Applications of Multi Agent system for Distributed Generation in Smart / Micro Grid

B. Ragavendra, Assistant Professor
Electrical and Electronics Engineering
Erode Sengunthar Engineering College
Erode, Tamilnadu

R. Senthil Kumar, Assistant Professor
Electrical and Electronics Engineering
Erode Sengunthar Engineering College
Erode, Tamilnadu

S. Tamilselvi, Assistant Professor
Electrical and Electronics Engineering
Erode Sengunthar Engineering College
Erode, Tamilnadu

G. S. Satheesh Kumar, Assistant Professor
Electrical and Electronics Engineering
Erode Sengunthar Engineering College
Erode, Tamilnadu

***Abstract*— Multi-agent systems are a subject of continuously increasing interest in applied technical sciences. Smart grids are one evolving field of application. Numerous smart grid projects with various interpretations of multi-agent systems as new control concept arose in the last decade. Although several theoretical definitions of the term 'agent' exist, there is a lack of practical understanding that might be improved by clearly distinguishing the agent technologies from other state-of-the-art control technologies. In this paper we clarify the differences between controllers, optimizers, learning systems, and agents. Further, we review most recent smart grid projects, and contrast their interpretations with our understanding of agents and multi-agent systems. We point out that multi-agent systems applied in the smart grid can add value when they are understood as fully distributed networks of control entities embedded in dynamic grid environments; able to operate in a cooperative manner and to automatically (re-)configure themselves.**

Keywords*— *computer scienc; information systems; multi-agent syste; smart grid; power systems; agent-based control systems

I. INTRODUCTION

Agent-based systems have been implemented in the field of technical engineering, having been adopted as new concepts for control systems during the last few decades. Derived from the computer sciences [9], the broad usage of agent technology in the technical domain has resulted in an ambiguous use and interpretation of the notions 'agent' and 'multi-agent systems'; this is especially apparent in current smart grid research projects. The common understanding of the term smart grid in research projects encompasses the development of new power control strategies and communication systems to face the challenges (e.g. fluctuating power generation, higher dynamics in grid frequency and grid voltage) which arise from the expansion of renewable energies (e.g. photovoltaic systems, wind turbines, and combined heat and power systems) and new electrical loads (e.g. heat pumps and electrical vehicles) [8], Numerous smart grid projects labeled with the term 'agent' sprouted up in the last few years, exhibiting various interpretation of when and how to apply the term 'agent' [19]. It seems that engineers use the term 'agent' without a common understanding of what it actually embodies. In the present paper, we aim at providing a clear definition of multi-agent systems in the realm of smart grid distributed control applications1. We do so by first identifying the characteristics that a control system should posses to be appropriately labeled as an agent system by emphasizing the differences between agents, optimizers, closed-loop controls, and learning systems. Second, we systematically analyze the interpretations and implementations of multi-agent systems in recent smart grid projects. We then contrast our understanding of agents and multi-agent systems with the existing multi agent based smart grid projects and discuss which systems can be really understood as such. Finally, we describe the extent, to which agent technologies may be of further value in improving smart grid applications, and give directions for future research and practice in the realm of agent based systems.

II. SMART GRID – DEFINITION AND APPLICATIONS

Firstly, weather dependent fluctuation of the power supply of renewable energies (e.g. wind turbines or photovoltaic systems) makes the indispensable balancing of power generation and consumption more challenging. Secondly, the generated renewable electricity is fed mainly into distribution and low-voltage grids. In the past, energy was only consumed in these grids while it was produced by large fossil power plants connected to the transmission and sub-transmission grids (see Fig. 1). Thus, the recent primary grid infrastructure (e.g. local transformers, circuit breakers, lines) is designed and parameterized for these unidirectional flows. In combination with the rising electricity generation in distribution grids, problems (e.g. overvoltage and over-currents) are to be assumed.

Thirdly, the rising amount of distributed energy generation affects the grid frequency today already. Since the frequency is a grid-wide value, it is also necessary to ensure that the controllers of distributed energy resources are parameterized properly to ensure a stable grid. European standardization committees are currently addressing the 50.2 Hz problem, which occurs with a common switching threshold of 50.2 Hz in current inverters. This parameterization involves the danger of a major disturbance in the main grid when suddenly several gigawatt of generation disconnect in case of an underload (frequency above 50.2 Hz) and cause thereby an overload [17]. Fourthly, new applications and business models such as consumption of self-produced energy, electric vehicles, or the bundling of distributed generation to virtual power plants, will change the current static time-invariant behavior of grids to a more dynamic one.

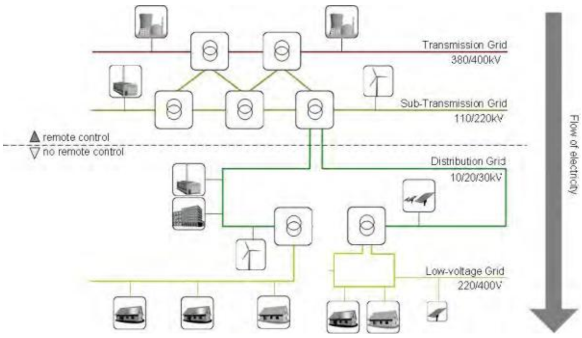

Fig 1: Structure of today's (centralized) electricity supply system

Numerous different smart grid control systems have been developed to find cost-efficient solutions and to approach the above-mentioned problems. One of the most popular concepts to encourage users or systems to consume power when it is produced by the fluctuating energy resources is known as Demand Side Management (DMS). Mainly based on dynamic pricing, DMS encounters users or devices to redistribute electric demand over a certain period of time. Another example for a smart grid control concept is the pooling of distributed generation and loads that are collectively controlled by a central control entity. These systems are known as virtual power plants. Furthermore, various projects can be found which take the control of socalled 'micro-grids' into consideration. Here, micro-grids are understood as small, local distribution grids containing electric generation and loads, which can be totally separated from, or (re-)connected to, the main distribution grid. Among these examples numerous other smart grid control concepts have been developed. [12] gives a broad overview about recent smart grid projects in Europe.

III. STATE-OF-THE-ART VERSUS AGENT TECHNOLOGY

In this section we discuss and define an agent from an engineer's perspective. Agents are first defined in an independent application way and then discussed in the context of smart grid applications. While [9] and [14] discuss the difference between agent technology and various IT domains (e.g. artificial intelligence, web-services and expert systems and grid computing) we analyzed the differences between well established engineering control technologies and agent technology. This section begins with computer science's definition of agents. Based on that, we differentiate in detail between an optimizer, a closed-loop controller, learning systems, and an agent. While numerous definitions of agents have been discussed in the past, we here post the definition of Jennings and Wooldridge. We consider their approach a good balance between an overly-restrictive and a too-loose definition. A survey of 'agent' definitions can be found in [11]. Jennings and Wooldridge understand an autonomous intelligent agent to be a software artifact which exhibits the following capabilities:

"**Reactivity** Intelligent agents are able to perceive their environment, and respond in a timely fashion to changes that occur in it in order to satisfy their design objectives.

Proactiveness Intelligent agents are able to exhibit goal-directed behavior by taking the initiative in order to satisfy their design objectives.

Social ability Intelligent agents are capable of interacting with other agents (and possibly humans) in order to satisfy their design objectives."

It seems that these attributes are to some extent also manifested in engineers' state-of-the-art control technologies. To a certain degree this assumption is valid. For the sake of clarity, we work out how an agent can be distinguished from other control technologies, and why that makes sense. In the rest of the paper we use the term 'agent' instead of 'intelligent agent'. We do so because we believe that labeling a software artifact as 'agent' only offers added value if agents at least constitute a certain degree of intelligence, thus exhibiting the above listed attributes. Hence, the adjective 'intelligent' is dispensable.

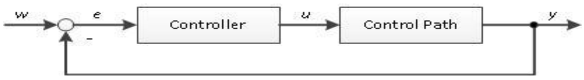

Fig 2: Basic structure of a conventional closed-loop control

IV. "MULTI-AGENT SYSTEMS" IN RECENT SMART GRID PROJECTS

In this section, we review the most recent smart grid research projects labeled with the term 'agent' or 'multi-agent'. We do not claim to provide a complete listing of all smart grid multi-agent systems. Rather, we intend to carve out common interpretations and implementations of the agent technology by illustrating some representative examples. Therefore, we only considered the domain of distributed agent-based control systems. Furthermore, we refer to the more general term 'control entity' (CE) to describe the diverse systems (and their differing interpretations of agent systems) instead of using the term 'agent'. We discuss under which circumstances CEs and control systems can be understood as multi-agent control systems.

The majority of previous multi-agent labeled systems consist of distributed CEs, which are responsible for trading energy on local electricity markets (LEM) by sending bids. In distributed CEs scenarios, CEs calculate energy sales or energy purchase prices based on their individual cost functions. The cost functions for CEs are composed of the specific power device's (e.g. combined heat and power plant, photovoltaic system, or simply a dwelling with different loads) cost function for which the CE is responsible. After calculating the cost-minimal operation of the power equipment, the CEs send bids to their dedicated LEMs. The LEMs subsequently match the CEs' energy offers and demands and send the auctions outcome. CEs can either act as sellers or buyers at the local energy market [4], [5], [18]. In addition to the descripted basic market-oriented structure (continuous lines) a further upper trading level is visualized in the figure (dashed lines). In this level, LEMs can trade energy at an upper electricity market (EM). However, they only do so if they were not able to locally match all supplies and demands of the CEs. Such a cascading system can be found in [18]. With few exceptions, such as these market-oriented systems usually are nonpredictive systems. Thus, they only calculate energy for the next time intervals that range between 500 milliseconds and several minutes and do not calculate a cost optimal schedule (e.g. for the next 24 hours). In most all market-oriented systems labeled as MAS, control entities are only connected to their dedicated local energy market.

Hence, these MAS are not programmed to search or adapt their strategies to other local or global markets. Furthermore, current market-oriented multi-agent systems are mainly programmed for one dedicated market type. For example, the abovementioned systems can handle only bids within an auction based, active power market. However, an agent should be capable of handling all types of markets (e.g. active, reactive, and spinning reserve markets) and all offered products (e.g. spot deals or forward transactions). Grid-oriented systems constitute the second important application field of multi-agent based distributed control systems in the smart grid. These control systems are primarily responsible for ensuring a grid operation in a normal state, which implies an operation within the standardized voltage, power, and frequency limitations of the grid. For example, extends the marketoriented approach of with a local frequency measurement and adjustment. Therefore, the CEs are responsible for the DESs only receiving a set point from the central CE. Furthermore, in previous grid-oriented projects, distributed control systems capable of performing an automatic reconfiguration of their control

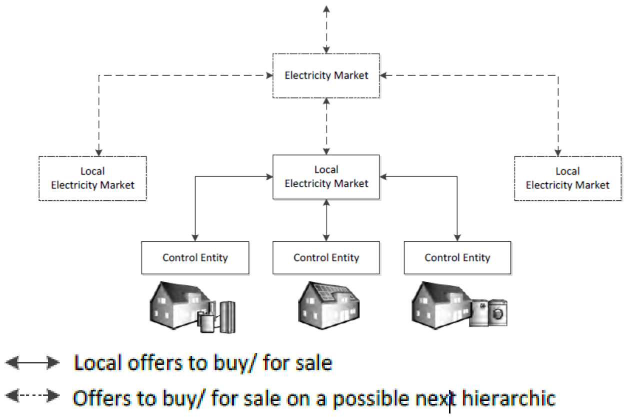

Fig. 3: Common structure of systems labeled as MAS applying an auction based active power spot market.

V. GRID-ORIENTED MULTI-AGENT SYSTEMS

The development of distributed renewable systems obliges network operators to extend their (sub-)transmission control systems to the distribution and lowvoltage grids. To preserve operational personal from workload increase, which even today necessitates automation [15], multi-agent systems could be a suitable solution. Industrial manufacturing and industrial process automation already demonstrate that agent-based systems bring sizable advantages when applied as a control system for uncertain, difficult to predict and varying environments. Biological wastewater treatment plants or production systems with repetitive plugging of equipment are the most noteworthy example which Metzger et al. surveyed. These conditions seem – in a weakened form – also present in future electricity distribution grids. The following paragraphs discuss where agent technology in grid oriented control is of value. Since voltage and frequency control demonstrate the most important and most discussed grid values in smart grid research, we have subdivided this section accordingly. Further, we discuss micro-grid control systems within a separate paragraph, since it is responsible for all values which are important for stable and reliable grid operation.

A. Voltage Control in Distribution Grids

In addition to frequency control, network operators are responsible for controlling grid voltage. In contrast to the grid frequency, the voltage depends on the grid's topology, encompassing the grid impendency, grid structure, and the active and reactive energy flows of consumers and generators connected to the grid. Voltage control in distributed and low-voltage grids was not important in the past due to the unidirectional energy flows and the associated static drop of voltage along the power line. The transformers in low-voltage grids were adjusted in the way that the voltage was high enough even at the end of the grid. Over-voltage problems are assumed when the current static transformer parameterization remains unchanged while the number of distributed generators (e.g. photovoltaic systems or combined heat and power plants) rises. In order to keep the voltage in the permitted ranges, one approach is to involve the distributed systems in grid stabilization by means of dynamic adaptation of the active (P) and reactive power (Q) depending on the grid voltage. These distributed systems need to be coordinated to avoid voltage oscillation in the grid and to ensure a maximal production of renewable active energy. For this purpose, the controllers can be extended to agents, capable of coordinating and negotiating injection of power. To reduce the configuration efforts of the agents and to allow automatic adaptation when the grid structures change, agents should be capable of detecting grid position. These changes in grid structure can develop because, first, short circuits or earth faults need to be recovered, or, second due to an islanding of the grid section in which the agent is located. In both cases manual reconfiguration and coordination of the distributed controllers' parameters seems inappropriate. Thus, agents which realize automatic configuration may be valuable assets in this scenario. Especially in regions with a high percentage of overhead lines (as in the United States) automatic troubleshooting of electricity grid is of paramount interest.

B. Grid Frequency Control

The gradual substitution of conventional power plants with distributed renewable energy systems compulsorily increase the influence of distributed systems on the frequency. To ensure a stable and reliable grid in the future frequency control need to be coordinated among those millions of distributed systems, since large frequency changes can lead to an unstable power system. In today's central European electricity grid (ENTSO–E4 grid), the transmission grid operators are responsible for the frequency control. The frequency control is divided in three control levels which differ in their time of activation: a) primary control (frequency-response reserve), b) secondary control (spinning reserve), and c) tertiary control (replacement reserve). In case of a frequency deviation, the control levels are activated step-wise, beginning with the primary control, via the secondary control and ending at tertiary control (if the deviation still exists). The primary control reacts within a few seconds (max. 30 seconds) to frequency deviation by automatically adapting the power of some generation units in the electricity grid according to a given static. After one minute, the secondary control replaces the primary control and tries to restore the frequency to the nominal value (in Europe 50 Hz). If it is not possible to restore the frequency with the secondary control after five minutes, tertiary control is manual (e.g. via phone) requested by transmission operators. All forms of operating reserve (frequency-response reserve, spinning reserve and replacement reserve) are traded on the operating reserve market. Currently only larger power plants are allowed to participate on the operating reserve markets.

Assuming that the current operating reserve mechanism remains unchanged, while in the future small distributed generation units are also allowed to trade replacement reserve, agents might be of value when enabling automated participation of distributed energy systems at the operating reserve market. As a control entity for a distributed energy system (e.g. a combined heat and power plant) the agent would autonomously negotiate at the operating reserve market in order to operate its distributed energy system cost-optimally. A Balancing-Agent, which is responsible for the frequency, offers active energy for consumption when the frequency is about to drop and buys energy - which is left unused - when the frequency rises. Here, the Balancing- Agent appears as a central coordinating unit to which the other agents are dedicated. As mentioned above, it is questionable if a control entity which is slowly connected to the operating reserve market server shall be deemed an agent in strictest sense. The automatic negotiation can also be implemented using web-services. But as described by [14] web-services are not agents. Hence, labeling negotiating control entities as agents would only make sense when they demonstrate proactiveness and social behavior as described. Consistently, proactiveness and social behavior are only feasible if alternative courses of action exist. It is the control entity which is capable of deciding, for example, to either offer at the operating reserve market or to any other energy market, which would constitute a freedom, on the basis of which a control entity may develop its proactiveness. Furthermore, social behavior only evolves if other control entities and, with that, possibilities of cooperation (e.g. as virtual power plant) exist. Besides the question of how distributed energy resources can participate passively at the frequency control via a replacement reserve market, it still remains unclear how they can participate, without causing grid destabilization. As mentioned above, recent photovoltaic inverters were configured to disconnect from the grid if the frequency reached the limit of 50.2 Hz. If a large amount of systems would react accordingly, this would cause serious grid problems [17]. Thus, the parameterization of the distributed energy system via cooperating agents – as applied for voltage control – would be conceivable. But other than the voltage, the frequency constitutes a grid-wide value. This would imply the coordination of millions of energy systems, which seems unrealistic mainly due the associated high communication traffic. Assuming that, in the future, only some power units are responsible for the supply of frequency-response and spinning reserve power, a multi-agent system might be an appropriate solution for an automatic, autonomous, and self-parameterizing control system of the power plants control, as described in [1].

C. *Micro-Grid Control*

Micro-grids seem to be the most appropriate smart grid domain for the applications of multi-agent based control systems regarding the recent numerous micro-grid projects [19]. [3] defines micro-grids as small, local distribution systems containing generation and loads that can be separated totally from the distribution grid. Micro-grids constitute, indeed, perfect environments for the application of MAS, for the following reasons: First, other than the main grid, the micro-grid demonstrates a small separate system comprising of a limited number of control entities. That makes the coordination and the assigned communication efforts manageable. Other than in the smart grid parameterization, for example, of the frequency controllers becomes feasible. Second, micro-grids in disconnected mode are fully responsible for the stable and reliable operation of the grid. That encompasses, besides the voltage control, the frequency control and protection issues as well. The indispensable energy balance needs to be ensured, while, caused by disconnection, only a reduced number of devices that can provide reserves exist. Likewise, the micro-grid control system needs to react to regular changes in the grid topology (e.g. disconnection of distributed energy resources or loads). Hence, as described in, MAS would be a valuable asset, because other than in a centralized micro-grid control system, no manual adaption of the central control algorithms/models is necessary. Within a MAS automatic adaption of the distributed control parameters takes place if topology changes occur. Numerous multi-agent based micro-grid control systems can be found in literature. [19] give a broad overview about recent multi-agent based micro-grid controls. In this section we illustrated that the terms 'agent' and 'multi-agent' systems applied in the smart grid are of value when automatic, cooperative, and coordinated reconfiguration of distributed devices (e.g. distributed energy systems or grid equipment) is required during runtime. We discussed the application of multi-agent systems for frequency control, voltage, micro-grid control (grid-oriented), and economic-oriented control systems, since they constitute the major smart grid control domains. Further applications, such as the optimal coordination of an electric vehicle fleet or substation monitoring and diagnostic systems, can be considered as further possible applicable fields for multi-agent systems. However, it is recommended to carefully consider if either multi-agent systems or current state-of-the-art control technology should be applied, as the case pops up on a case by case basis. Furthermore, the term 'agent' should only be used if the control systems evince the above mentioned abilities: proactivity, reactivity and social behavior, and not only as a synonym for state-of-the-art control technologies.

VI. Conclusion

This article has sought to justify why and when multi-agent systems are suited for smart grid applications. First, we have posed that state-of-the-art control technologies should not be understood as agents, but, in turn, agents should be understood as software artefacts that exhibit the functionalities of optimizers, controllers, and learning systems, accompanied by the capabilities of practical reasoning and social interaction. Second, we contrasted our understanding of agents with interpretations of recent smart grid projects labelled as multi-agent control systems. These projects have already demonstrated the effectiveness of multi-agent systems, although they implement agents only in the broadest senses: due to the decentralized structure, data is locally processed where it is produced and local negotiation effects a coordination of the distributed systems. However, to explore all agent benefits and to sharpen the notion, we suggest terming control entities as agents when they encompass all of the above mentioned functionalities. The assets are: i) automatic reconfiguration in case of time-invariant environment changes (e.g. grid topology changes); ii) automatic initiation of and participation in (economic) interest groups (virtual power plants); and iii) automatic adaption to changing control strategies (e.g. in case of grid islanding). Coordination of thousands of distributed, fluctuating, electricity generators and a robust operation of our electricity grids constitutes an enormous future control challenge. This dynamic, distributed, and widespread environment seems to be perfectly suited for the application of agent-based control systems.

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