afterwards it is possible to think about feeder automation. Fig. 4 presents a small representation of a distribution feeder and its natural structure divided by switches. As it can be seen, the distribution feeder starts from the substation breaker and it goes towards each switch, passing through intersections such as point 2, from where the feeder is split in others sub-feeders or laterals. One of the basic functions of each switch is to sectionalize the feeder in several parts firstly for construction purposes, and then afterwards for control purposes. At this point, it is possible to say that the feeder is composed by several individual blocks separated by different types of switches.

Historically, switches between blocks were operated manually. However, in a first automation step, mechanical actuators were included to allow local or remote control actions over a switch. Another particular point about switches is that they must be equipped to act under load conditions, which in fact is a restriction of the switches installed in most of the grids. Essentially, the first step enables the second step, where it is necessary to control the switch by an electronic control unit, or to control the switch by manual pushbuttons. Through this pathway of an electronic control unit installed upon the switch actuator it is possible to implement a remote control interfaced by a communication system. Thus, the option for switch-breaker automation can be based on a local intelligence allowing them to act automatically under the decision of an agent and under the supervision of an operator. Obviously, decision making processes can be implemented, either under an intelligent agent paradigm using devices in a server/computer of each block, or under a combination with both local block agent and central decision making with human intervention remotely.

Now, in order to illustrate the automation process, consider an automated system for switching all switch-breakers of the Fig. 4, where the main goal is to minimize the number of interruptions in each block. In this case, it is necessary to establish a goal model for the system and identify a set of rules in order to achieve the goals. Assuming that each block is an agent, it is also necessary to establish a cooperation process and a way of communication between them. So far, it was not mentioned about which is the environment of our block agents, and how they can percept and act changing the environment. This demands a formalization based on software architecture engineering, which is a key factor that will affect the whole implementation. Next section will explore in detail the Prometheus methodology to define the architecture of the automation proposal.

4. Proposed multi-agent architecture

The first step in building any complex system is to formalize the reasons for which this system must be built. However, specifying *goals* over the distribution grid operation can be a slippery task. In fact, despite of achieving acceptable *states of affair*, the goals must agree with the mission of the utility as an enterprize, respect grid standards and regulations, foster sustainability, and protect the interests of customers and stakeholders. Furthermore, goals can vary considerably depending upon the utility policies.

By following the Prometheus methodology (Pagdgham & Winikoff, 2007), a goal map for the proposed design was specified. We emphasize that the resultant set of goals is not complete in the sense of approaching all issues of distribution grid operation. Conversely, the goals were developed as general as possible with focus on tacking critical matters of the distribution grid operation and the smart grid paradigm.

Fig. 5 depicts the main goals applied in developing the proposed design. Similarly to any cognitive mapping, the top-down analysis shows causality from abstract to tangible concepts. Hence, the goal map includes technical matters such as to `protect the integrity of the equipments` and to `operate under high levels of service adequacy and security`, as well as smart grid matters such as to `foster DERs to participate in the operation issues`. As expected, some sub-goals already suggest that an agent abstraction should be assigned to the blocks of the distribution grid. For instance, when a sustained fault occurs in a distribution feeder, fault isolation is achieved by separating the faulted block from the remaining network. Then, service restoration is endeavored to connect as much blocks as possible to alternative supplies, aiming at minimizing the number of customers under service interruption. The sub-goal `DG islanded operation` itself points even more to a block-oriented paradigm. In order to minimize customer interruptions and foster the exploitation of DER capabilities, DG islanded operation procedures have been verified. Given the spatial distributed signature of DGs and their restricted capacity in supplying feeder's customers, DG islanded operation is expected to be achieved only in certain set of blocks of the grid.

After going ahead with the Prometheus phases, the functionalities and agents illustrated in Fig. 6 and 7 were derived. The functionality names are self-explainable as well as they are related with the goals and possible percepts/actions according to the diagrams. Agents are assigned to the distribution system operator (DSO), DGs, EVs, and loads. These agents are then modeled as clients of a management and control service provided by `block agents`. The percepts `node voltage`, `switch status`, `neigh-power flow`, and `FPI` stand for
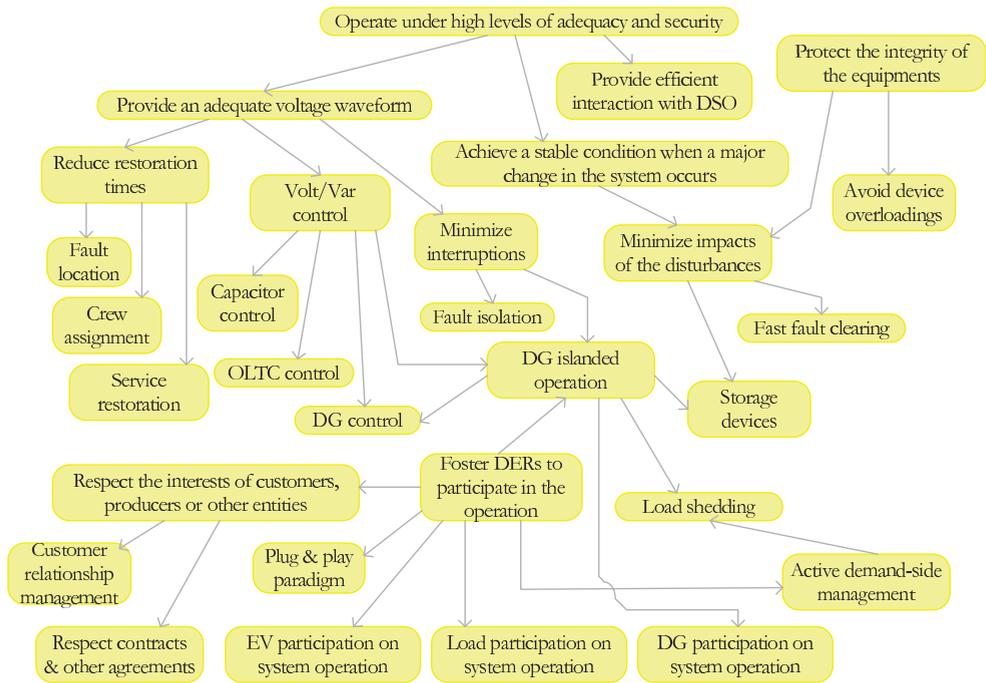
Fig. 5. Goal overview for the agent-based architecture.

electric voltages, operational status of a switch (open, close, in-service, out-of-service), power flow at an aggregated component, and fault passage indicator, respectively. On the other hand, `client subscription` and `client update` denote percepts referred to client attempts in subscribing or updating subscriptions to the block management and control services.

In order to pursue all goals, each `block agent` is responsible for feeding and sharing information with its neighboring agents through the electric utility communication system. Hence, actions related to searching for clients and neighbors as well as the information flow rules are designed as presented in (Issicaba et al., 2010). Other actions, such as `send Q setpoint` and `send tap setpoint` are applied when inadequate node voltages are perceived. For instance, if local low node voltages are identified, the tap of a capacitor component can be increased step by step up to a limit aiming at voltage correction. DG control setpoint conveyance through `send P setpoint` actions are also performed to reduce the power flow at the DG ties in case the entity representing the DG agrees contractually with such scheme. This reduction is crucial in case DG islanded operation is desired. At last, DMS report sending actions are triggered when protection plans are changed or outages are assigned.

Since JASON (Bordini et al., 2007) was utilized to interpreted AgentSpeak coded agents, percepts are represented by literals, saved in a belief base, and used to trigger plans selected
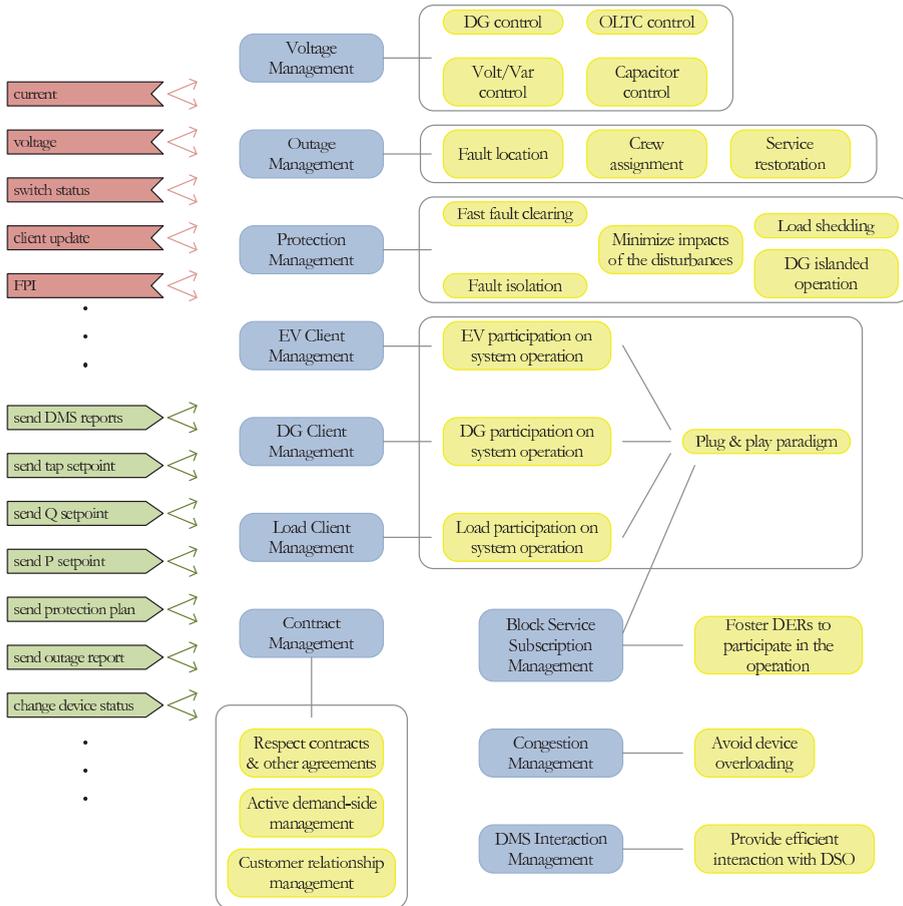
Fig. 6. Role overview for the agent-based architecture.

from a large library. As an example of planning, let us take the sub-goal `DG islanded operation`. In case a sustained fault current is identified, breaker action from standard automation must clear and isolate the fault leaving some blocks disconnected from the main grid. Therefore, to cooperate in order to maximize the customers served by DG islanded operation, each `block agent` cyclically evaluates the ability of its assignee to survive the islanding process when connected to the downstream remaining grids. If there is not enough client power reserve to supply the remaining grid, the `block agent` will set a plan linking the breaker action to its own isolation actions. This increases the chances of the remaining `block agents` to achieve DG islanded operation and minimizes customer interruptions. This particular plan was implemented similar to the followings.

```
@DGislanded_operation_plan04
+!protection_planning_instance
:   reserve(PathId,MWreserve,MWLoading,MVARreserve,MVARLoading)
```
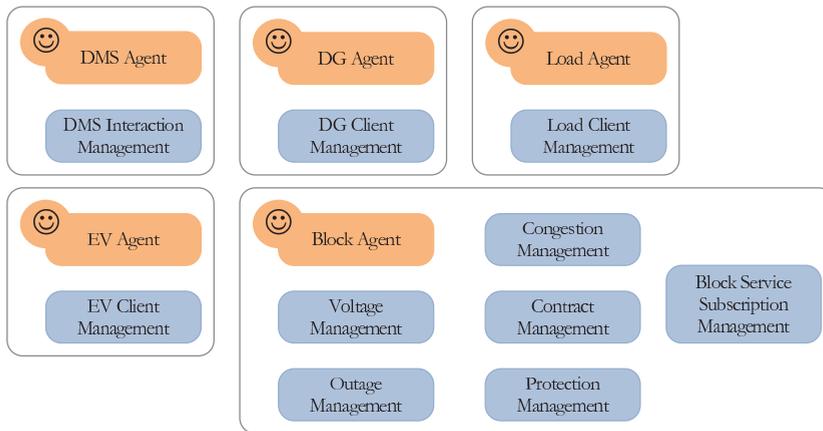
Fig. 7. Agent role overview.

```
[visited=no] & (MWreserve < MWLoading | MVARreserve < MVARLoading)
<- setplan(fault,PathId,isolate_itself).
```

All goals and sub-goals must have at least a plan to tackle them. These plans are activated repeatedly depending upon their own contexts and the agent's interaction with the environment.

5. Environment modeling: emulating the distribution grid operation

One of the key aspects about agents is that they are situated in an environment. In the proposed architecture, agents perceive and act upon the basic protection and control layer of the distribution grid. Therefore, the distribution grid itself is the environment and the architecture must utilize the sensors and actuators available in the distribution grid automation. Of course, since our architecture is aimed to a real-world application, a rigorous model to simulating the environment is required before any field test. This leads to a complex software environment modeling featured as partially observable, stochastic, sequential/time-dependent, dynamic and discrete-event/continuous-time (Law, 2007; Russell & Norvig, 2002).

Hence, an object-oriented modeling was developed for each entity of the distribution grid automation. This modeling was based upon works in the area (Manzoni, 2005) and elements from power system analysis software (GDFSUEZ & RTE, 2004). Over the grid representation, a combined discrete-continuous simulation model (Law, 2007) was devised where the distribution grid operation is abstracted as a sequence of operation states marked by state transitions. Discrete state transitions are caused by events such as the failure of a component or DG unit, fault-clearing breaker action, and relay-based load shedding. Also, electrical continuously changing state variables are modeled by differential equations and solved through numerical integration. The operation states are sequentially evaluated up to the convergence of performance indices following a Sequential Monte Carlo approach (Rubinstein & Kroese, 2008). Numerical integration was implemented using the fourth-order
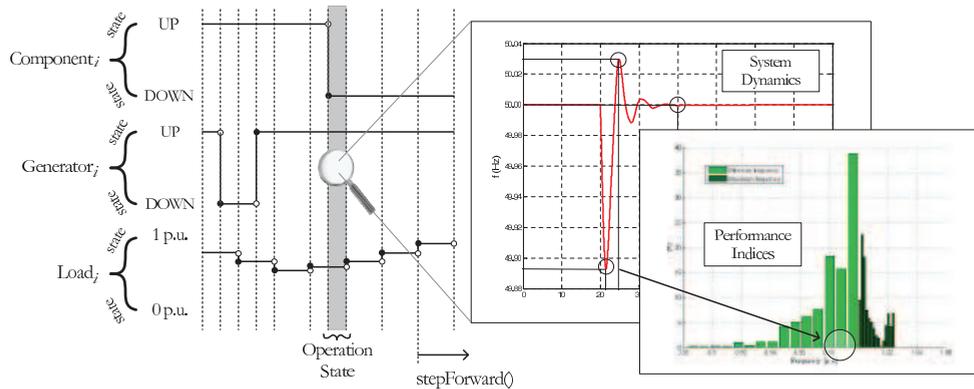
Fig. 8. Sequence of operation states in the combined discrete-continuous simulation model.

Runge-Kutta method from the Flanagan's Java Scientific Library (Flanagan, 2011). Fig. 8 illustrates how the operation states are created and evaluated in the simulation model.

More descriptive, the stochastic failure/repair cycle of grid components and DG units is represented by two-state Markov models, as introduced in (Billinton & Jonnavithula, 1996). DG units and network components state residence times are assumed to be exponentially distributed, and are sampled using the equation below (Billinton & Li, 1994)

$$T \leftarrow -\frac{1}{\lambda} \ln U \tag{1}$$

where T is the state residence time of the component/unit, λ is the transition rate out from the current state, and U is a uniformly distributed random number which is sampled at $[0,1]$. The loads patterns are represented using a deterministic load model consisting on 8736 peak load percentage levels (Subcommittee, 1979), each associated to one hour of the year. From an electric steady-state perspective, components and DG units are modeled by their equivalent $\pi-$ and $PQ-$ representations (Kundur, 1993). The continuous-time dynamic behavior of the electrical and electromechanical variables follows the formulation presented in (Machowski et al., 2008).

During simulation, when a state transition is assigned, protection and control actions may take place in an attempt to improve the system operation. These actions include the basic distribution automation actions plus those which were planned by the software agents. The agent's plans and actions are considered in the simulation model through interaction between the agent architecture and the environment, and following the structure depicted in Fig 9.

As suggested in (Bordini et al., 2007), the overall simulation platform is implemented such that AgentSpeak agents interact through speech-act based communication as well as with a shared environment coded in JAVA language. In this approach, the modeled environment named `DistributionGridEnv` extends JASON's environment class and works with a model class named `DistributionGridSimModel`, which in turn abstracts the combined discrete-continuous simulation. The classes `OperationState`, `StateComposer` and `StateEvaluator` are then responsible to abstract, produce, and evaluate operation states, while the `IndexComposer` class must update and manage the performance indices.
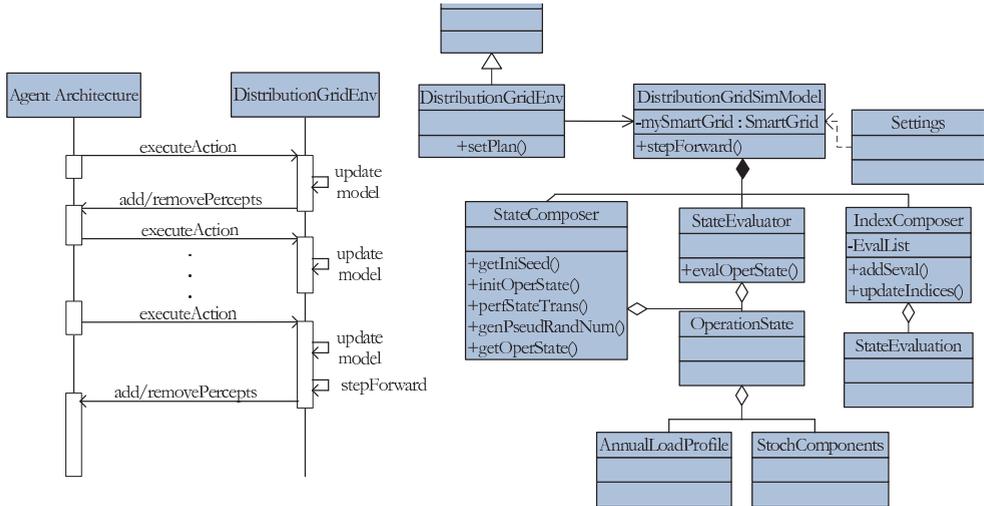
Fig. 9. Diagrams for the environment modeling and its interaction with the agent architecture.

In the whole simulation, each AgentSpeak agent follows a JASON's reasoning cycle where the environment's executeAction method is invoked to control elements of the distribution grid and/or to infer over protection planning. This may cause the model to be updated and *percepts* to be added or removed via addPercept or removePercept method invocation. In case a new *percept* is identified, its correspondent literal ℓ is added to the agent's belief base, as well as the triggering event $+\ell$ is added to the agent's event queue. Depending upon the contexts of the agent's plan library, the triggering event $+\ell$ may (or may not) cause *intentions* to be pursued and, eventually, more interactions with environment. Once all *intended means* are finished, the environment is allowed to step forward up to the next state transition instant by environment's stepForward method invocation. Note that this assumes that agent planning in the field is completed prior to the next state transition. This is considered a reasonable assumption given the step size and hourly resolution of load variation.

As previously remarked, the resultant sequence of operation states is evaluated in terms of performance indices. These performance indices involve both standardized distribution grid reliability indices as well as other user-tailored indices required to verify the impact of DERs on the grid operation. Usually, distribution grids are assessed from a customer service perspective rather than operation state classifications. Hence, customer service information is aggregated in systemic indices. The following systemic indices (Billinton & Wang, 1999; Brown, 2002) are applied in the performance evaluation of the electric distribution grids.

1. System Average Interruption Frequency Index: This index measures how many sustained interruptions an average customer will experience over the course of a year.

$$\text{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customer served}} \tag{2}$$

2. System Average Interruption Duration Index: This index measures how many interruptions hours an average customer will experience over the course of a year.

$$\text{SAIDI} = \frac{\text{Sum of customer interruptions durations}}{\text{Total number of customer served}} \tag{3}$$

3. Customer Average Interruption Duration Index: This index measures how long an average interruption lasts over the course of a year.

$$\text{CAIDI} = \frac{\text{Sum of customer interruptions durations}}{\text{Total number of customer interruptions}} \tag{4}$$

4. Average Service Availability Index: This index measures the customer weighted availability of the system over the course of a year.

$$\text{ASAI} = \frac{\text{Customer hours of available service}}{\text{Customer hours demanded}} \tag{5}$$

5. Average Service Unavailability Index: This index measures the customer weighted unavailability of the system over the course of a year.

$$\text{ASUI} = \frac{\text{Customer hours of unavailable service}}{\text{Customer hours demanded}} \tag{6}$$

6. Energy Not Supplied: This index measures the total energy not supplied by the system over the course of a year.

$$\text{ENS} = \text{Total energy not supplied by the system} \tag{7}$$

7. Average Energy Not Supplied: This index measures the average customer total energy not supplied over the course of a year.

$$\text{AENS} = \frac{\text{Total energy not supplied by the system}}{\text{Total number of customer served}} \tag{8}$$

Load node indices are also considered including the failure rate λ_i, unavailability U_i, mean time to repair r_i, at node i. Furthermore, other load point indices related with steady-state and dynamic behavior are addressed. More details about the simulation model and its evaluation are presented in (Issicaba et al., 2011).

6. Numerical results

This section presents quantitative and qualitative results for the application of the agent-based architecture in a modified edition of the test system RBTS-BUS2-F1 (Allan et al., 1991). Fig. 10 pictures a single line diagram for this system as well as the grid segments for which the block agents are assigned. These assignments were derived from the basic grid protection segmentation given by the breaker positioning.

The design of this system follows general utility principles and practices regarding topology, ratings and load levels (Billinton & Jonnavithula, 1996). Network parameters and additional data are introduced in (Issicaba et al., 2011). Verification and validation of basic performance indices for this system, disregarding any agency, are shown in (Issicaba et al., 2011) as well.
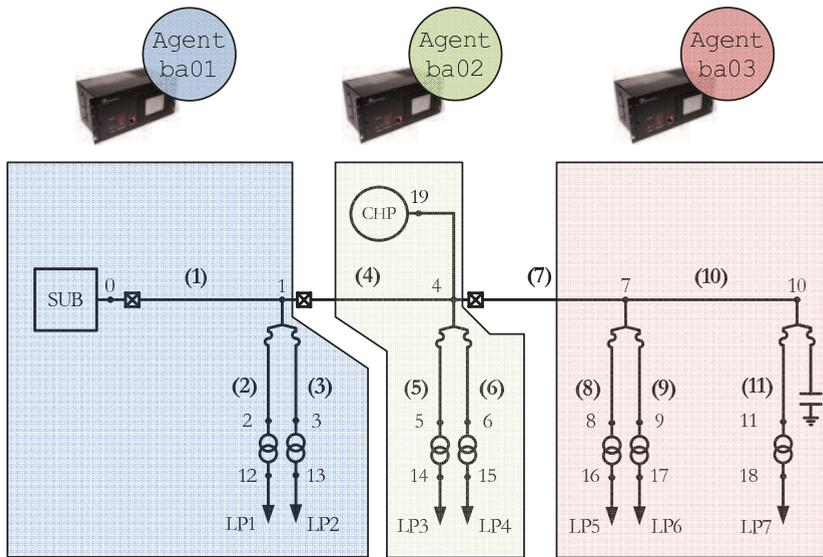
Fig. 10. Distribution network under operation the agent-based architecture support.

The electrical steady-state and dynamic behavior of this system were validated using the power system analysis software EUROSTAG (version 4.3) (GDFSUEZ & RTE, 2004).

Note that the applicability of plans of action depend upon the grid under control. For instance, it is not possible to support voltage control whether equipments to control voltage are not available. Therefore, for the sake of clarity and consistency, the test system was evaluated considering that only the plan `@DGislanded_operation_plan04` and its sub-plans were allowed. Hence, simulation with and without `block` agent were performed. The coefficient of variation (β) minimum value (Rubinstein & Kroese, 2008) was narrowed to 5% and all simulations were subjected to the same seed sequence of events to guarantee the comparison validity. Comparative results are presented in Table 1.

Index	without agents		with agents	
	Value	β (%)	Value	β (%)
SAIFI (interruptions/cust./yr)	0.134205121	1.84714948	0.105423358	1.84002804
SAIDI (h/cust./yr)	3.628097573	4.80371101	3.480572107	4.99916932
CAIDI (h/interruptions)	27.033972705	-	33.015189308	
ASAI	0.999584696	0.00199583	0.999601583	0.00199255
ASUI	0.000415304	4.80371101	0.000398417	4.99916932
ENS (MWh)	8.388050112	3.11734276	8.082481157	3.21803404
AENS (MWh/cust)	0.012865108	3.11734276	0.012396443	3.21803404
Number of simulated years: 12365				

Table 1. Comparative evaluation of grid performance indices

The outcomes show an improvement in quality of service. The most affected index was the SAIFI which reduced 21.45%. This means that an average customer should expect 21.45% less sustained service interruptions during a year due to the agent-based architecture. This was expected since the plan `@DGislanded_operation_plan04` is assigned to the goal *minimize*
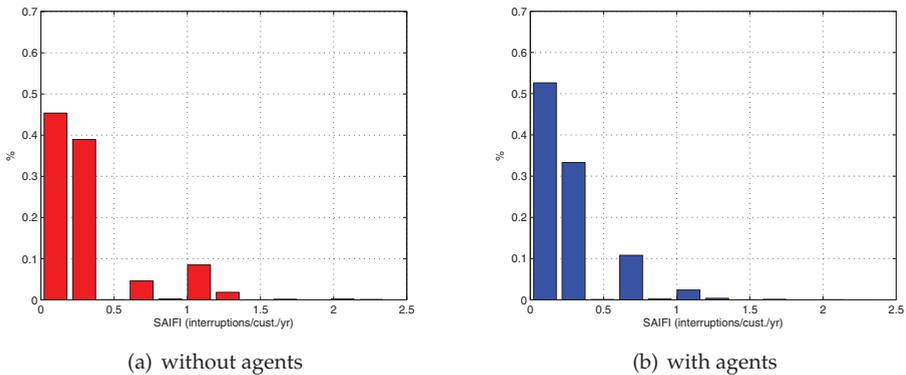
(a) without agents   (b) with agents

Fig. 11. Estimated SAIFI probability distributions.

Node number	without agents			with agents		
	λ	U	r	λ	U	r
12	0.1182	3.7543	3.2633	0.1182	3.7543	3.2633
13	0.1111	3.5390	3.3688	0.1111	3.5390	3.3688
14	**0.1651**	3.5701	3.2666	**0.0761**	3.1140	2.9519
15	**0.1562**	3.7508	3.4494	**0.0672**	3.2963	3.1502
16	0.2137	3.9129	3.5053	0.2145	3.9152	3.5072
17	0.2152	3.6364	3.3204	0.2161	3.6388	3.3224
18	0.2508	4.0187	3.4918	0.2517	4.0211	3.4935
19	**0.1474**	0.7432	0.6927	**0.0584**	0.2871	0.2778

Table 2. Comparative evaluation of load point performance indices

interruptions (see Fig. 5), and infer directly in the grid protection rules aiming at serving the customers through DG islanded operation when necessary.

Since time-dependencies are explicitly represented in the combined discrete-continuous simulation model, the performance index histograms to the distribution grid operation can be rigorously derived. Fig. 11 depicts an histogram of the SAIFI values obtained during the 12365 year simulation (samples). Observe how the actual impact of the agent-based architecture can be enlightened by the index histograms. Due to the agent support, SAIFI values equal or superior to 1 interruption/customr/yr became rarer events and, depending on the quality of service regulation, this may avoid penalties to the utility. Finally, load point performance indices are also shown in Table 2. Nodes 12 and 13 (from block 01) have the same performance indices since they are not affected by the DG islanded operation plans. On the other hand, the performance indices at nodes 14, 15 and 19 (block 02) have improved significantly due to the proximity with the DG and the ba02's planning. In particular, these nodes became more reliable and, consequently, more attractive to the connection of new customers/industries and DGs. Moreover, nodes 16, 17 and 18 kept almost the same indices with slightly differences. Observe that the reduction in customer interruptions is caused by the increase in successful DG islanding processes. Therefore, a larger amount of information about the system electrical/electromechanical dynamic behavior is produced, supporting the establishment of new agent plans regarding control schemes such as load shedding.

7. Conclusion and final remarks

Implementing agent-based systems is an interesting task that involves a lot of correlated areas within the computation and artificial intelligence sciences, as well as specific expertise linked to the application area. In order to reach and implement some fundamental aspects about agent-based systems, it is necessary to use some computational mechanisms that will allow the embodiment of autonomy, intelligence and mobility, among other characteristics, during the agent processing. Since the 1990s, several features have been introduced into the computation area, perhaps affected by the growth of the World Wide Web (www) and the rapid rise of e-Commerce, which enabled the construction of agent-based systems.

Based on these features, it is clear that there is much activity in this area around the world. Several middlewares, platforms, frameworks and environments have appeared in the last years in order to help programmers developing multi-agent systems. In the JAVA world, it is mandatory to highlight first the combination of JAVA, JASON and AgentSpeak as a successful way to code multi-agent systems, and second some advances in the pre-conceptual architectural phase to modeling agent-based systems. Undoubtedly, methodologies such as Prometheus are essential to model any agent-based system.

From the technological front, one of the challenges into smart grid concepts applied to distribution grid automation is to monitor, control, and coordinate the electrical grid efficiently with intelligence. Certainly, agent-based technology may be considered as an efficient way to deal with these challenges, providing flexible and autonomous software systems to solve a growing number of complex problems. This chapter has introduced agent-based technology through the two perspectives: simulation and modeling, and grid automation. Therefore, a new agent architecture was presented, where agent plans can be tested through the reliability studies, highlighting the benefits of some smart control solutions into distribution grids.

8. Acknowledgements

9. Nomenclature

AC   Alternating Current
AM/FM Automated Mapping Facility Management
BDI   Belief-Desire-Intention
CIS   Customer Information System
CT   Current Transformer
DA   Distribution Automation
DC   Direct Current
DER   Distributed Energy Resources
DG   Distributed Generation

DMS   Distribution Management System
EV   Electric Vehicle
FPI   Fault Passage Indicator
GIS   Geographical Information System
IED   Intelligent Electronic Device
RTU   Remote Terminal Unit
SA   Substation Automation
SCADA Supervisory Control and Data Acquisition
TCM   Trouble Call Management System
VT   Voltage Transformer

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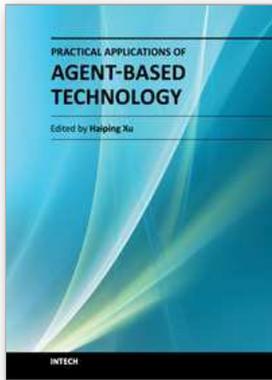
Practical Applications of Agent-Based Technology

Edited by Dr. Haiping Xu

Agent-based technology provides a new computing paradigm, where intelligent agents can be used to perform tasks such as sensing, planning, scheduling, reasoning and decision-making. In an agent-based system, software agents with sufficient intelligence and autonomy can either work independently or coordinately with other agents to accomplish tasks and missions. In this book, we provide up-to-date practical applications of agent-based technology in various fields, such as electronic commerce, grid computing, and adaptive virtual environment. The selected applications are invaluable for researchers and practitioners to understand the practical usage of agent-based technology, and also to apply agent-based technology innovatively in different areas.

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