Applications of Multi-Agent Systems in Smart Grids: A Survey

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***Abstract*— The Smart Grids (SGs) are regarded as the new generation of electric power systems, combining the development of Information Technology (IT), distributed systems and Artificial Intelligence (AI) for more features on the real-time monitoring of the Demand / Response (DR) and the energy consumption. An approach based on the use of Multi-Agent Systems (MAS) to study the management of distribution systems, simulating the characteristics of SG. This paper presents the different platforms used for the implementation of MAS for the control and operation of smart grids. The MAS' applications in SG available in the literature are also developed in this paper.**

Keywords – Smart Grid; distributed systems; Artificial Intelligence; Multi-Agent Systems.

I. Introduction

The need for new energy strategies that are efficient and sustainable has stimulated the development of the Smart Grid where power generation is gradually shifting from few large centralized conventional generators to many small decentralized distributed energy generators. Future SGs will be composed of a mesh of networked Microgrids collaborating to deliver electricity to consumers. Microgrids, in their turn, will be composed of different collaborating distributed energy resources. SGs are also composed of smart information and communication technologies sub-system that enable it to disseminate necessary information in a timely manner to be able to process it and take proper control and management actions.

One of the challenges of SG is to implement the information and communication technologies subsystem that will enable the energy management component to make decision about delivering power in efficient ways while taking autonomous actions in controlling different subsystems to respond to events related to energy generation, distribution, and consumption. The paradigm of MAS currently offers an attractive alternative to implement cooperative and collaborative systems such as the SG. MAS constitute a new field of research in full effervescence and technological development. MAS are particularly useful for designing distributed systems requiring autonomy of their entities (e.g., bargaining agents, drones, etc.). MAS use new programming paradigm to implement agents, which is bringing about new programming paradigm for software engineering called Agent-Oriented Programming (AOP) [1].

MAS are used in several application areas because of their architectures, which are based on agents that provide a natural way to address current technological problems. Because of their advantages, agents are widely used in the fields of network management, e-commerce, healthcare patient monitoring, distributed Artificial Intelligence (AI), distributed systems and software engineering [2], [3].

Other surveys have been done on the application of MAS in SGs [4], [5], [6], [7], [8]. Roche et al. [4] briefly described the operation of MAS and the importance of their integration in SG as a tool for energy management by presenting a number of earlier studies and experiments used in this area. Narkhede et al. [5] presented the latest applications of MAS for operation and control of SG, including simulation, operation, Microgrid and virtual power plant control, Demand / Response (DR), and service restoration. Li, Zhou, Zabet and Mantazeri [6], [7] examined the major challenges in modern power systems in terms of a new generation of distributed Power Generation (DG) such as SG and they introduced MAS technology as a solution for some challenges. Rohbogner et al. [8] discussed the applicability of MAS paradigm for the management and control of SG of the viewpoint engineer. Our survey complements these existing surveys in regards to presenting a comprehensive review of the literature till 2013 on the application of MAS in SGs with focus on simulation, management, and control. The novelty of this survey is that it outlines the main steps in the MAS approach: modeling and implementation, as well as the volume of information provided.

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This paper is organized as follow; Section II gives an overview about SGs. A description of the relationship between MAS and SG will be discussed in Section III. Section IV presents briefly different platforms used for the Implementation of MAS. Finally, Section V concludes the article.

II. Smart Grids: The New Generation of Electric Power Systems

Research groups in universities, national research laboratories, and industry around the world huddled in the study of the development of a new generation of electric power systems called "Smart Grid" (SG). SG integrates technological advances in computing, telecommunications, distributed systems and Artificial Intelligence (AI) to the stages of generation, transmission and distribution of electricity. The integration of these technologies will provide a communication layer that will allow the SG to exchange information among its subsystems and components. In addition to generation, transmission, and distribution subsystems traditionally managed by operators in coordination with service providers, SG will include also interactions that involve customers through dynamic markets.

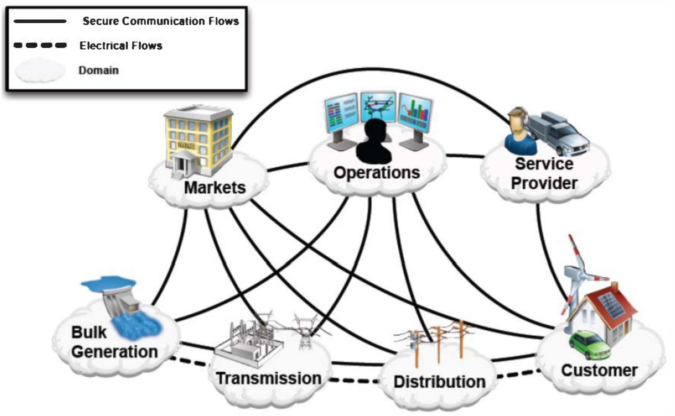

Figure 1. Components of Smart Grid [9].

Smart Grids have the following characteristics [10]:

- SGs promote the participation of consumers in the grid. Consumers can produce energy through different distributed energy resources (e.g., solar energy), see in real time how much electricity they are using, and thus they can decide to engage in a Demand/Response plan.
- SGs accommodates all types of generations and storage options in a plug and play mode. Generation can be either centralized, such as nuclear that we typically have in a plant, or distributed using different natural resources (e.g., wind, solar).
- SGs enable the introduction of new product services in the market. New real time market place of buying and selling electricity and services are possible.
- SGs optimize the operation of electricity in the grid system.
- SGs have self-healing properties and are resilient to attacks such as cyber and physical attacks. They are expected to recover quickly from natural disasters like tornadoes and hurricanes.

These new generations of electric power systems transform conventional electrical systems into a large "information system" computing, where the aforementioned characteristics of distributed control and knowledge of the state of the network would enable interesting functionalities such as [11], [12]:

- Auto-recovery system.
- High quality energy delivery.
- Resistance to cyber-attacks.
- Integration of distributed generation.
- Accommodation of energy storage.
- Monitoring and control of user's consumption.
- Estimation of user's demand distribution.
- Real-time reconfiguration of the distribution system using "online" measurement.
- Operation and maintenance cost optimization.

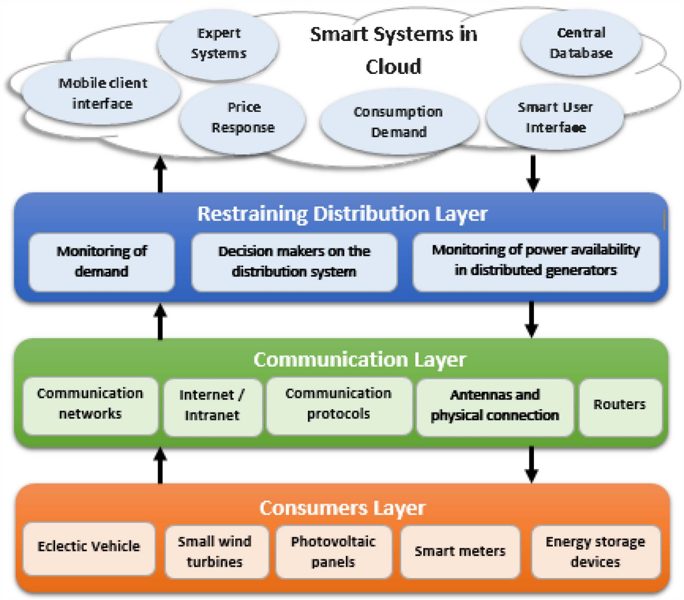

Figure 2. The Smart Grid layers.

SG can be through of as a layered system where communication layer is overlaid over the power layer to implement different needed functionalities. Fig. 2 shows SG functionalities divided into layers, namely the consumer, communication, and the distribution layers. The information flows in both directions between layers. Each layer has its own equipment and technologies. For instance, the consumer layer includes components of SG equipment such as electrical vehicle, solar panels, and smart meters. The effort put into developing these technologies is motivated by the growing deregulation of the energy market and the pursuit of science and energy from the environmental responsibility and sustainability point of view [12].

III. Smart Grids and Multi-Agent Systems

Developments of SGs will involve dealing with a big amount of data collected in a distributed manner. This data are communicated among equipment and devices to support decision-making process. Certainly, handling the amounts of data to be acquired and processed in such distributed systems to extract useful information bring its own challenges. Computational intelligence techniques are used to extract knowledge and overcome some of the challenges.

In "intelligent" systems, data is pre-processed, processed, and then information is extracted for decision-making. The decision is based on the aims to be achieved. Given the distributed nature of SGs, new developments in distributed artificial intelligence techniques spawned the MAS technique development [13].

A. Advantages of Multi-Agent Systems in Smart Grids

In SG controls play an important role, providing essential infrastructure for consumers and stakeholders to monitor and control their energy production and usage. The intermittent nature of wind and solar energy will require intelligent control with possible ways for shifting demand side management system.

The SG is made of millions of controllable appliances; the control system should work efficiently on a large scale and be fault tolerant [14]. We present here comparison between SG characteristics/requirements and their analogies with MAS:

- The SG components are often distributed and the energy management system is tightly associated with the communications between stakeholders and entities (agents) to exchange information. MAS are by nature distributed and concurrent, they are independent entities engaged in the system, they have their own perception of the environment, goal and agenda and they try to achieve the best for themselves while behaving strategically. Therefore, in that case when using MAS the amount of data to be disseminated (with its according costs) will be greatly reduced in comparison to other in-depth communication methods.
- SG is a holistic system and the failure of some part of it (the breakdown of a transmission line or cut down of a substation, transformer….) shouldn't affect the whole activities and operations. Flexibility denotes the ability of a system to be adaptable (i.e., to behave as required in different situations). The flexibility of MAS is given by the fact that agents are independent and able to perceive their environment and then adapt their actions accordingly.
- SG should demonstrate the plug-and-play concept for integrating energy storage, loads, and sources at the building level with the external utility grid. Plug and play adaptability is widely proven by MAS, by nature MAS are able to be scaled up by adding other agents or by dispersing them in new environment with new resources and capacities.
- As SG will be composed for an aggregate of Microgrid, the control can be delegated to micro grids. In this vision, the MAS can perform tasks locally if they have sufficient knowledge and resources, and they can interact with other surrounding agents to help in the completion of tasks or decisions. The problem of control can be approached from a variety of perspectives including cognitive science, heuristic search, and machine learning.
- SG leverage the widespread of the information and communication technologies, these smart technologies are platform-independent and language free. In this perspective, an agent can be developed by a large set of languages and communicate with the other agents in the system regardless of what language they were programed.

1) Advantages of Multi-Agent Systems in Demand/ Response

One of the goals of the SG is to develop grid modernization technologies, tools, and techniques for Demand/Response (DR) with the ability to dynamically optimize grid operations and resources and incorporate Demand/Response and consumer participation [15]. To do so, it is important to understand demand patterns and behaviors, and predict how they might change [16]. Consumers' energy demand is complex, given the wide range of interlinking behavioral and technological factors combined in many different configurations. The relationship between individual consumer factors and energy consumption, and the wider context of public energy supply and society is complex on a range of different spatial and temporal scales.

In this vision, to overcome the Human-automation interaction in smart grid, social scientists try to understand society of humans, how and why they behave the way they do, and try to predict and understand how they work. In the other hand, the entities in the MAS are information processing, computational entities with finite memory and finite processing capabilities that make decision in finite time, consequently autonomous MAS can interestingly synthesizing these capabilities into building complete multi agent system with complete decision making through techniques like machine learning and problem solving algorithms. As a result, MAS can take inspiration from the customer model and put behavioral design and engagement at the core of Smart (or Micro) Grids to help drive energy savings at peak times.

2) Advantages of Multi-Agent Systems in simulation

The envisioned SG infrastructure is highly dynamic. Experimentations on actual deployment are the best way to verify their functionality and proof of concepts. However, implementations are not always available for testing and verifications as they are costly to implement, therefore accurate simulation of the system play a critical role for large scale verifications and performance evaluation. To this extent, MAS are likely to simulate the stakeholders in smart grid system. Software agents bear many of the social characteristics such as negotiation, autonomous decision-making, collaborative interaction etc., and the concepts have been realized with them (i.e., the JADE platform). The result is a highly dynamic infrastructure, broken down to its basic most energy consumption entities according to the energy profile surveys by U.S. Department of Energy (DoE) and therefore MAS is near to the real-world model. In the literature researchers have demonstrated the convenience of MAS. Stamatis and Thiago [17] have analyzed, designed, and built a simulator based on software agents that attempts to create the dynamic behavior of a Smart Grid. Pipattanasomporn and Feroze [18] have proposed MAS that can facilitate the seamless transition from grid connected to an island mode when upstream outages are detected which denotes the capability of a MAS as a technology for managing the Microgrid operation.

B. Applications of Multi-Agent Systems in Smart Grids

This section discusses the applications of MAS in SGs.

Roche et al. In [19], [20], provided a system of energy management in Smart Grids, to achieve a higher level of flexibility: the designed system must adapt to the most changes in the architecture of Microgrid. Therefore, in [19] the MAS is hybridized by optimization algorithms: Metropolis Particle Swarm Optimization with Mutation Operator algorithm (MPSOM) and Imperialist Competitive Algorithm (ICA) based on Meta-heuristics, and implemented in Java based on JADE (Java Agent Development Framework) Middleware for MAS to obtain an autonomous simulator: configurable and adaptable to different problems and structures. In [20], the approach is performed through two applications: The first application is to develop a system of energy management for gas turbine power plants, to minimize operating costs and emissions. The second system consists of developing a Demand / Response (DR) management system and relies on the use of the assets of customers to curtail and shift local loads. The MAS was successfully developed in JADE.

Dimeas et al. in [21]–[23], proved that the MAS intend to give maximum autonomy to each of the Distributed Energy Resources (DER) Microgrid units and loads. This implies that Local Controllers (LCs) should be smart and able to communicate with each other to form a large intelligent entity. Their role is not to maximize the own unit performance, is to improve the overall performance of the Microgrid. Therefore, the architecture must include economic functions environmental factors and technical requirements. These features mean that Multi-Agent Systems (MAS) can be a great candidate to develop decentralized control. The authors developed MAS based on Java Agent Development Framework (JADE) and tested it on the Microgrid in a Lab.

The work of Feroze in [24] was to design, develop and implement a multi-agent application that ensures the security of critical loads and support for non-critical loads belonging to various owners of distributed energy resource.

For the implementation of MAS, various open source toolkits agent builder are compared to clearly identify the most suitable agent toolkit for MAS implementation.

C. Machine to Machine in Smart Grids

Machine to Machine (M2M) refers to a set of protocols for machine to machine communication. They dictate the rules and ways machines can share and exchange information. M2M provide the necessary communication infrastructure in SGs for information exchange and control. In fact, SG counts mainly on the two-way communication to provide a highly controllable and reliable system [25].

M2M makes it possible for different agents to share their real-time consumptions/production and also share information when a substantial power reduction is needed to avoid an outage. These different agents share their estimations in terms of energy reduction and thus making the whole system work towards the same goal given the fact that it is decentralized [26].

There are numerous existing M2M protocols such as Modbus and BACnet (Building Automation and Control networks) that are highly used in industry. These protocols provide a two-way communication for providing frequent sensory data and also for control.

D. Energy efficiency in Smart Grids

Energy loss is very high in the current grid. In fact, it appears in all parts of the grid, from the generation of power to the consumption. There is loss in power plants, in transmission lines, in consumption units such as residences and companies and also due to human habits that affect the loss significantly. It has been found that 20% of the power is lost when leaving the AC or the lights in the house while the users are not at home.

The new grid is in need of an energy management system which is a key component of a Smart Grid that reduces the wasted energy by adjusting heating and cooling usage through collecting data from meters and report best slot of time for optimizing energy. Energy efficiency helps the users save money by consuming less and also by reducing the global demand in the grid that results in the decrease of price of electricity in the grid. Therefore, energy efficiency helps the users and the grid in achieving global energy and also increasing the grid's reliability [27]. A multi-agent Energy Management System (EMS) is among several EMS architectures that have been proposed to cope with heterogeneity of SGs; several research projects have been carried out to test the efficiency of a multi-agent EMS. The latter proved that it can lead to important energy savings and efficiently improve energy usage [28].

IV. MODELING AND IMPLEMENTATION OF MULTI-AGENT SYSTEMS

A. Multi-Agent Systems modeling

Agent Oriented (AO) approaches have emerged as a powerful technology that can support the design and development of complex systems [29]. The power of these agent-based approaches to solve complex problems enables the implementation of systems that are flexible and autonomous. However, this flexibility in solving complex problems comes with challenges. To overcome these challenges, research has focused on the design of suitable methods to support the development of agent-based complex systems. The methods are classified as semi-formal methods and formal methods.

The semi-formal methods used mainly UML (Unified Modeling Language) extensions such as MESSAGE / UML [30] and MaSE [31]. Some of these methods are based on MDA (Model Driven Architecture) such as INGENIAS [32] and TROPOS [33] approach. The advantages of the MDA approach comes from the use of models at different phases of application development. Indeed, models are used to specify different levels of abstraction (analysis, design, implementation), facilitating the management of the inherent complexity of MAS. In contrast to semi-formal methods, formal methods are based on mathematical notations as ForMAAD [34] and RIO [35].

B. *Plattforms for Multi-Agent Systems development/Multi-Agent Systems implementation*

The concept of platform is related to the implementation of MAS [36]: it is the environment that manages the lifecycle of agents and wherein the agents have access to certain services. Several multi-agent platforms exist; we selected a set of popular and regularly updated platforms, covering all aspects of multi-agent systems, including agent models, interaction, coordination, and organization.

1) *ZEUS*

ZEUS [36] is a multi-agent platform developed by the research program of British Telecom intelligent system research laboratory. ZEUS allows the design of multi-agent distributed systems. This platform, developed in Java, automatically generates Java code from the agents specified graphically.

The concepts of the platform ZEUS is based on:

- Agents;
- Their goals;
- Their tasks;
- The facts.

The uniqueness of Zeus is its full integration of all stages from design to deployment. It provides theoretical and practical tools, uses real techniques of programming technology. However, it supports only one agent model, which limits the range of possible MAS designs.

2) *AgentBuilder*

Developed by Reticular Systems Inc., AgentBuilder [36], it is based on BDI (Believe – Desire – Intention) models Agent [37] and AGENT-0 language [38]. It is remarkable for the quality of its software and a good academic model. AgentBuilder is a commercial design software for "intelligent" agents i.e., cognitive and collaborative agents. AgentBuilder consists of two main components: the toolkit and runtime system.

This platform developed with Java, consists of a Graphic User Interface (GUI) and a high-level "Oriented-Agent" to define the commitments and actions language. It also allows defining ontologies and protocols for inter-agent communication (KQML: Knowledge Query Manipulation Language).

3) *JADE (Java Agent Development Framework)*

JADE [39] is a multi-agent (multi-host) platform developed by distributed Bellifemine. F., Poggy. A., Rimassa. G. and P. Turci by Telecom Italia Lab "Tilab formerly CSELT" in 1999. This platform aims to simplify the construction of interoperable MAS, achieve compliant applications with the standard FIPA97 (Foundation for Intelligent Physical Agents) to facilitate the communication of JADE agents with non-JADE agents, and optimize the performance of a distributed system agent.

JADE includes all accredited component that manages the platform: Agent Communication Channel (ACC), Agent Management System (AMS), and Director Facilitator (DF).

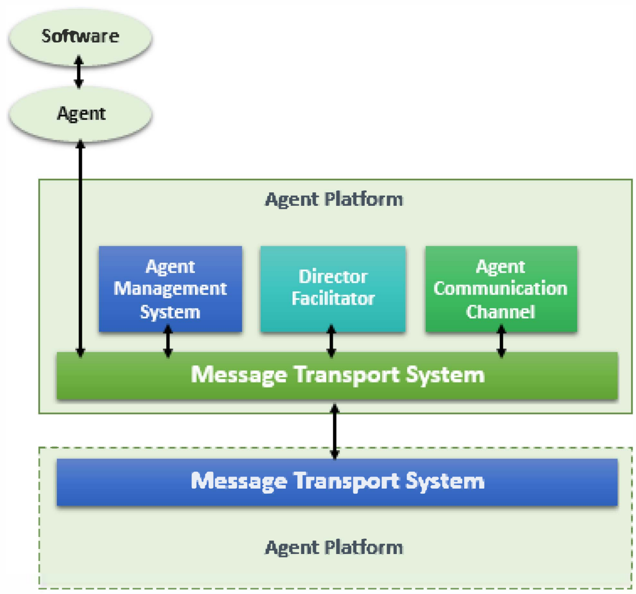

Figure 3. Software Architecture of the JADE Platform.

- **DF**: Provides services of "yellow pages" to the platform;
- **ACC**: Manages communication between agents;
- **AMS**: Oversees the registration of agents, their authentication, access and use of the system.

JADE developed in Java, runs on all operating systems, including all required components that control the MAS, and has a very specific architecture for building so-called "standard" agents. For this, JADE platform includes a Runtime Environment, a class libraries, and suite of graphical tools. The JADE platform is well suited to implement mobile agents and grid environment presents a navigation space for their satisfactory performance.

JADE provides:

- Independence and asynchronous processing;
- Safer and better tolerance;
- Reducing the network load.

4) *MADKit (Multi-Agent Development Kit)*

MADKit [40] is a platform for MAS developed by Olivier Gutknecht and Jacques Ferber in Laboratory of Computer Science and Robotics and Microelectronics of Montpellier. MADKit was motivated by the need for a more flexible platform possible, and able to adapt to different agent models and application areas.

MADKit is a modular multi-agent platform and scalable, written in the Java language. It allows the creation of MAS based on the relational model Aalaadin or AGR (Agent / Group / Role): agents are located in groups and play roles. MADKit takes advantage of object-oriented programming: MADKit features are contained in the MADKit kernel.

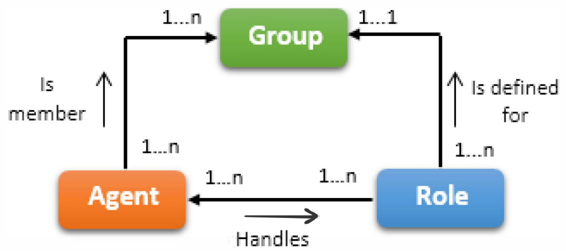

Figure 4. The Aalaadin/AGR model.

One of the main advantages of this platform: it defines a basic structure for the representation of an agent, group, and message. It is relatively easy to provide all agents designed by different programmers / different projects.

V. CONCLUSION

The development of SG and related technologies combine advances in distributed systems, Artificial Intelligence, control, and information and communications technologies. SGs are expected to exhibit high level of autonomy, self-healing, and reliability and to provide features such as reconfiguration, protection, restoration, and interaction with users through demand response. MAS are promising technologies in implementing such features and are being investigated to be used in SGs. This paper presents a review of MAS and their significance in using them in SG technologies.

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