Intelligent Energy Management System

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***Abstract*- Energy management is nowadays a subject of great importance and complexity. It consists in choosing among a set of sources able to produce energy that will give energy to a set of loads by minimising losses and costs. The sources and loads are heterogeneous, distributed and the reaction of the system, the choice of sources, must be done in real-time to avoid power outage. The goal of this paper is to present a system able to self-regulate a heterogeneous set of power sources and loads organised as a coherent group of entities that is called micro-grid, in order to optimize several criteria such as: cost and efficiency. This system is based upon the Multi-Agent Systems paradigm. Each micro-grid entity is modelled as an autonomous agent able to interact and with it owns decision making mechanism. It takes into account the characteristics of the source or load types it belongs to and self-organizes with other agents in order to globally optimize the given criteria.**

I. INTRODUCTION

Energy management is, nowadays, a subject of great importance, because of the need of facing petroleum shortage and earth global heating. However such a management has to deal with many problems arising from the nonlinearities that may appear, like the behaviour of power converters or the enforcement of constraints of the different components of the system, or from the difficulty in selecting, among a set of sources able to produce energy, the one that will give energy to a set of loads. The sources and loads are of different types and are usually distributed around the main grid. Moreover the prediction about how the system may react as well as the choice of sources must be made in real-time to avoid any power outage. Loads also have a stochastic behaviour which can be partially forecast and can be situated also very far from the source location, which adds the transmission losses. In the end each source has its specific characteristics such as production cost, environmental constraints, capacity, etc, that must be accounted for in the source selection. Finally, the stability issues of a power network with many distributed generation units of significant rating is still an open problem.

The goal of this paper is to present a system able to self-regulate a heterogeneous set of power sources and loads organised as a coherent group of entities that is called micro-grid, in order to optimize several criteria such as: cost and efficiency without any interruption of the load supply, which is a mandatory constraint. Indeed, if the amount of produced energy is not enough to supply the energy demanded by the loads, the system has to supply the difference with the energy available on the grid which is generally more expensive.

The sources in a micro-grid can be photovoltaic arrays (PV), wind turbines (WT), Fuel Cell (FC) systems, batteries or supercapacitors (SC). The last two components can also be regarded either as loads since they can store energy from other components or sources since they can provide energy to the loads when necessary. Each source has an autonomous behaviour, its own characteristics and interacts with the other sources in order to fulfil the system goals. For example, a photovoltaic array generates power from solar radiation and its production can be supposed to be null when no solar radiation is available. As for the FCs it can be assumed that it can supply power at any time depending on the amount of available hydrogen, but limiting its starts and stops to avoid the reduction of the fuel cell lifetime: the best is to start fuel cell if it is supposed to work for long time spans (several days).

The Multi-Agent Systems (MAS from now on) paradigm has been chosen for the design of the energy management system. Each entity is modelled as an autonomous agent able to interact and with its own mechanism for decision making. The characteristics of the source type have been taken into account and each entity collaborates with other agents in order to globally optimize the given criteria. The problem is distributed (geographically), open (new sources/loads can enter/exit the system), dynamic (changes happen during the life of the system both in its parameters and in available system components). This paper is structured as follows. Section II presents the background needed in terms of problem description and MAS principles. Section III details the architecture of the system and section IV shows some experimental results and section V concludes.

II. BACKGROUND

A. Problem description

The optimal management problem consists in fully exploiting the capabilities of renewable sources and accumulation systems in micro-grids defined as coherent groups of sources and loads.

This means optimizing the full exploitation of the renewable sources, minimizing the amount of energy required by the conventional (fossil fuel based) generation plants which is bought from the grid. The microgrid is assumed to have a distributed generation system from renewable sources. Either the storage of energy or the sale of excess energy to the grid are used by the system, whenever there is a positive or

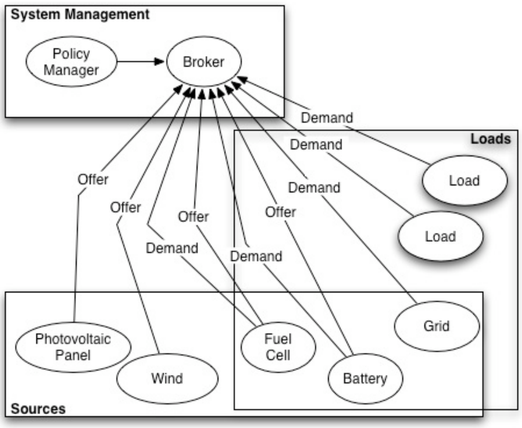

Figure 1. The different agent societies involved in the solution approach

negative difference between the overall power produced by the renewable sources and the loads within the micro-grid. Storage is performed to maximize the life-time of each storage device, minimizing its losses and keeping it fully charged at the beginning of each working cycle.

The components of the micro-grid, called elements from hereon, can be divided into three types: the sources, the loads, and the storage systems.

For each type, several parameters are fundamental, as summarised beneath:

Sources:

- Power: it is the power that the elements can supply to the system, expressed in [W]; the generated power is assumed positive.
- Capacity: it is the amount of energy that the source can supply, expressed in [Wh] the energy supplied from the source is assumed positive.
- Condition: for most renewable sources it is the available power depending on the weather condition (speed of wind, solar radiation, etc…). This parameter is to be known to evaluate the availability of a source.
- Efficiency: it is the ratio between the output and input power of the system (electrical or mechanical power), usually given in % and obviously lower or equal to 100 %. The efficiency can be linked to the produced power, and the maximum power point can be different from the maximum efficiency point.
- Cost: it is the cost of energy. With some sources like wind generator or photovoltaic plant, this cost is composed by two terms: the purchasing cost and the management cost. The former is the initial cost for installing the generation system which must be spread over the entire lifecycle of the system, the latter is the real cost of consuming materials for energy generation. This last cost is basically null for PV and wind plants, while fuel cells have a cost, because of the price of hydrogen. It should be noted that the purchasing cost of the sources has been neglected in this analysis.

Loads:

- Power: it is the maximum power that a load demands, in [W]; the absorbed power is assumed positive
- Reversible: sometimes some loads can be active meaning that they can provide energy; a load generates power, for instance during the descent phase of a lift

Storage systems:

- Charging power: it is the maximum power than the storage system can absorbed while charging in [W].
- Discharging power: it is the maximum power that the storage system can provide to the system in [W].
- Capacity: it is the total amount of energy that the system can store in [Wh].
- State of charge (SOC): it is the current amount of stored energy. It is usually given in percentage of the capacity.
- Efficiency: it is the ratio between the amount of supplied and demanded energy.

The “environment” shared by the element includes the “DC bus”, constituted by two electrical wires and a capacitor.

At this stage, each generation system is modelled as a AC system, meaning that no proper modelization of power conversion part has been done. A further step of the analysis will be the proper modelling of the sources and the corresponding power conversion system (power stage, control system, maximum power point tracking - MPPT).

B. Multi-Agent Systems

An agent is an autonomous and proactive system that evolves in an environment capable of interacting with other agents or with the environment in order to satisfy its objectives [15]. Multi-Agent Systems are used for a wide range of applications such as: complex systems modelling and simulation, open dynamic systems, optimisation, etc.

Among the coordination techniques in the agency field the Contract Net protocol is one of the best-known [14]. The FIPA[1] description of the contract net protocol [7] is adopted in this paper. This protocol is based on two roles: initiator and participant. The initiator is the manager who is interested in delegating a task or asking a service. The participants are the members of the network which can receive the call for proposal and make propositions to the initiator. The first message consists in a call for proposal from the initiator to the participants. The answers to this call for proposal can be to refuse, to send a not-understood message or to make a proposition. In the last case the initiator chooses among the proposals it accepts and refuses the others (or all if no proposal is adequate). Then, after a lapse of time, the participant under contact informs the initiator of the result; which can be a failure, an acknowledgement of the end of the task or a result of the work done.

III. System Architecture

The proposed approach to the problem consists in modelling its fundamental elements by using agents (or agent societies). Figure 1 shows the resulting three main agent societies:

- **System Management:** It is the society where the demand and offer of power are satisfied by adopting a

[1] Foundation for Intelligent Physical Agents in charge of standardization of agents concepts. www.fipa.org.

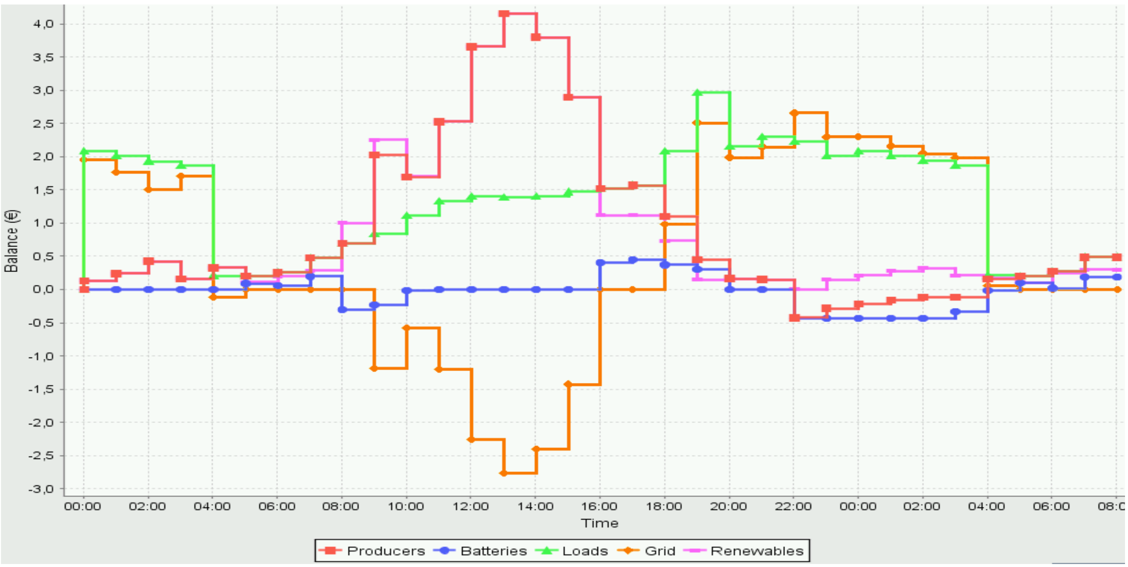

Figure 2. Simulation results for the described case study (power produced/consumed)

general strategy based on physical, ecological, economical constraints and the demand forecast.

- **Sources**: it includes all sources. Grid, Battery and Fuel Cell belong to this society when they produce power.
- **Loads:** it includes external loads, Grid, Battery and Fuel Cells (belonging to this society when asking for power).

The details of each element will be provided in the following.

A. System Management

Broker: It is responsible for the brokerage between Consumers and Suppliers. It gives the list of possible customers to each Buyer which requests it. Then the Buyer is responsible for finding the best offer according to its needs (amount of power, price, duration of the service, …).

Policy Manager: according to previous experience (it is an 'intelligent agent', probably implementing an expert system) it decides which Source can play the role of Supplier or Load. For instance it decides that at a specific time range it would be better to produce hydrogen and it orders to Fuel Cell to buy power (converted in hydrogen by the reforming phase).

B. Source

A source can be modelled by a society of agents as described below for the battery. The Battery society will be reported as an example of source. At this stage the configuration presented below should be sufficient to deal with all the considered sources.

The Battery is composed of the following agents (see):

Buyer: it is responsible for negotiating the purchase of energy for charging the battery. It dialogues with the Broker agent (System Management society). When buying power, the Battery plays the role of *Consumer*. The energy is bought at a price that depends on the seller source. The Buyer agent sends a Demand message to the Broker in order to notify it that he would buy (it also specifies the amount of power it needs) and receives a list of sellers that are available for the specific time slot. The Buyer agents start the negotiating phase and buys at the best price. The implementation of the agent is assumed to use a contract-net protocol for finding the best offer.

Seller: it is responsible for finding a Consumer (one or more) that can buy the produced energy. In this case the Battery plays the role of *Supplier*. It enters into dialogue with the Broker agent in order to get the list of buyers. There can be at least two kinds of price policies: fixed production (free: photovoltaic cells), or variable production (price according to several different parameters: batteries, fuel cells, grid). The goal of the Seller is to gain as much as possible. A discount policy can be offered to some sources for specific hours (this is to encourage battery recharging and hydrogen production for Fuel Cells). Discount policies are decided by Local Managers according to the requests coming from the Policy Manager agent of the System Management society.

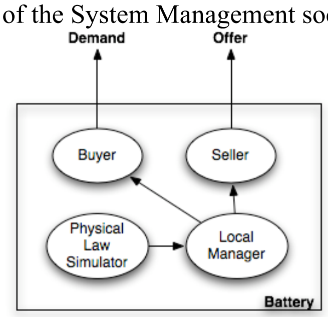

Figure 3. The Battery society reported as an example of both source and load society

Charge Optimizer: responsible for maintaining safe work conditions for the battery. It requests an urgent recharge when the battery voltage goes below a specified value, it also manages the battery charging process by monitoring the received energy and by stopping it when the proper level of charge is reached.

Physical Law Simulator: it is responsible for simulating the battery physical model. It updates the parameters related to the battery lifecycles and computes the available power according to the formulas below.

The physical state of the battery is characterized by the following parameters:

- EN: Nominal Energy of the battery (usually expressed in [kWh])
- Life-cycle: a cycle of charge and discharge of the battery down to the 10% of its rated energy. The producer of each battery declares the average maximum number of admissible life-cycles. Over that number, the performance of the battery degradates drastically. If the discharge goes below 10%, the number of residual cycles and the life of the battery reduces.
- Number of Equivalent Life-cycles: if the battery performs a minimum charge-discharges cycle from 90% to 10% of its nominal energy, it is considered as an equivalent life-cycle. The number of equivalent life-cycles just count the performed cycles.
- NLC: Nominal Life-Cycles. This parameter is declared by the battery producer and represents the battery length of life.
- Daily discharge percentage: the minimum level of battery (assumed here equal to 10% of the rated charge)
- The battery efficiency η is calculated according to the following formulas [13]:

IF $\frac{E}{EN} < 0.2$ **THEN**

$$\eta = \frac{1}{100}\left[-\frac{5}{3}\left(\frac{E}{0.1 * EN}\right)^2 + \frac{290}{3}\right]$$

ELSE

IF $0.2 \leq \frac{E}{EN} < 0.8$ **THEN**

$$\eta = \frac{7}{36}\left(\frac{E}{EN} - 0.8\right)^2 + 0.2$$

ELSE

$$\eta = 0.2$$

Where E= energy exchanged during the time-slot.

Constraints on battery behaviour

- In order to avoid stressing the battery and reducing its life, it is assumed hourly energy variation is not more than 10%.
- The battery cannot discharge to less than the 10% of its EN.

Local Manager: It is responsible for the local policy to be adopted. The local policy is a consequence of the general policy decided by the Policy Manager at the System Management level (for instance Battery sells power from 6 to 8 pm, Battery charges-buys power from 8 to 10 pm). It asks the Seller or the Buyer to start the selling/buying activity when necessary.

C. Wind Plant Society

The configuration of this society is very similar to that represented for the battery, except that Buyer agent is not present. Moreover the Physical Law Simulator agent simulates the physical behaviour of a wind turbine.

Local Manager agent. The behaviour is quite simple, since it always proposes selling all the produced power.

Physical Law Simulator (PLS) agent. It calculates the produced energy on the basis of the wind speed. In the implementation, the plant is assumed to have a rated power of 10kW. It is assumed, as in usual wind turbines, the produced power is proportional to the cube of tangential wind speed as represented in this formula: P[Watt] = α V^3 with α=80 for a 10kW rated power source plant. The selling price for energy is 0,07 €/kWh. (current price at which the national electric energy producer buys energy from local producers).

D. Photovoltaic Panels Society

The structure is very similar to that of wind plants. There is no buyer agent, since this source has no load capability (no storage device in it).

Physical Law Simulator (PLS) agent. It calculates the produced energy on the basis of solar irradiation with a linear law. For a plant with rated power of 10kW, the formula is:

$P = \beta G$

where G is sun radiation and β=10,5 for a 10 kW rated power source plant. This is an approximation that however does not affect the validity of proposed approach.

E. Grid Society

The buyer and seller agents compose it. They always ask to sell and buy an almost infinite amount of power (several magnitude orders greater than power managed within the cell) at a fixed, time-depending price.

F. Loads society

Loads society is composed of cell elements that consume power. They can be actual loads as well as rechargeable elements.

Each load is composed of only two agents: the buyer agent and the physical law simulator agent. The latter is responsible for simulating the physical behaviour of the load according to a prescribed law or by randomly selecting the data set belonging to one day from available historical data.

IV. EXPERIMENTAL RESULTS

The described system architecture has been realised by using the JADE platform and employed to perform several simulation implementing variations of the management policy as well as different configurations in terms of involved network elements.

In order to improve the realism of the simulation, a few sets of environmental historical data have been used for solar irradiation and wind speed. Loads data used to feed the simulator have been collected by real data coming from historical sets of an industrial area and a prevalently residential area. In order to test the behaviour of the system in different conditions, the available sets have been randomly mixed so that meteorological conditions and load values substantially differ from day to day. Simulation is performed in discrete time and parameters can be set in the initial configuration window shown in .

Figure 2 shows simulation results obtained by one of the studied configurations composed by two photovoltaic arrays (maximum power 40kW each), two wind turbines (maximum power 40kW each), two batteries (30KWh nominal each) and one load (described by the already introduced historical data sets).

It is worth to note that the photovoltaic and wind plants are supposed to be positioned in different locations and therefore subject to different meteorological conditions at the same time. This is a simple approximation to the real situation although the correlation between meteo conditions in near locations is not considered (since locations are not defined).

It should be noted that the load curve profile has been set up on the basis of real microgrid load demands respectively in industrial and residential area. The peak power of this microgrid is 30 kW.

Curves in Figure 2 represent exchanged power with the following notation:

- Produced power: the sum of power contributions coming from all sources (wind turbines, photovoltaic plants and batteries if used as source at the specific time)
- Batteries power: the sum of all the power produced or stored by all batteries at the specific time. When positive the batteries are introducing power in the network, when negative the batteries are storing energy.
- Load power: (sum of) the power consumed by the load(s).

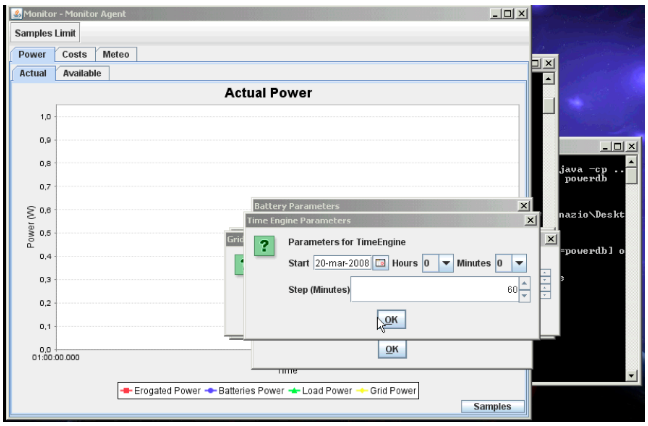

Figure 4. Parameters used to start the simulation. On the back the main window that will show simulation results.

- Grid power: the amount of power provided by the external grid (when positive) or the amount of power provided to (absorbed by) the grid (when negative).

The power produced by photovoltaic plant is shown in Figure 5. This behaviour directly comes from the experimental data recorded on a real plant. This is a typical power curve of a photovoltaic plant on a daily scale, presenting a peak of generated power around noon. The total produced power in Figure 2 takes into account these power profiles. Figure 6 shows the power produced by the wind turbines. At a first approach the behaviour is is governed by sudden quick variations of the wind tangential speed and consequently of the generated power (again data are collected from measures done on a real installation) and therefore the contribution of this source although useful can hardly be used for hourly planning the overall management policy. Figure 7 shows the power supplied by the battery in order to help renewable sources in fulfilling the load demand of power.

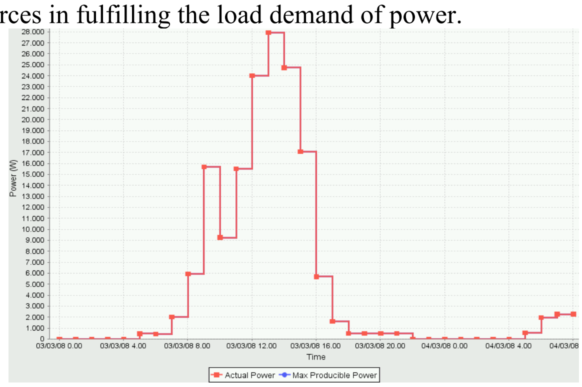

Figure 5. Power produced by photovoltaic plant in the reported experiment

In this figures the following variables are plot: the max producible power represents the maximum power which could be potentially provided by the battery in each time slot. The maximum consumable power, on the contrary, represents the power which could be potentially absorbed by the battery in each time slot; when the battery is fully charged the first gets its maximum value and the second is null. The actual power is the amount of power really given by battery (included its sign). It can be seen that the battery is recharged in time for the expected demand of power forecasted at about 6.00AM. Battery recharging policy is one of the most important tasks (in order to ensure power availability in critical hours) and in the proposed experiment it is performed during night time (even by buying energy from the grid if necessary) and every time an excess of renewable power is available.

The selected management policy prescribed that batteries are totally recharged during night time in order to be able to contribute to fulfil peak demands of power in the following morning. This can be easily seen in Figure 2 (from 22:00 to 4:00) as well as it can be noted that during day time from (5:00 to 18:00) no grid power is required (power is even sold to the grid in part of that period) because renewable sources and batteries are sufficient to fulfil load's needs.

It should be noted whenever the power from renewable is positive and it is higher than the load power, the battery charges. When the accumulation system is completely charged the excess of power is sold to the grid: in this case grid power is negative.

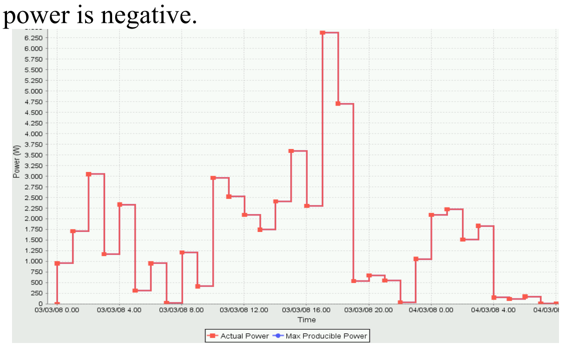

Figure 6. Power produced by wind turbines in the reported experiment

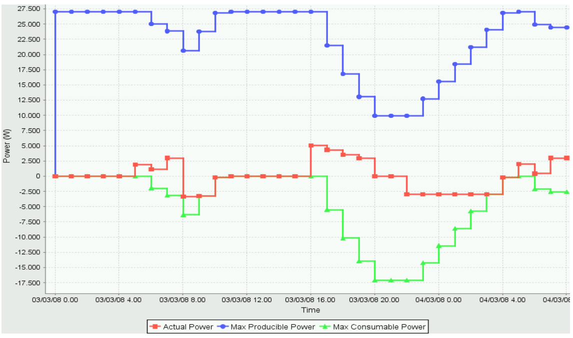

Figure 7. Power supplied by the battery (maximum available power is reported as well)

The dual situation exists when load power is generated from renewable sources. In this case the accumulation system gives the whole charge and the remaining power is provided by the grid.

V. RELATED WORKS

Considering the importance of energy management and the different problems raised it is not surprising that there exist several works on this subject. Some of these works, [1,8,5,10,4,3], use optimisation techniques such as genetic algorithms or neural networks in order to control or predict a sub-network similar to what we called micro-grid. The main problem with such approaches is that they do not take into account the openness of the problem. It means that sources and loads are known by advance and cannot change. Moreover, the control is centralised in a main algorithm which make it unscalable and do not allow to express local rules and handle them. The Contract Net protocol [14] has already been used in MAS dedicated to power management [6,9]. This paper uses an organizational model based on different societies of sources and loads and an enriched interaction protocol (FIPA version [7] of the CNET protocol [14]). MAS have also been applied to similar problems such as the approach proposed in [2] but they frequently use unrealistic energy models. For a survey on MAS for energy management the reader can see [11,12].

VI. CONCLUSION

This paper presents an Intelligent Energy Management System based on MAS. The system is composed of different type of energy producers, called sources, and energy consumers, called loads. Each source or load is represented by an autonomous agent able to take decisions and interact with other agents according to its current state and specific goals. The MAS controls a coherent set of sources and loads connected to the grid. Interactions between agents are based upon the contract net protocol.

This system has several advantages. First, each sources or loads can have specific (and separate) characteristics, constraints and decision mechanisms. In this way, it is easier to model each entity (source or load). Second, as each agent is independent, the system is open in the sense that sources and loads can appear or disappear during the system lifetime. Third, the interactions-based management approach allows the system to self-organize in order to satisfy the goals and constraints of each agent. A state satisfying all agent goals and constraints is a kind of optimal solution for the energy management problem.

In the future we plan to make more experiments using the implemented simulator and real testbeds. Moreover, we are designing other techniques for agent decision-making. For instance we are working on a learning mechanism that could prove useful in order to learn new and more efficient management strategies.

ACKNOWLEDGMENT

The authors would like to acknowledge the contribution of Ignazio Lipari in the realization of the simulation software system.

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