Multi-Agent Systems For Grid Energy Management: A Short Review

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***Abstract*—The electric grid is currently undergoing important changes: it is evolving from an entirely centralized structure to a decentralized one, mainly due to the massive development of distributed renewable energy sources. This evolution toward what we now call the smart grid requires new control methods. These methods must be able to withstand new requirements, such as the highly distributed nature of the grid, the ability to run in islanding mode, the intermittency of renewable energy sources or the limited bandwidth for communication.**

Multi-agent systems (MAS) have characteristics that meet these requirements, in contrary to classical analytical methods: the grid is considered as a collection of simple entities called agents corresponding to sources, loads and other components, and evolving in a given environment. A certain degree of distributed or collective intelligence can be achieved through the interaction of these agents with each other, cooperating or competing to reach their goals.

This article is a short review of several multi-agent systems published in the literature and used for grid energy management. It presents a number of concepts and experiments used by researchers to apply this promising method. Various approaches and their results are compared, in order to give the reader a global perspective of the state of the art in this precise domain.

I. INTRODUCTION

Population and economic growth throughout the world are currently provoking tensions in the energy sector: demand is continuously increasing, while environmental regulations, like carbon dioxide emissions limits, are getting stricter and stricter. And we cannot expect to see these tendancies change in the coming decades. As a consequence, the electrical grid, which is one of the main infrastructures for energy transport, has to evolve to adapt to this new situation.

The backbone to this renewed electrical grid is known as the smart grid, a wide concept in which a modernized electrical grid with large proportions of carbon-free energy resources will interact with a communication and control network. By allowing a new decentralized structure to exist, electricity generation will happen in much lower scales in terms of power and in much higher scales in terms of generator count. In other words, we will have to manage a lot more generators with low power ratings ; one large coal-fired plant could be replaced with several hundreds of wind turbines.

This evolution will cause a major problem: how do we manage the energy of so many generators and use it efficiently and reliably with even more loads? Classical control methods are not well suited for systems of this scale, and another control system must thus be found. Multi-agent systems (MAS), a theory mostly used in computer science until recently, are a very promising alternative solution.

The following of this paper gives a review of how multi-agent systems are used as energy management tools in the literature. Section II gives information about multi-agent systems in general and their main characteristics. Then, the following section III, is a state-of-the-art of several publications in which MAS are used for grid energy management. The various simulations and experiments conducted by researchers to test their MAS are detailled in section IV. Finally, section V is a short discussion about existing and future MAS and their application to grid energy management.

II. A POWERFUL CONTROL METHOD, MULTI-AGENT SYSTEMS

Multi-agent systems are not new. Their first consistent descriptions in the literature trace back to the 1990's, as in [1]. Their existing applications range from crowd management to robot automation, biomedical simulations and power engineering.

A. *Definition*

Agency and agents are concepts that are rather difficult to define, and the multiplicity of existing definitions tends to prove it. Basically, a MAS can be viewed as a collection of autonomous and intelligent entities called agents, evolving in an environment they can perceive and act on. This environment can be considered as everything but the agent itself.

These agents have a kind of intelligence of their own that gives them a certain degree of autonomy, depending on how they are structured. They can have beliefs, desires and intentions, as in the BDI model (Beliefs, Desirs, Intentions) [2], but also some precise knowledge, etc. (see Fig.1 for an example). According to McArthur *et al.* [3], these properties give them three main characteristics:

- reactivity: they can react to changes rapidly,
- pro-activeness: they are driven by their objectives,
- social ability: they can negociate, cooperate or compete by communicating with each other in a common language.

Several types of agents exist, with various degrees of intelligence [1]. For example, simple agents, called reflex or reactive agents, only show some simple reactions to stimulis and are mostly used when fast response times are needed, like for protection. However much complexer agents, such as intelligent agents, have extended intellectual capabilities and can use their resources and skills to reach their goals. Learning agents can gain knowledge from their environment, for instance. For MAS, the role of the environment is essential. The separation between agents and their environment allows them to be distribuable and thus used in very diverse kinds of situations. The intelligence of each agent is not handicaped by a change of environment. On the contrary, agents will react differently depending on their surroundings.

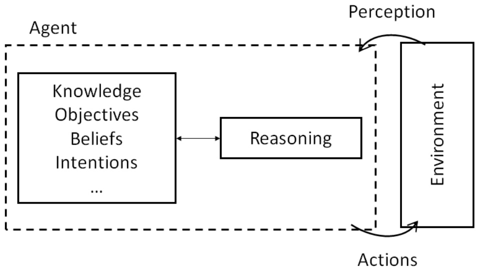

Fig. 1. An intelligent agent can have several different structures, and have beliefs, goals, intentions, etc. Their other specificity is their ability to percieve and interact with their environment.

The inner strengh of MAS, at least in the case of energy management, is the ability of agents to interact with each other. An interesting analogy of a MAS is a human group: some aspects of agents can remind us of humans living among a society. By communicating with each other, agents can coordinate themselves and cooperate to try to achieve a common goal. Together, all agents thus have a form of distributed or collective intelligence.

B. Advantages of MAS

One might wonder what are the advantages of MAS over classical analytical control methods. Classical control methods are indeed fully functional in today's grid: analytical methods, neural networks, expert systems, artificial immune systems [4], etc. However, they will be too limited and far too complex to implement in the future smart grid, made of hundreds of thousands of controlable appliances: they are unable to work efficiently on large scale and faulty systems. These methods require larges amounts of data to be transmitted and processed, which is very cost-intensive. MAS differentiate themselves from these techniques with three main advantages:

- *Their view of the environment is local and their knowledge limited.* Their view can be limited to their neighbors and/or the other agents they need to know of. This property is a requirement in the case of a very large system. The usefulness of this property is linked to a communication problem: the more agents are known, the more they need to communicate with each other to cooperate, even though agents only need to know about their close neighbors. This is a decisive reason in why MAS are chosen for grid energy management: if the view of agents can be limited to their neighbors in the grid, the microgrid they belong to, the amount of data to be transmitted (and the corresponding costs) is dramatically reduced in comparison to other communication-intensive methods. A simple example would be an agent managing the energy at a house: it needs to know of the neighbors' houses and of the other microgrids' connection points to exchange power with them, but knowing about another house 1000 km from there is entirely useless. Having very limited needs, a MAS is thus scalable.
- *They are flexible, plug & play and fault-tolerant.* The structure of a MAS or of its environment can change without any significant consequence for the functioning of the MAS itself. In the case of a grid, if a generator or a load is added or deleted (that is, turned on or off), the MAS will acknowledge this modification and take it into account. This is a substantial evolution in comparison to analytical control methods, were all possible events and changes have to be taken into account when designing the control system. Here, the MAS is capable of doing it by itself. Fault-tolerance can be observed when a part of the MAS fails, due to a broken component or a cut communication channel. A MAS is capable of continuing to work (trying to reach its objectives) even without some parts of its structure and can adapt to it. Another interesting aspect of flexibility in MAS is the possibility to add new functionalities without having to completely redesign the system.
- *They are well-suited for distributed problems.* The two previous characteristics enable this third one: MAS are well-suited for solving difficult problems, where the computation can be distributed among several agents. Thanks to the ability of agents to operate autonomously if needed, and together as a MAS at the same time, the complexity of the control system can be highly reduced by distributing it among communicating agents. In fact, this is what a MAS for a smart grid would do: the whole smart grid will be divided into microgrids containing several generators, loads and storage devices. Intermediary layers, consisting of groups of microgrids for example, may be added inbetween. The control of the grid is thus decentralized, unlike today's control systems like SCADA (Supervisory Control and Data Acquisition): a bottom-up approach needs to be used. Decisions, like accepting to execute an action, can be taken locally or in a distributed way. A consequence of this is that agents are not dependent on a physical support, and can be located anywhere if they can communicate with the system.

In addition to these characteristics, other advantages can be mentionned, like the fact that a MAS architecture is not dependent on a particular technology: different programming languages can be used and interact together, if proper messaging tools are used. Some basic standards were created by the Foundation for Intelligent Physical Agents (FIPA) [5] for agent creation, communication, etc. to help achieve interoperability of MAS.

III. MAS FOR GRID ENERGY MANAGEMENT

McArthur *et al.* [3] and Funabashi *et al.* [6] explain that MAS have been applied to several types of problems in power engineering: diagnostics, distributed control, modeling and simulation, protection, maintenance scheduling, etc. This paper focuses mainly on distributed control, and more precisely on energy management in (micro)grids.

A. MAS design methodologies

In order to design a MAS, several methodologies exist, like Gaia introduced in [7] and used in [8]. Their process is often the same: specify, analyze and design. Specifying the system and its objectives carefully is essential in determining what its tasks are. From this, the roles of the agents can be defined and some models created. The interactions between agents are then listed, leading to a basic MAS.

To define these interactions, FIPA proposes a platform allowing agents to communicate with each other, by defining a standard for messaging and creating two directory concepts: an agent management service (like white pages, a list of registered agents) and a directory facilitator (like yellow pages, a list of registered services) [9]. Regarding communications, they are usually based on languages like ACL (Agent Communication Language) and KQML (Knowledge Query and Manipulation Language), that define how messages are written. Ontologies also play an important role by defining which vocabulary the messages use: they help to define concepts and how they relate to each other [10], [11], [12].

In terms of implementation, agents can seen as three-layered architectures [9] as in JADE: a message handling layer for processing messages, a behavioral level for defining when tasks are to be carried out, and a functional level for defining the actions the agent will perform.

For those interested in designing their own MAS, McArthur *et al.* [9] lists several interesting methodologies, recommandations and tools for designing and implementing a MAS for power engineering.

B. MAS platforms

Many different tools are available for designing and implementing MAS, like JADE, ZEUS, SkeletonAgent or MadKit [11]. The most commonly used for the type of applications we are interested in is Java-based JADE [13], which supports FIPA standards and appears to have a good documentation [14]. Another advantage of JADE is the existence of a directory service (similar to white and yellow pages) which is useful for listing agents and their abilities. In the following, [14], [15], [16], [10], [17] have chosen to use JADE, whereas [11], [12] chose ZEUS over JADE for its friendlier GUI (Graphical User Interface), and others developped their own framework as [18] or [19].

C. MAS architectures

Due to the multiplicity of systems to manage and the degrees of intelligence of agents, many different MAS architectures are possible. However, most papers show a basic structure based on two or three hierarchical layers as in [20], [17] or [15] (see Fig.2):

- a top layer corresponding to a distribution network operator and a global market operator, that coordinate several microgrids by optimizing global energy market operations at a strategic level,
- an intermediary layer with microgrid operators, in charge of coordinating the components of a microgrid: these agents optimize the operation of the microgrids by dispatching energy between generators and loads,
- and a bottom layer with the agents controlling each of these components (usually generators, loads and storage), with various degrees of intelligence giving their ability to react in real time.

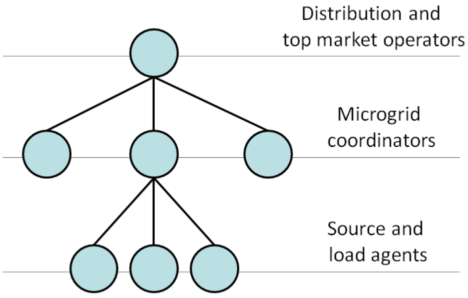

Fig. 2. Most papers use a two- or three-layered architecture for their MAS, made of distribution network and market operator agents, microgrid coordinators and sources and loads agents. Each circle represents an agent.

Due to a lack of standards in this field, several other types of architectures exist. As in [21], types of agents can fall into two categories: traditionnal agents, like generator and load agents, and ancillary agents, used for forecasting, trading, planning and other roles. A management category is added in [17]. To give a few more precise examples, Rumley *et al.* [18] use three types of agents: feeders (load masters), loads and neutral agents. For Pipattanasomporn *et al.* [11] and Feroze [12], it is four: distributed energy resources, control, user (to display information) and database (created by the MAS framework ZEUS) agents. In [14], other types are added: buyer and seller as previously, but also bulletin board, weather forecasting, monitoring, price aggregation and manager agents. A particular architecture named ABCDIR (Agent-Based Control of Distributed Infrastructure Resources), based on many types of agents and groups of agents called globs and co-ops, is presented in [8] with extensive explanations. Other architectures can be found, like in [22], in [23] with the PowerMatcher system, or in [19] were only traditionnal agents are used.

D. MAS and agent goals

A MAS has the advantage of allowing two types of goals to be defined: local and global goals. Generator, load and storage agents, named local controllers in [15], have their own goals that can be, for example, to sell as much energy as possible for generators and to buy the cheapest energy for loads (if they are in a competing energy market, which is not always the case). Microgrid agents, similarly, can try to minimize imports and maximize exports from and to the main grid. A hierarchy of goals must also be established to avoid conflicts: the most important one is to match demand with generation, and only then come economical concerns which appear with the liberalization of electricity markets [10]. An extensive list of local and global goals is given by Kaegi-Kolisnychenko [20] for the studied architecture.

E. Power dispatch algorithms

In order to efficiently dispatch power between generators and loads, various approaches are available. All these approaches try to match generated power with consumed power (in other words, clearing the market: demand = offer), as their prioritary task, but the method they use differs.

Most algorithms are market-based and aim at minimizing costs: load and generator agents announce their bids and coordinator agents try to match them according to these prices and the corresponding powers. The way initial bidding prices are rarely discussed, but can for instance be determined based on operational costs for generators or on current spot market prices for power bought or sold from the grid.

Dimeas and Hatziargyriou [17] use such an auction algorithm in order to solve the "symmetric assignment problem" of power dispatch. This algorithm uses several iterations, were agents can negociate with each other, to find a compromise between generation and demand bids, similarly to the economical offer-demand concept. Coordinating agents manage the auction by setting the rules and announcing the start and the end of the rounds. Another similar auction algorithm is proposed in [20].

In some more advanced algorithms, agents are capable of forecasting what they should be able to produce or consume in the future, with a certain probability. Forecasting of renewable energy resources production is difficult due its dependence on weather. This field is still little explored, but some papers already take it into account. Most of the time, forecasting is only simulated (i.e. the algorithm only receives forecasting results). In [6] and [17] for instance, agents have to announce what they will produce or consume in the next 15 minutes, while in [16] and [20] use day-ahead forecasting.

One might wonder what forecasting is useful for. It is essential in making scheduling possible. Thanks to this, agents can know in advance what they will have to do in the near-future and can thus optimize their functioning according to that. A simple example is stopping a turbine for maintenance: if the MAS can know in advance that the turbine will be stopped, it can try to find an alternative to the power of the turbine by starting another one or finding another available generator without have to shed loads.

A common dispatch procedure is detailled in [6]: a microgrid coordinator then makes a priority list of the offers and pairs them. If the pairing is not perfect, the remaining energy is sold to the main grid, and the missing amount of energy is bought from the main grid (without any limit). Pairing is achieved thanks to buyer and seller agents spawned by load and generator agents, increasing the number of agent types to six. The number of these seller and buyer agents depends on the amount of energy to be sold or bought: one agent corresponds to a fixed amount of power, 10 kW for example. The same process is being used for buying and selling power to the grid.

Logenthiran *et al.* [15] use short-term contract nets, for their simplicity and allowing changes in the topology of the MAS whithout much impact on the dispatch performance. However, in this case, agents are not able to negociate. It also uses an algorithm named PoolCo to dispatch energy based on an energy market and schedules. Load controllers can submit bids for buying and selling power from each other (the transactions are managed by the microgrid controller), and microgrid controllers can do the same from other microgrids (managed by the top market operator).

Numerous other publications examine how these algorithms work and evaluate their performance ; even a patent was applied on one [24]. A mathematical background to energy dispatch is provided in [17]. Interesting details (price volatility, dispatch and commitment algorithms, etc.) can be found in [20]. These problems being too specific for the scope of this paper, they won't be further analyzed here.

F. Other interesting aspects

Some papers explore several aspects that other papers tend to neglect. For example, in [18], Rumley *et al.*'s dispatch algorithm takes into account line characteristics (like losses, voltage drops and thermal limits) to estimate the maximum power a line can stand, and hereby select the appropriate power dispatch solution. However, agents are not synchronized, which would be problematic in a real test case. A short study of the complexity of the algorithm and an estimation of the number of messages exchanged between agents are also provided. Kaegi-Kolisnychenko [20] also proposes a reconfigurable zoning algorithm, in order to determine the influence zone of each generator over its neighboring loads, and that can overlap several hierachical levels. Solutions for zone exploration (so that each agent can have actual data about its neighborhood ; an alternative to the directory method of [15]), demand elasticity, voltage control and supply restoration are also presented.

Feroze [12] includes a degree of demand side management with two types of loads: critical and critical loads. This allows to decide which loads to shed first in case of a lack of power, and test if critical loads can be powered correctly with renewable energy sources in case of a power outage. Philips *et al.* [8] and Kok *et al.* [23] propose two solutions to categorize sources, loads and other grid components in order to help simplify the creation of the ontology and of the agents. Hiyama *et al.* [25] and Dimeas and Hatziargyriou [17] take into account communication delays that degrade the performance of the load-following system. The number of iterations required by the auction algorithm for dispatching power is studied in [17]. Finally, Tolbert *et al.* [21] describes agents for stability, in charge of compensating non-active and reactive current.

IV. MAS TEST CONFIGURATIONS

Let us now see what kinds of grids the previously mentionned MAS were tested on. But before proceeding to that, we need to define what a microgrid is. This type of small grids is indeed commonly used for MAS tests.

A. An elementary grid structure, the microgrid

The smart grid is expected to evolve into a multitude of small and interconnected local grids [22]. The deregulation of the electricity markets in many countries, and especially in Europe, should allow easier entry and exit of energy producers into the market. This should in turn foster the development of low-power renewable energy resources in a distributed, or decentralized, way.

These local grids are called microgrids and simply consist in an aggregation of energy sources and loads connected to the same low-voltage electrical network. Energy sources can range from natural gas microturbines to solar panels or wind turbines. Some microgrids also include energy storage devices, such as batteries or pumped-hydro, in order to help improving the energy efficiency of the local grid.

Another particularity of microgrids is their ability to operate in two ways: either connected to the main grid or in islanding mode. In the former case, the microgrid can exchange energy with the neighboring microgrids and the rest of the grid, whereas in the latter one, the microgrid is isolated. This particular situation can occur if the microgrid is located in a geographically isolated area, or in case of a power line failure. For example, thanks to solar panels, some prioritary loads can be powered even without access to the main grid, with the MAS detecting and adapting to this new situation. In the real world, examples of microgrids include large shopping centers, campuses or industrial parks when connected to the main grid [6]. In islanding mode, microgrids are already commonly being used in islands distant from coasts or in remote communities, in the mountains for example.

The relative simplicity of these microgrids makes them an interesting choice to run tests for new control theories like MAS. Rahman *et al.* [22] even presents a new concept based on microgrids: intelligent distributed autonomous power systems (IDAPS), where demand is supply-driven (instead of the contrary for today's grid). They represent an elementary grid structure that is representative for most of the grid's control issues, except scalability of course. Microgrids can also integrate thermal generation with electricity production, as in [23].

B. Computed-based simulations

In most architectures, the scale of the grid is limited to a few interconnected microgrids or a single one. Most of these microgrids are made of all or some of the following components: photovoltaics, microturbines, small wind turbines, loads and battery storage. For example, Funabashi *et al.* [6] use a microgrid with photovoltaics, a microturbine, a fuel cell, three loads and a grid connection to test its MAS. The originality of the tests of this paper is that they clearly take into account the influence of weather. Three test cases are defined: one in a fine and sunny day, another on a rainy day, and a third one on a fine day but with clouds at 1pm. Negociations are carried out every hour, and their results show that prices tend to increase when the weather is bad or not windy (meaning less power will be available).

Pipattanasomporn *et al.* [11] and Feroze [12] simulate a simple microgrid in Matlab in order to analyze the behavior of the microgrid in case of a connection fault. Component models run on one computer with Matlab and communicate with another one hosting the MAS, through FIPA standard messages sent over TCP/IP. Rahman *et al.* [22] describes a simulation based on data from the microgrid on Virgina Tech's campus. A webservice is used for interfacing a Matlab/Simulink model of loads and generators with the MAS. Philips *et al.* [8] base their tests on a military four-tent microgrid, consisting of several controlable generators and loads. Tests are run with Matlab/Simulink and the implementation of the MAS and its simulation results are largely discussed in the report. Logenthiran *et al.* [15] compare the results of the MAS it proposes with these of PowerWorld Simulator, a commercial product for grid simulation. Results from the same simulated grid show that the MAS performs well. Rumley *et al.* [18] compare their results with Nagata and Sasaki's [26] and find satistying results. In [23], a field test is run with five differents installations gathered into a virtual power plant. A large network containing 154 buses and 9 generators, which is much more complex than the other structures, is used in [20], extensive tests are run on the proposed algorithms.

C. Real scale tests

Computer-based tests are essential, but real scale tests are required to validate the proposed algorithms. In the reviewed publications, several examples can be found. At first, in [14], within the GridAgents framework, a MAS has been deployed to control hardware at several locations in Australia. PDAs are connected to loads and generators and computers are used for more computationally-demanding tasks. A microgrid includes loads (an HVAC and two cool-rooms) and classical generators (such as a gas turbine, photovoltaics, a wind turbine and battery storage). Communications are IP-based, and use both wireless and wire technologies.

Dimeas and Hatziargyriou, in [10] and [16], describe a MAS installed on the Greek island of Kythnos within the MORE-Microgrids European project. The choice of this location results of a new code that regulates operational and technical aspects of energy production, by providing equality between private and public generation means, competing on the same energy market. The microgrid there is made of photovolaics, battery banks and a diesel generator. It uses single phase AC for power transport, PLC and RS485 for data transport, and powers 12 houses. It is controlled using a computer with JADE and a load controller on Windows CE. Current, voltage and frequency are monitored by an intelligent load controller (ILC) developped during the project. Due to the isolation of the microgrid, intelligent load shedding allows to distribute the load shedding to several houses instead of just one.

V. CONCLUSION AND PERSPECTIVE

This paper showed that MAS are very promising, but also that the lack of standards induces a very large variety of techniques and methods being used in the literature. MAS are emerging as a new paradigm for controlling and managing energy in modern grids such as microgrids and smart grids. Moreover, no real alternative appears to offer equivalent results with a similar infrastructure (especially in terms of data volume and computational power). Efficient energy management being a necessary condition for making the smart grid real, MAS will most probably play an important role in the years to come.

However, much work still has to be done before industrial products can be commercialized. Although the performance of MAS is interesting and allows new functionalities such as scheduling, storage or emergency islanding, some issues still need to be tackled. The main ones are stability issues (frequency, voltage, etc.), which were not discussed in this paper and still need to be investigated precisely, and market-based energy dispatch, which is still nascent. An appropriate degree of decentralization will also have to be found: a full decentralization would probably not be optimal, as with full centralization. Large scale tests should also be run, but will require high computational power in order to simulate an entire grid and validate the MAS. Roossien [27] proposes a first approach in this direction. Other problems, linked to MAS themselves, like data security, ontologies and platforms are also raised by McArthur *et al.* [3]. Once these problems will have been solved, precise standards will have to be developped in order to allow a large scale deployment of MAS in the industry.

REFERENCES

[1] J. Ferber, *Multi-Agent Systems: An Introduction to Artificial Intelligence*. Addison-Wesley, 1999.

[2] M. Wooldridge and G. Weiss, *Multi-Agent Systems*. The MIT Press, 1999.

[3] S. McArthur, E. Davidson, V. Catterson, A. Dimeas, N. Hatziargyriou, F. Ponci, and T. Funabashi, "Multi-Agent Systems for Power Engineering Applications - Part I: Concepts, Approaches, and Technical Challenges," *Power Systems, IEEE Transactions on*, vol. 22, no. 4, pp. 1743 –1752, nov. 2007.

[4] V. Hilaire, A. Koukam, F. Lauri, M. Cossentino, and M. Cirrincione, "An energy management solution based on artificial immune systems and agents," 2010.

[5] (2010) Foundation for Intelligent Physical Agents. [Online]. Available: www.fipa.org

[6] T. Funabashi, T. Tanabe, T. Nagata, and R. Yokoyama, "An autonomous agent for reliable operation of power market and systems including microgrids," in *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on*, april 2008, pp. 173 – 177.

[7] F. Zambonelli, N. Jennings, and M. Wooldridge, "Developing multiagent systems: The Gaia methodology," *ACM Transactions on Software Engineering and Methodology (TOSEM)*, vol. 12, no. 3, p. 370, 2003.

[8] L. Philips, H. Link, R. Smith, and L. Welland, "Agent-based control of distributed infrastructure resources," Sandia National Laboratories, Tech. Rep., 2006.

[9] S. McArthur, E. Davidson, V. Catterson, A. Dimeas, N. Hatziargyriou, F. Ponci, and T. Funabashi, "Multi-Agent Systems for Power Engineering Applications - Part II: Technologies, Standards, and Tools for Building Multi-agent Systems," *Power Systems, IEEE Transactions on*, vol. 22, no. 4, pp. 1753 –1759, nov. 2007.

[10] A. Dimeas and N. Hatziargyriou, "Control agents for real microgrids," in *Intelligent System Applications to Power Systems, 2009. ISAP '09. 15th International Conference on*, nov. 2009, pp. 1 – 5.

[11] M. Pipattanasomporn, H. Feroze, and S. Rahman, "Multi-agent systems in a distributed smart grid: Design and implementation," in *Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES*, march 2009, pp. 1 – 8.

[12] H. Feroze, "Multi-agent systems in microgrids: Design and implementation," Master's thesis, Virginia Polytechnic Institute and State University, 2009.

[13] (2010) Java agent developpement framework. [Online]. Available: http://jade.tilab.com/

[14] G. James, D. Cohen, R. Dodier, G. Platt, and D. Palmer, "A deployed multi-agent framework for distributed energy applications," in *AAMAS '06: Proceedings of the fifth international joint conference on Autonomous agents and multiagent systems*. New York, NY, USA: ACM, 2006, pp. 676 – 678.

[15] T. Logenthiran, D. Srinivasan, and D. Wong, "Multi-agent coordination for DER in microgrids," in *Sustainable Energy Technologies, 2008. ICSET 2008. IEEE International Conference on*, nov. 2008, pp. 77 – 82.

[16] A. Dimeas and N. Hatziargyriou, "Design of a MAS for an island system," in *Intelligent Systems Applications to Power Systems, 2007. ISAP 2007. International Conference on*, nov. 2007, pp. 1 – 3.

[17] ——, "Operation of a multiagent system for microgrid control," *Power Systems, IEEE Transactions on*, vol. 20, no. 3, pp. 1447 – 1455, aug. 2005.

[18] S. Rumley, E. Kaegi, H. Rudnick, and A. Germond, "Multi-agent approach to electrical distribution networks control," in *Computer Software and Applications, 2008. COMPSAC '08. 32nd Annual IEEE International*, 28 2008-aug. 1 2008, pp. 575 – 580.

[19] J. Lagorse, D. Paire, and A. Miraoui, "A multi-agent system for energy management of distributed power sources," *Renewable Energy*, vol. 35, no. 1, pp. 174 – 182, 2010.

[20] E. Kaegi-Kolisnychenko, "Distribution management system including dispersed generation and storage in a liberalized market environment," Ph.D. dissertation, EPFL, Lausanne, 2009.

[21] L. Tolbert, H. Qi, and F. Peng, "Scalable multi-agent system for real-time electric power management," in *Power Engineering Society Summer Meeting, 2001. IEEE*, vol. 3, 2001, pp. 1676 – 1679 vol.3.

[22] S. Rahman, M. Pipattanasomporn, and Y. Teklu, "Intelligent distributed autonomous power systems (IDAPS)," in *Power Engineering Society General Meeting, 2007. IEEE*, june 2007, pp. 1 – 8.

[23] J. K. Kok, M. J. J. Scheepers, and I. G. Kamphuis, *Intelligent Infrastructures*, 2010, ch. Intelligence in Electricity Networks for Embedding Renewables and Distributed Generation, pp. 179 – 209.

[24] G. L. Gibson and W. Troxell, "Agent based auction system and method for allocating distributed energy resources," US Patent WO/2007/065 135, 2007.

[25] T. Hiyama, D. Zuo, and T. Funabashi, "Multi-agent based control and operation of distribution system with dispersed power sources," in *Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES*, vol. 3, oct. 2002, pp. 2129 – 2133 vol.3.

[26] T. Nagata and H. Sasaki, "A multi-agent approach to power system restoration," *Power Systems, IEEE Transactions on*, vol. 17, no. 2, pp. 457 –462, may 2002.

[27] B. Roossien, "Field-test upscaling of multi-agent coordination in the electricity grid," in *Electricity Distribution, 2009 20th International Conference and Exhibition on*, june 2009, pp. 1 – 4.