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Structure and classification of unified energy agents as a base for the systematic development of future energy grids

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ABSTRACT

The ongoing conversion of our energy supply encounters a great interest of many different market players that were originally located in different industries. As a consequence, a vast amount of proprietary solutions for "smart" energy applications is flooding the market. This tends to be rather a problem than part of the solution for the systematic development of future energy grids. Here, the absence of necessary unifications and standards blocks further developments that would enable the creation of novel, market-driven and hybrid control solutions for various types of technical systems. To overcome these problems, we present in this article our notion and the definition of a unified autonomous software entity that we call Energy Agent. Based on the energy conservation law and a generalized energy option model, we claim that our Energy Agent approach has the capabilities to enable cross domain interactions between different types of energy systems and networks. Further we will outline a systematic development process for Energy Agents that considers implementation, simulation, test-bed application and a real on-site usage. By taking into account these development stages, we expect to concurrently develop a novel laboratory that enables to competitively test and validate new and hybrid control solutions before they are applied in real systems.

1. Introduction

The ongoing transformation of our energy supply systems, from a centrally organized and controlled to a decentralized and autonomously acting energy system is facing major challenges. The list of requirements in this context is enormous and ranges from the preservation of the usual security of supply, over a reduction of greenhouse gases, an incorporation of different energy carriers, up to an economic, competitive and at best less expensive supply of energy. Recent research focusing on Smart Grids and Smart Markets presented a number of possible approaches for this purpose, as for example commonly discussed solutions for demand side management, island operations or demand response (Amin and Wollenberg, 2005; Ramchurn et al., 2011; Siano, 2014). Regardless of which solution will be applied in the future or which solution is developed hereafter, it is undisputed that information technology is and will be the key enabler and thus the main factor for a successful transformation of our energy supply. In this context, the main task for computer science will be to manage and integrate the vast amount of different and mostly incompatible control solutions for varying technical systems that are producing, consuming or storing energy in a particular form.

Due to this highly diversified nature of tomorrows' energy grid, new control solutions have to be found that tackle the rising demand for coordination. Coping with the challenge of fluctuating electricity production by a growing number of smaller energy converters, dependent on meteorological factors as wind or sun, or heat-operated combined heat and power plants (CHP), already strains conservative control solutions. Meeting the high requirements with regard to availability of electricity supply, minimization of frequency- and voltage-deviations and other regulatory and socio-economic factors does finally overstrain these control concepts as we may find them in today's electricity grids. While the physical grid infrastructures and the processes therein become more and more complex, the control solutions are lagging far behind. Many proprietary solutions can be found, but in a broader surrounding, as for example in the European Union, applied control mechanisms are still far away from a general consensus or accepted standards. In addition, with an exclusive focus on electrical grids, further degrees of freedom needed for non-electrical energy flows and systems have not yet been comprehensively addressed and exploited. Nevertheless, further spreading ideas and new technologies have already been considered and investigated, as for example Power to Gas, where electrical energy can be converted to hydrogen or methane and can be fed into

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transportation and distribution networks for natural gas (Gahleitner, 2013). Complementary ideas can be found with compressed air storages (Lund and Salgi, 2009), the above mentioned CHP's (Paepe et al., 2006), long-term heat storages and other.

All these examples underline once more the trend towards highly diversified, hybrid, distributed and complex interconnected future energy supply networks. New and robust control mechanisms have to be found that allow the utilization of energy-related degrees of freedom of both single and aggregated technical systems. Such new control systems should not intend to substitute existing and well-functioning (real-time) control systems on site. Rather, they have to complement existing control solutions and link them in a novel way in order to extend functionalities in relation to the underlying network or to an organizational affiliation in a suitable manner. Additionally, due to the high number of involved technical systems and the resulting amount of information and data, it cannot be expected that the overall system may potentially be controlled from a few central points. Distributed monitoring and control is required, which leads to the application of Agents and Multi-Agent Systems (MAS) as this paradigm inherently describes the distributed and autonomous characteristic of systems in future energy systems. From a scientific perspective this approach is not new and several authors have already shown the applicability of agents for specific energy applications (e.g. Jackson, 2010; Kouluri and Pandey, 2011; Maia et al., 2011; Fortino et al., 2012; Vytelingum et al., 2011). For a large-scale use, however, consistent modeling approaches, accepted validation methodologies or standards are still missing.

In this article we present a novel approach and definition for a unified Energy Agent that aims to be deployed on actual (real) systems on site by applying a systematic development process. For this purpose, the development process takes into account Multi-Agent based Simulations (MABS), as well as test bed-applications that are connected to MABS and thus allow for the necessary pretesting and validation of communication and negotiation mechanisms. The authors strongly believe that the utilization of a unified Energy Agent in connection with a systematically defined development process is indispensable for further developments and the ongoing transformation process of the energy supply.

To give a structured view on our approach, this article is subdivided as follows: In the subsequent section we discuss related work and provide a rough overview about current Smart Grid research activities. This will be followed by our definition of an Energy Agent, which is based on thermodynamic fundamentals in Section 3. Section 4 will describe the mentioned development process and will outline the consequences for the internal structure of an Energy Agent. In Section 5 we describe our approach for possible agent actions based on a cross-domain option model and in relation to the underlying technical system. The subsequent Section 6 will present an exemplary application of our energy option model for a battery and a μCHP, while the article concludes with the discussion and a final conclusion in Sections 7 and 8. This article represents an extension of our previous publication on the MATES conference 2013 (Derksen et al., 2013).

2. Theoretical backgrounds and problem statements

In this section we provide a short introduction to Multi-Agent Systems (MAS) and Multi-Agent based Simulations (MABS). In this sense we outline the effort to create a MAS or a MABS respectively and give a brief overview on methodologies to build them in a systematic manner. Further, we discuss current Smart Grid approaches. The section ends with a discussion on the need for a systematic development of future energy networks.

For the purpose of this paper an agent can be seen as a computational entity that is situated in an environment and that is capable of autonomous interactions with this environment. Other optional properties and abilities that are further associated with intelligent agents are their capability to communicate (needed for social abilities), a reactive or proactive behavior and the capability to learn (e.g. Sudeikat et al., 2006). If the overall system consists of a set of loosely coupled agents that act and cooperate with each other in the same environment, a Multi-Agent System (MAS) is formed. MAS may be implemented to deal with problems whose complexity overstrains the capabilities of monolithic systems. For the practical problem solution agents have to rely on the above mentioned communication capabilities and possibly also on the ability to collaborate, negotiate, delegate responsibility and the ability to trust. These subjects are discussed in detail in literature (cf. e.g. Wooldridge, 2009).

The effort to build a MAS can be seen as very high. From the perspective of software engineering this requires various modeling and implementation tasks that are caused by the autonomy of the agents. In the first place, system developers have to consider agents with their different autonomous behaviors (e.g. with a deliberative characteristic), based on an operating system, a particular software or agent platform and by using object oriented techniques. Further, the possible interactions between agents have to be related to common data structures, as well as approved protocols, in order to enable error-free communication and negotiation processes between agents.

Large-scale MAS, with several thousands of autonomous entities, require further modeling activities for the grouping of agents. Since interactions in a full-meshed manner, where each agent communicates with every other agent, are most likely neither necessary nor beneficial for the performance or the achievement of objectives of the MAS, the forming of groups has to be modeled and automated. Such groups, in turn, can be formed and organized in various ways, as for example in a manual and rigid or an automatic and dynamic manner. In this context one specific approach is the organization of agents in so-called holonic systems. Here, groups of agents (so-called holons) are hierarchically structured, while one agent acts as representative for this group and organizes interactions between other or parent holons (Gerber et al., 1999). In recent years this type of agent organization is frequently used in Smart Grid research applications and corresponds basically to a hierarchical decentralized organization of complex systems (Vyatkin et al., 2010).

Further modeling and implementation efforts result from the question what rules of conduct or which laws agents are subjected to. This has to be defined by binding policies that must be accepted and complied with by the agents. But to identify and model such behavior is, depending on the domain in question, already a complex process. In order to not overstretch this aspect here we refer to Aldewereld et al. (2011) for further reading. At this point, however, we would like to state that this is a crucial key aspect for a comprehensive and successful application of agent systems.

The last aspects for modeling and implementation we want to mention here is of great importance for cyber-physical systems or so-called physical agents. Such agents are delegated to control or support actual technical systems and can be understood as autonomous entities like robots, on-site control systems and other, capable of interaction with further agents in a larger context. If they are used this way, agents need to have suitable knowledge about the actual capabilities and the current state of the underlying technical system in order to determine the degrees of freedom for possible further actions. Additionally, knowledge about the actual environment is required in order to react on various situations in this environment and find appropriated solutions for occurring problems or challenges. Therefore, this results in further efforts for the development of

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