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What the term Agent stands for in the Smart Grid Definition of Agents and Multi-Agent Systems from an Engineer's Perspective

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Abstract*—This paper aims to initiate a discussion of what an agent in the context of Smart Grid is. But not as usually done from a computational perspective but rather from an engineer's perspective. This discussion seems to be missing with respect to the following questions periodically occurring when Smart Grid researchers get in touch with agent technology. What is the difference between an optimizer or an Energy Management System and an agent? Why are web-services not enough for a future Smart Grid control system? How are multiagent systems structured? These are only some of the questions we will discuss to arrive at an application-oriented definition of an "agent", understandable for Smart Grid researchers of various disciplines. Fostering such an interdisciplinary discussion seems to be essential when trying to point out the advantages of control systems based on multiagent technologies.

I. Introduction

TAKING into account the recommendations of Wooldridge and Jennings [1], not to oversell the agent paradigm as the "magical problem solving paradigm", our aim in this paper is to discuss the applicability of the agent paradigm for the (still imprecise) idea "Smart Grid". In short, we want to scrutinize whether prior and current Smart Grid research uses the term agent only to jump on the agent technologies bandwagon. Thus, we will shortly introduce the core idea of the Smart Grid first, followed by a definition of Energy Management. Second, we will explain what an agent can be understood as in the Smart Grid. This paper aims to encourage the discussion of what an agent, applied in the Smart Grid, really is. Further, we will try to find an easily understandable definition of an agent in the Smart Grid and will finally examine the advantage of using the term agent and the implementation of the associated information technology. For a software oriented definition we refer to basic agent literature, describing an agent with some or all of the following attributes: autonomous, socially able, reactive, proactive, cooperative, goal-oriented, self-adapting and learning, flexible [2]. Our paper ends with a conclusion, summarizing the supplementary advantage of the usage of the term "agent", of the application of the agent paradigm for distributed Smart Grid control systems, and a definition of an agent in the Smart Grid from an engineer's perspective.

II. The Smart Grid Vision

Regarding plans defined by the European Union, central Europe strives slowly towards an energy supply powered by renewable energies [3]. With a rising amount of renewable energy resources, it will be more challenging to ensure a continuously secure and reliable energy supply. The weather depended fluctuation of the power supply of renewable energies (e.g. wind turbines or photo-voltaic systems) makes it necessary to build up either storage capacity, a Smart Grid, or a combination of both technologies to maintain the power supply in the future. In this paper we concentrate on the challenges associated to the Smart Grid vision and the application of the agent paradigm. Comparing the different visions of Smart Grid [4],[5], a set of common core ideas can be identified: The Smart Grid embodies the communication infrastructure to connect different distributed energy resources (DERs) with the aim of:

1) Adapting the demand side to the mainly fluctuating supply side of energy.

2) Integrating the distributed energy resources as systems providing not solely active energy but also ancillary services (e.g. reactive power supply) to stabilize the distributed network or specific network sections.

3) Exploiting storage capacity in the low and distributed energy network, for example using the batteries of electric vehicles or thermal storage in combination with electro-thermal heating systems located in single-family dwellings or public buildings (such as public baths, nursery schools or hotels).

To reach these aims, a various number of different DERs need to be coordinated at runtime. Therefore, appropriate control systems must be developed and tested. But which control system is the most promising one? Is it a distributed control system following the agent paradigm? Despite previous research, mainly demonstrating the feasibility of the Smart Grid idea [6], comparatively little effort has been devoted consequently to carving out the technical differences between an agent based control system and other control paradigms. During our literature review we could not find a paper which works out the meaning of the term “agent” with special regard to Smart Grid applications. In this paper, we want to fill this gap by examining first the difference between an Energy Management, as the overall task in a Smart Grid, and different control systems carrying out the task of Energy Management. Second, we will discuss what an agent can be understood as in the Smart Grid.

III. Energy Management and Control Systems

The term Energy Management System (EMS) is closely linked to the term Smart Grid. Energy Management (EM) describes the task of planning and controlling energy resources in an optimal manner in a well-defined environment (physical system). Thus, an Energy Management System comprises the hardware and software that perform the task of Energy Management for a dedicated physical system. The way in which the task of EM is carried out and how the EMS is implemented and designed, depends on the properties and requirements of the underlying controlled physical system. This definition of an Energy Management System suggests that a multiagent system (MAS) can be defined as one control paradigm to carry out the Energy Management. In short, a multiagent system is not a synonym for the term Energy Management System. It is rather one possible control paradigm which can be applied to Energy Management System. Regarding the vision of Smart Grid there will not be only one Energy Management System for the one physical system “Smart Grid”. Rather, the Smart Grid will consist of a plenitude of EMS, or more generally, control systems, each responsible for a dedicated physical system with different constraints. Thereby an EM can be designed as an multiagent system. While the distinction between the EMS and the used control paradigm seems to be trivial, Smart Grid scientists usually use a weak delineation of these terms in their daily work. This leads to confusions and questions that we want to answer in chapter IV. But first, we will give a small overview about the different control systems (in the Smart Grid). We differentiate between control structures and control concepts which conjointly form the control system. While only control structures are important for our main discussion in section IV, we must keep in mind that control systems can evince an economical or network oriented control concept. The control structure describes the logical structure of interacting control entities. Depending in which control entity the information processing (usually a sort of optimization) is fulfilled, it can be differentiated between central-hierarchical, decentralized, and distributed-hierarchic control structures (cf. Figure 1).

A. *Central-hierarchical Control Structure*

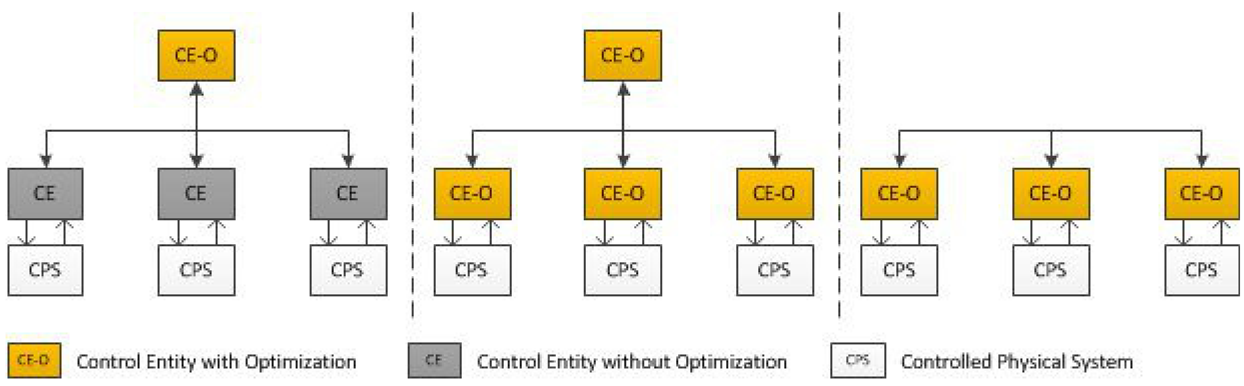
In today's European energy supply systems, a central-hierarchical control structure is mainly applied. Also, the majority of industrial processes follow a central-hierarchical structure nowadays.

Central-hierarchical control structures consist of one (central) control entity (CE-O) of the higher level that coordinates an assigned group of control entities in a lower control level (CE). Pursuing an optimization goal or a production recipe, the higher level output values are the input values (set points) of the control entities that are members of the underlying control level. Figure 1 (a) exemplarily depicts a two level control system. The blue control entity (CE-O) is on the higher control level. The CEs are on the lower control level, receiving only set values from the CE-O.

Virtual Power Plants (VPP) are typical applications usually following a central-hierarchical structure. Here, the idea is to optimize/bundle the production and consumption of electric energy for a number of different distributed physical systems (e.g. households, business enterprises or single devices, like Combined Heat and Power Systems) in a central control entity. After central calculation of the optimal operation schedule, VPP control entities (CE) receive an actuating variable either to run, stop or changing the power.

B. *Distributed-hierarchical Control Structure*

In a distributed-hierarchical structure, the different control entities are connected via one central unit. While the local control entities (CE) in a central-hierarchical structure only receive an actuating variable which they have to follow, in the distributed-hierarchical structure all control entities are



responsible for their single local optimization. In the latter structure, every control entity sends an abstracted value (e.g. a financial bid for negative or positive power for a time slot) to a central control entity to ensure the global optimum, e.g. for a low voltage electric network (cf. Figure 1 (b)).
Most former projects working on the subject of agent systems are structured in distributed-hierarchical way. For example, [7] applied distributed agents, each responsible for one consumer or producer, sending financial bids to a Balancing Group Manager (BGM). The BGM tries to match the received bids in an iterative processes based on the economical basis stated by Chavez et al. [8]. As examples for implementation of a distributed-hierarchical structure as real field-test, the projects eTelligence [9] funded by the German government and the ongoing project of the Energy Research Centre of the Netherlands (ECN) called INTEGRAL [10] can be named. Also these systems pursue an interaction between the control entities only using systems to trade active energy.

C. Decentralized Control Structure

In a fully decentralized structure, the single distributed physical systems are fully controlled and optimized by their associated local control entity (CE). In this control structure no dedicated central or master control entity exists (cf. Figure 1 (c)). Thus, distributed control entities can communicate in a peer-to-peer manner. Conceivable but not mandatory, is a dynamic election of one distributed control entity as a master, i.e. responsible for coordination. It might strike you that this is much what we described as a distributed-hierarchical structure. But with the possibility of migrating the role of a "master" to another active control entity we elude the problem of a single point of failure.
Previously, only scarce research has been conducted focusing on fully decentralized control systems in a simulation or a field test. Although associated with the research fields of organic computing Kamper has developed a model that allows every physical system, independent how huge it is (e.g. washing machine or the entire Smart Home), to directly get in contact with other physical system via their associated control entities. [11]

IV. The Term Agent in The Smart Grid Context

In this section we will discuss and define an agent and a multiagent system more from an engineer's perspective rather than a computational perspective. We consider this application oriented definition and discussion of MAS, and what an agent really is, as essential. We do so, to facilitate engineers of Smart Grid applications to understand the difference between current well-working control techniques but also to convince them of the advantage which can arise with the application of agent technology in the Smart Grid. Engineers working in the field of Smart Grid might have heard somehow of the term agent or multiagent systems, but usually a practical implementation is intangible for most of them. Questions like the following periodically occur: What is the difference between an agent and an embedded systems with an optimization running on it? What is the difference between a closed loop control and an agent? From a computational point of view these questions certainly seem like comparing apples and oranges. But at least, these questions indicate that engineers still have problems appreciating multiagent technology. After giving the reader the relevant background and motivation, we want to pose and discuss the most common questions and remarks directed to researchers of information and agent technology by researchers of other Smart Grid disciplines.

A. Why is an "Internet of Energy" based on web-services not enough?

As [12] describes, the use of web-services or even web-service choreography is inadequate, when distributed systems' interactions (between control entities) can only partially be defined at design time. In a future Smart Grid different still undefined interactions between several imprecisely defined stakeholders need to be handled. From this point of view it seems that future energy systems need more than only an "Internet of Energy" based on web-services. An iteratively growing Smart Grid requires highly dynamic, flexible and extensible control systems able to (re-)organize themselves without need of specifying all dependencies at design time. However, this assumption does not mean that web-services are an antiquated and useless technology. Quite the contrary. As proposed in [12] and [13] a combination of both technologies can be suitable. The agent might composite web-services to reach goals, intentions or strategies of the users or organizations that the agent is working for. But real autonomy, as required and defined by most basic agent literature, can only be reached by agents. Because agents are aware of themselves and aware of the existence of other control entities (and their services) and can interdependently decide to invoke a service or to carry out an invoked service or not. Thus, agents are not bound to dedicated control entities or services but rather are able to send requests to any other agent in order to find appropriate services helping to fulfill their internal intentions. In the Smart Grid this might be interesting when different stakeholders propose services for different physical systems, for example maintenance services. In this scenario the agent need to search for the best fitting service (for its beneath physical system).

B. Why is an agent more than a software implemented optimizer?

The classic mathematical definition describes optimization as the task of finding the best element (minimal or maximal value) from a set of available alternatives. From a technical or computational view, an optimizer is a software or technical system which performs this task. Since the optimization equations, the objective function, and the set of constraints are system dependent, the physical systems' dynamic needs to be known at the optimizer's design time. Having in mind that the Smart Grid is a continuously changing system with various technical systems, an optimizer, in the classic understanding, seems not to be appropriate enough. Although optimizers work goal oriented, much like the agent, the missing automated self-adaption of its equations distinguishes the optimizer from an agent. Especially in Smart Grid applications, such a goal oriented adaption of the equations is necessary. This can be illustrated by means of a simple example: A technical system performing the Energy Management, designed as a mass product, needs to be end user-friendly and installer-friendly. Thus, complex and time-consuming configuration and parameterization need to be reduced to a minimum. Taking into consideration that physical systems are not identical (e.g. Smart Homes have different heating systems), it is hardly possible to design one optimization algorithm that fits each system as well as the individual behaviors of the dwellers. For this reason, we propose learning and self-adapting systems which can automatically adapt the optimizer's parameters and equations to the underlying physical system, the users' or dwellers' individual behavior and to interactions with other control entities.

C. Why is an agent more than a digital closed-loop control?

Regarding the core definition, with its closed loop base, it seems like the closed-loop control is fairly similar to an agent. Because somehow one might say that the closed-loop control is also autonomous. Not in the sense of interaction but more in the sense that a closed-loop control is coming to a “decision”, having local knowledge about the system's condition from the feedback variable. However, this single feedback variable does not provide knowledge of the system's dynamic or cannot be seen as a form of awareness of itself and the system environment. We approximate to the definition of an agent when thinking of model predictive control, that is equipped with a model of the system dynamic. Furthermore, the (model) predictive control, as the name suggests, can predict the state of the controlled physical system and therewith might be declared as proactive other than the classic closed-loop control which is only reactive. According to researchers working in the field of agent technologies, a control system is proactive when it is able to find alternative solutions in case a problem occurs. Additionally, proactive systems should allow for searching for other control entities to enable cooperative interaction. Agents are able to communicate and interact with other control entities in a cooperative manner distinguishing the (closed-) loop control from an agent. More specifically, an agent can communicate with other control entities to find a stable optimal solution for the whole interconnected system and for its own physical system. Closed-loop controls are not even aware of themselves or the other control entities. This might be critical in case of several closed-loop controls influencing one control path. Regarding the Smart Grid idea, controlling e.g. the electric network frequency or the network voltage, a reliable coordination of the dynamic of these grid coupled (small) energy resources via their associated controllers or control entities, will become essential.

D. Is a multiagent system necessarily fully distributed structured?

Former research focused on agent-based Smart Grid systems mainly followed a distributed-hierarchical structure [7], [9], [10], [14]. We argue that a truly multiagent system should provide the possibility to communicate and interact with any control entity in the system. This is not the case in distributed-hierarchical systems. We propose that the interaction with all participating entities of the system is necessary, not only from an agent's theoretical but also from a Smart Grid application's view. Structuring a control system in a distributed-hierarchical manner constitutes a curtailment of agent's autonomy since freedom of action is restricted to one single entity. Thus, we want to suggest to entitle control systems as multiagent systems, which follow a fully distributed structure, only. Also, this seems to be an appropriate structure for a multiagent system applied in the Smart Grid. Since, due to the judicial requirement of a discrimination free energy supply, and additionally, because fully distributed systems permit the cooperation of agents in the way that distributed entities can organize themselves e.g. in energy communities. Regarding the core definition of an agent and a multiagent system this cooperative behavior is one important pillar of the agent definition.

E. Is it sufficient that a system is labeled as MAS system when it only trades power?

In an evolving interdisciplinary system like the Smart Grid, the interaction between control entities should go beyond solely trading active or reactive energy. Communication should be extended, allowing systems to exchange information about their devices’ performances, to cooperate, e.g. to improve the local weather forecast, or to offer maintenance services or to customize services to different customers. To reach such communicational flexibility, control entities need to be aware of themselves as well as of other control entities. This raises the need for a meta language for multiagent systems, like proposed by the Foundation for Intelligent Physical Agents (FIPA) [15]. FIPA permits requests of the agents' used ontology and language. Only such an abstract language, characterized by a minimum of necessary communication methods, ensures an interaction (independent of a certain topic) and therewith the autonomy of an agent.

F. Why is an agent more than a computational energy assistant interacting with its users?

Important aspects in context of agent-based technologies in the Smart Grid constitute the interaction between the user and the control entity. Agent-based systems can adapt to the individual characteristics of inhabitants and thus have the potential to increase subjective comfort. In consequence, this may result in a more positive evaluation of the technology. That is, the systems' adaptability to individual needs and changes in preferences or behavior over time may be crucial for the success of the systems and related technologies. Such user adapted solutions distinguish agent-based solutions from common smart home applications (i.e. energy assistance systems). Perfectly adapted to individual user characteristics, the agent systems may reduce necessary control input from the dweller's side leading to lower workload. Further, agent-based systems are able to independently carrying out actions e.g. to enhance energy efficiency rather than solely providing information (as in case of energy assistance systems). Increasing automation further reduces dwellers' workload.

Although agent-based automation may enhance user comfort by concomitantly increasing energy efficiency, it is necessary to maintain the opportunity that inhabitants engage in the control process when desired. This constitutes a fairly difficult challenge for future agent-based concepts since long periods of automated processes without user interaction may lead to inadequate user behavior in times user-based action is desired/demanded [16]. Future agent -based systems need to account for this issue finding a perfect balance between adequate automation and desired user input.

V. Conclusion

Beginning with a short introduction of the Smart Grid idea and the relation between Energy Management Systems and control systems we analyzed what an agent can be understood as in a future Smart Grid. We discussed some typical questions that mainly come up when engineers of Smart Grid applications get in touch with multiagent systems. The aim was to show the urgent need of finding an application-oriented, engineer friendly definition of multiagent systems and the agent paradigm in the Smart Grid. Furthermore, we wanted to initiate an interdisciplinary (computer scientist, economists, control engineers, mechanical engineers) discussion of that topic. Based on presented questions, we decline to classify agents as such, when the technical (control) system only exhibits one of the core agent attributes (cf. Section I.). We claim that only a combination of almost all agent attributes at least makes the term necessary and useful. For example, in the classic definition, an optimizer is goal oriented but not able to automatically reconfigure his objective function or his constrains. Following our definition, a control entity in the Smart Grid shall be labeled as an agent when:

- it is able to communicate in a cooperative manner with other control entities or rather agents.
- it is responsible for the automatic Energy Management of an underlying physical system.
- it consists in a minimum of the following different parts of software implemented systems: The *Learning System* which is adapting the computational optimizer's goals to the needs of the user, the changing physical system or to interactions to other agents. The *Optimizer* that calculates under given constraints the optimum and sends the set values to a reactive (Closed-) *Loop Control*.

Thus, in our understanding, the term agent is suitable when describing a combination of the named techniques running on a control entity. Therewith an agent is more than “only” a web-service, a (closed) loop control, an optimizer or a learning system.

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