Preprints of the 21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

Agent Based Modeling in Energy Systems: Parametrization of Coupling Points [⋆]

Shahbakhsh, Arash [*] **Nieße, Astrid** [**]

[*] *Group Energy Informatics, Leibniz University Hanover Appelstr. 9a, 30167, Hannover (e-mail: shahbakhsh@ei.uni-hannover.de).*
[**] *Group Energy Informatics, Leibniz University Hanover Appelstr. 9a, 30167, Hannover (e-mail: niesse@ei.uni-hannover.de)*

Abstract: Future multimodal energy systems (MES) including heat, gas and electricity sectors will be equipped with control systems, which have some degree of autonomy, and are adaptive to their environment. Smart control systems are able to communicate with other systems and other autonomous controllers. The resulting systems can be analyzed as a complex adaptive system (CAS), which has been successfully investigated using agent based modeling (ABM) in the past. In this study, the operational behavior of a MES using different agent parametrizations for coupling points is investigated. These properties can be categorized as fast-acting agents and slow-acting as well agents with and without dead-band and saturation. The result of every scenario points out the temporal evolution of pressure in gas , temperature in heat and voltage in electricity sectors. The bottom-up perspective allocates agents' parametrizations to the whole system behavior. The study shows the effect of dead-band, saturation and the gain of coupling points controller on the MES. In addition, the role of observers in analyzing systems in CAS paradigm is discussed. The results pave the way for setting up proper agents' parameters and designing proper observers.

Keywords: Multimodal Energy System, Agent Based Modeling, Complex Adaptive System

1. INTRODUCTION

Contemplating future energy systems, environmental concerns, societal tendency, technological trends and decisions of policy makers prompt fundamental changes. These changes can be bundled in three clusters: 1) increasing efficiency of energy system with coupling different energy sectors, 2) using renewable primary energy sources from solar and wind generation units, and 3) liberalization of energy for small generation units. The result is a *multimodal energy system* with intelligent and autonomous controllers in a distributed control system, known as smart multimodal energy system. The terms *distributed* and *autonomous* are related closely, the former requires local controllers and the latter demands the ability of decision making for local controllers. The term intelligent means here that controllers adapt their behaviors for a higher efficiency. The distributed control of future energy systems will not be orchestrated by a central control system, but their stability, performance and efficiency will be shaped by distributed local agents. The centralized control systems with a top-down structure seem to be inefficient if not impracticable for the future. As a result the operation of energy system and consequently its control system should be conceptualized anew. This transition from a centralized control to a distributed system demands a paradigm shift, because analyzing without this new paradigm necessitates lots of simplification and assumptions and even so they can not deliver a proper forecast for system behavior. The framework of this paradigm is defined as *complex adaptive systems.* The Theory of complex adaptive systems suggests the *agent based modeling* as a suitable analyzing tool. In addition, analyzing system in CAS view necessitates choosing proper metrics and designing observers for identifying special behaviors in CASs. In the following, we introduce the three contexts of our study: 1) Multimodal Energy Systems (MESs), 2) Complex Adaptive Systems (CASs), and 3) Agent Based Modeling (ABM).

1.1 Multimodal Energy System

The multimodal energy system (MES) in this study comprises electricity and heat as two energy vectors and gas as an energy carrier, which are all interlinked with coupling points. The energy generation concept is based on Distributed Energy Resources (DER) in distribution networks for all three sectors, and the control system concept is assumed to be fully distributed. The electricity and gas sectors have connection to super-ordinate transmission networks whereas heat sector is assumed to be a local network. The loads of all three sectors are modeled as passive loads, which follow a load profile. Modeling components of MES, their operational behavior and the function of control system take center stage in this study. To summarize, we study a MES including three sectors with focus on the operational behavior of distribution networks, distributed generators and coupling points.

The MES model works based on the principle of energy and mass conservation for presenting the state of energy

---

[⋆] This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under the project number 359941476.

system at specific points known as *nodes*. These nodes are for instance the connection point between distribution and transmission networks, the connection point of load or two sides of coupling points. The connections between two nodes are known as *branches*, which can be a power-line, a transformer, a pipeline or a coupling point. The Load profiles of consumers and the set points of control system are the inputs to the model of MES. As discussed in (Shahbakhsh and Nieße (2019)), the state vector X that represents the state of the MES is the output of MES model. Meanwhile, the elements of X are control variables, which must be kept in an acceptable range by means of the control system.

$$\mathbf{X} = [v\ p\ T]^T \tag{1}$$

In the electricity sector, the amplitude of complex voltage v for every node is the control variable. The nodes pressure p are the control variable of the gas network. The respective control variables for the state of the heat system is the temperature T of nodes.

In this work we have developed a per unit system, which converts the value of all variables into per unit and all calculations are performed in per unit system. This decision has two main reasons: 1)studying MESs requires converting the unit of variables between three sectors, therefore per unit system facilitates the calculations; 2)for the goal of this study, the actual value of variables is more confusing than helpful, even though the actual values can be extracted easily by multiplying the per unit with the reference values. The coupling points, power-to-gas (PtG), power-to-heat (PtH) and combined heat and power (CHP) are considered in this study as branches with a predefined efficiency factor. These slack points are modeled as load in one sector and as slack in another sector.

Considering the MES model as the environment, the control system with its actuators acts on this environment, e.g. the CHP controller is an agent on this environment, which controls and limits the energy flow from gas into electricity sector. In the next section, we introduce a framework for analyzing the effect of agents' action on shaping environment' behavior.

1.2 Complex Adaptive Systems

CASs comprise a group of systems on which autonomous agents interact with an environment and eventually with each other, e.g. systems, which have agents with simple internal rules like black-white points in the *Conway game of life* (Codd (2014)) as well as systems, which have agents with memory and logic like societal systems of animals and humans (Gilbert (1995)). According to Holland (Holland (2014)), *emergent behavior is an essential requirement for calling a system complex.* In addition, the following properties can be observed in many CASs: 1)Additivity is not more valid in CASs, i.e. the whole is more than the sum of its parts, 2)CASs are not ruled by orchestration but by choreography, viz. local autonomous agents shape the overall behavior of system and not a central coordinator, and 3)CASs are normally dynamic nonlinear systems. Our goal of using the paradigm of CAS is to identify the emergence in CASs, i.e. an order that is identifiable with a specific observer(Müller-Schloer et al. (2011)). This observer fill in the blank between chaos and order by recognizing the behavioral pattern of the whole system. Therefore, analyzing systems under the paradigm of CAS necessitates specifying suitable observer, which can measure and show the *hidden order* (Holland (2000)).

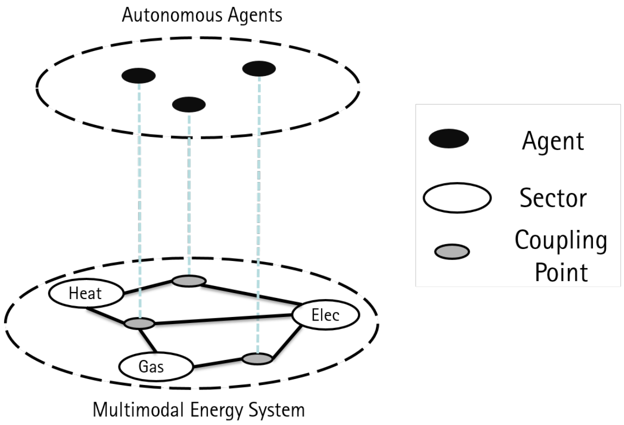

Fig. 1. The connections between the MES and its autonomous agents. As depicted, the autonomous system interact indirectly via the MES and don't include any direct communication or coordination. The MES layer shows the integrated energy system including electricity, gas, heat and the coupling points.

MESs including their control system cover some of these properties, therefore one is confronted with the decision to analyze the MESs in conventional analyzing frameworks such as general systems science view (Dekkers (2017)) or in the framework of CASs. Choosing either of these paradigms necessitates lots of assumptions. For example analyzing MESs in the framework of control theory requires defining operating points and linearization nonlinear models around them, even though the analysis does not deliver any informative result about the effect of agents' decisions on shaping the overall behavior of the MES. Therefore we choose the framework of CASs, which is suitable for finding the emergent behavior of the complete system. In (Macal, Charles M and North, Michael J (2005)), the ABM is suggested as an approach for analyzing CAS.

1.3 Agent based Modeling

ABM or individual-based modeling is a method for analyzing CASs. The application of this method has been shown in *Conway's game of life*, *Boids* (Borshchev and Filippov (2004)) and newly in developing collective intelligence as well in societal systems (Nava Guerrero et al. (2019)). The ABM makes possible the modeling of nonlinear and time-variant behavior of agents. Analyzing CASs with ABM involves these three requirements: 1)the environment, which is the MES in this study, 2)the agent rule sets represent the behavior of agents independent from the environment, which will be discussed later in detail and 3)time, which is assumed to be discrete, viz. the states of agents are updated in discrete time points at once.

Having these three requirements, we recap the process of the ABM. The agents perceive the environment via sensors in any arbitrary time point. The agents use their internal rule set to generate outputs and push them to the MES.

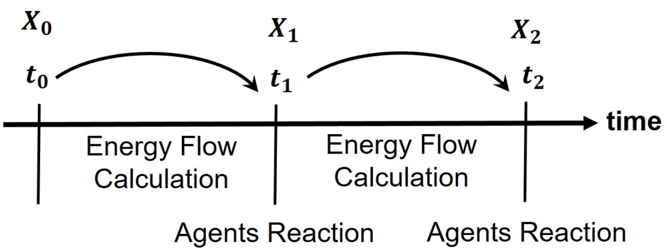

Fig. 2. State transition of energy system is assumed to be discrete. Agents reaction take place at once in discrete time as well.

The MES model calculates the vector $\mathbf{X}$ for the next time step and the process repeats. The interaction time points, at which data transfer takes place between the MES and the agents is depicted in Fig. 2. The figure shows that the MES model prepares the vector $\mathbf{X}$ and the ABM calculates the agent reactions for time points.

1.4 Research Goal

According to the defined contexts, our primary research goal is to find the relation between parametrization of rule sets and the whole system behavior, viz. how agent rule sets shape the MES response. Clearly, every parametrization results in different behavior, but some of them lead to a desired and expected response, which is stable, robust and resilient, whereas some others evoke an unwanted and unexpected outcome. If these undesired responses are not to be expected, we first face the problem to identify them. This fact raises the question what are the expected responses of the MES. Answering this question thus constitutes a prerequisite to identify the expected from the emerged and unexpected responses. Our secondary research goal is to find out the role of observers in analyzing MESs with CAS paradigm. In the conventional views of system theory, the appropriate signal and the place of sensors have been discussed deeply, but what are the effective attributes, metrics and observers that can demonstrate the whole system behavior.

2. METHODOLOGY

The methodology of this study follows this process: Based on the defined MES, an energy system scenario including topology of networks, the placement of coupling points as well as slack points and the load profiles is defined. After that, the rule sets of agents are specified, and the specified MES is tested under different agent's parametrization using proper observers.

2.1 MES settings

The studied MES is a simplified case of the test system as introduced in (Shahbakhsh and Nieße (2019)). The electricity sector includes 9 nodes (E1, E2, ..., E9) with two connections to the super-ordinate power grid at E2 and E3. The gas sector encompasses 11 nodes (G1, G2, ..., G11) with only one connection to the super-ordinate gas network at G8. The heat network involves 9 nodes (H1, H2, ..., H9) and has no connection to any external super-ordinate heat network. A CHP unit couples the node G11 with the nodes E1 and H9 of the electricity and heat sectors respectively. Depending on the efficiency factor of CHP, the fed gas is converted into electricity and heat. A PtH unit couples the node E8 to the node H1 and a PtG unit couples the node E6 to the node G1. The connections between sectors and also the input and output variables of coupling points are shown in Fig. 3. The topology of each sector is as same as discussed in (Shahbakhsh and Nieße (2019)). In course of this study, we consider that all loads of each sector in MES have constant profiles. This assumption sets up a static environment, which is a proper basis for investigating the effect of rule sets on shaping the system state.

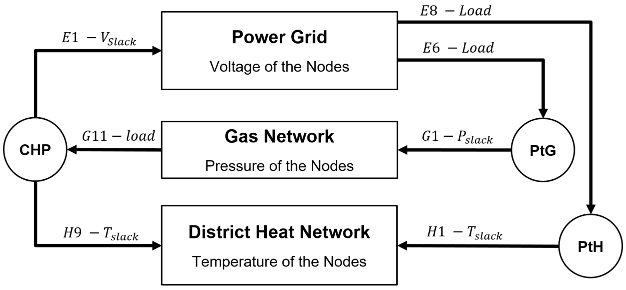

Fig. 3. The MES with the connections between sectors and coupling points.

2.2 ABM Settings

In the work at hand, autonomous controllers of coupling points CHP, PtG and PtH are modeled as proportional controller. In the reality, these controllers include two typical non-linearities: dead-band and saturation, which are modeled as well.

The CHP Controller controls the gas flow into the CHP regarding a threshold value, which can be the permitted or the scheduled energy flow. Depending on the efficiency, CHP has some waste heat, which is fed in the heat sector. The CHP controller generate an error signal, $\Delta\dot{V}$, which is the deviation from the permitted gas flow through the CHP. The output signal adjusts the voltage of slack node E1. In Fig. 4, the control loop of the CHP shows the inputs and output signals of the CHP and its agent.

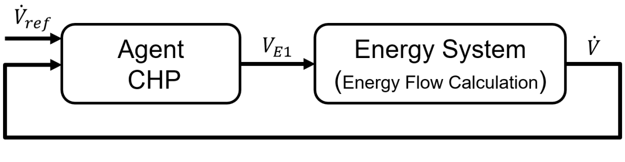

Fig. 4. The closed loop control of CHP shows the inputs and output signals of the CHP and its agent.

For calculating the output signal $\Delta\dot{V} = \dot{V}_{ref} - \dot{V}_{CHP}$, the agent follows its internal rule set as shown in Fig. 5. The parameters a, b, c, d, and α determine the behavior of agent and specify the dead-band, saturation and the gain of the controller respectively. The property dead-band represents the time lag that agents require to sense sensor signals and react to them. Agents whose sensing device has a lower lag time react faster. The property saturation represents the fact that every real actuator has a limited capacity. Agents whose actuator has more capacity will be saturated later and therefore can deliver more control effort. The parameter gain represents how big is the reaction of agent to error signals whereby agents with a higher gain react faster. The PtG agent controls the energy flow from the electricity into the gas sector. The output signal controls the pressure at G1. The PtG agent follows the same rule set as the CHP but with different parameters.

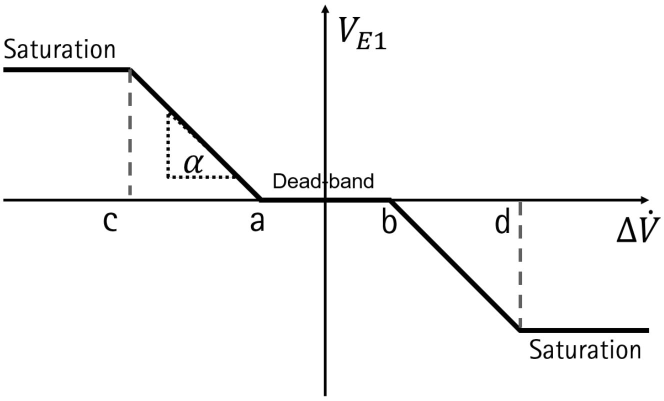

Fig. 5. The rule set for the agents of CHP, PtG and PtH includes proportional controller, dead-band and saturation. The parameters a, b, c, d and α determine the behavior of agent.

In this work, agents' parameters are time-invariant. We call one agent relatively faster than another when it has a faster reaction at least by one parameter, when all other parameters remain constant. Fast-acting agents have either a narrower dead-band, a bigger gain or they will be saturated later, e.g. if agents of heat exchange stations have a narrower dead-band and are consequently fast-acting, they react to the small ΔQ. The same is valid for the PtG and the CHP agent.

2.3 Implementation

The simulation environment MATLAB is used for implementation of MES model as discussed in (Shahbakhsh and Nieße (2019)). The ABM is developed as well in MATLAB environment, which is based on a class *agent* with the properties a, b, c, d and α as well as a method that represent the rule set. The behavior of the MES model with ABM is performed in two loops nested in one another. The inner loop represents the time period, at which the agents are in interaction with the MES and lasts 15 time units. In the outer loop, the energy demand is updated.

3. RESULTS AND DISCUSSION

The Behavior of the MES under different agent configuration and parametrization is tested. We use two different metrics in each case. The First metrics is the energy flow through CHP, PtG and PtH whereby the second observer includes the voltage, pressure and temperature at E6, G11 and H5. The first two nodes are connected to relatively big loads. Furthermore, these nodes supply other sectors and therefore can be interpreted as the shape of one sector from another sector's point of view. With this test, we determine the general effect of every coupling point on the MES.

The results in Fig. 6 sketch out the behavior of MES under four agent configurations: without agents, with CHP agent, with PtG agent and with PtH agent. The voltage at E6 and pressure at G11 are under the dominance of the CHP whereby the activation of PtH has more influence on the voltage at E6 than activation of PtG. The temperature at H5 is mostly under the effect of PtH as we expected. The energy flows between sectors as depicted in Fig. 7 show the importance of choosing a proper metrics and observer. Because the effect of activating PtG agent on the voltage and pressure in Fig. 6 is not recognizable, i.e. voltage and pressure with the plotted resolution are not proper candidates for observing the effect of the PtG agent.

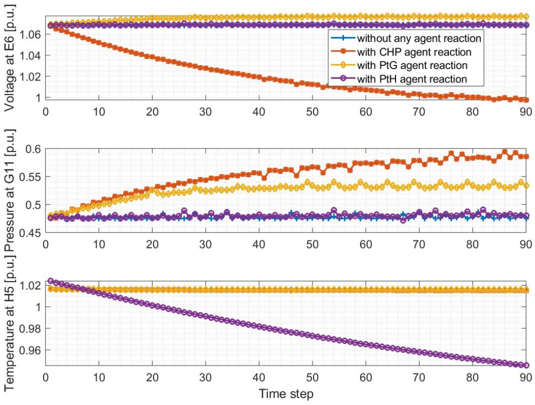

Fig. 6. Comparison the voltage at E6, pressure at G11 and temperature at H5 in MES under 4 agent conditions: without agents, with CHP agent, with PtG agent and with PtH agent.

The effect of the parameter gain α is investigated in the next test. The agents with a higher gain react to every error with a bigger control effort, therefore are defined in this work as fast-acting agents. This effect is identifiable in Fig. 8 by observing the temperature at H5. The big control effort of agents leads to oscillation as a side effect which is demonstrated in Fig. 9 by the energy flow through PtG.

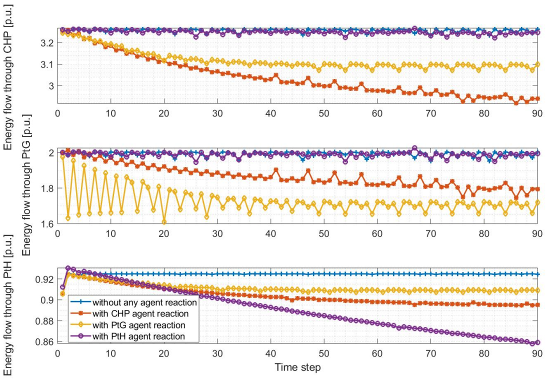

Fig. 7. Comparison the energy flow through CHP, PtG and PtH in MES under 4 agent conditions: without agents, with CHP agent, with PtG agent and with PtH agent.

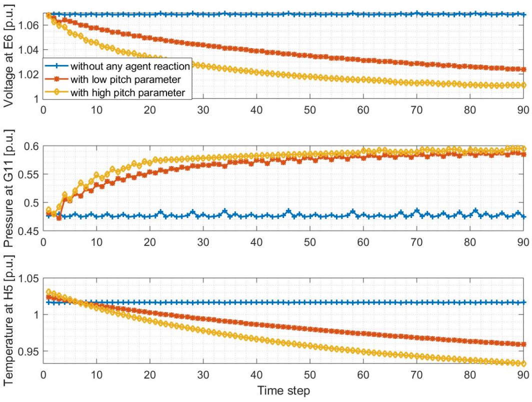

Fig. 8. Comparison the voltage at E6, pressure at G11 and temperature at H5 in MES under 3 agent conditions: without agents, with slow agents and with fast agents.

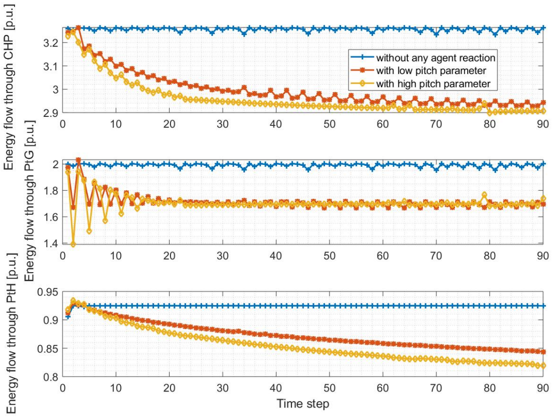

Fig. 9. Comparison the energy flow through CHP, PtG and PtH in MES under 3 agent conditions: without agents, with slow agents and with fast agents.

The effect of dead-band is investigated by testing the MES without dead-bands, with a narrow and a wide dead-band as presented in Fig. 10 and Fig. 11. Adding and stretching the dead-band slow down the system responses. Moreover, The interaction of agents leads to oscillation of system.

The results of testing the effect of saturation with and without dead-band are presented in Fig. 12 and Fig. 13. The energy flow diagrams show that adding saturation to agents decelerate the MES. In addition, the energy flow through PtG demonstrates an unexpected oscillation resulted from interaction between agents.

The presented results cast light on a big amount of data generated by MES including states of 29 nodes and energy flows through 34 branches in 90 time points. Every of these variables or any combination of them can serve as an attribute for any potential observer.

4. CONCLUSION AND OUTLOOK

Analyzing systems with CAS paradigm requires setting ABM and defining observers. This essay reports how MESs can be analyzed using different ABM parametrizations and configurations with different observers. By testing

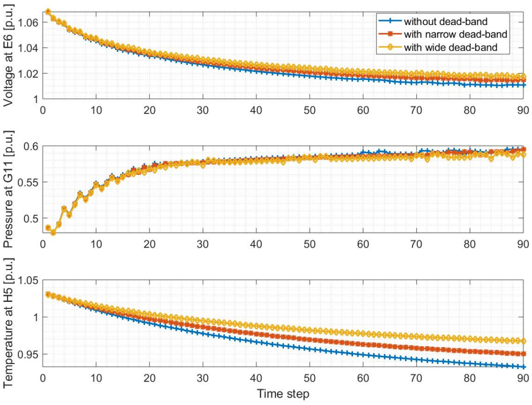

Fig. 10. Comparison the voltage at E6, pressure at G11 and temperature at H5 in MES under 3 agent conditions: without dead-band, with narrow dead-bands and with fast dead-bands.

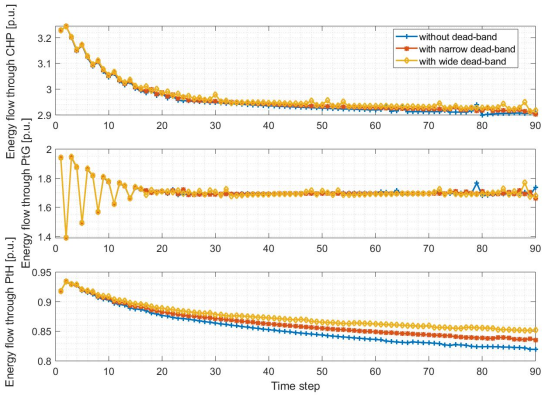

Fig. 11. Comparison the energy flow through CHP, PtG and PtH in MES under 3 agent conditions: without dead-band, with narrow dead-bands and with fast dead-bands.

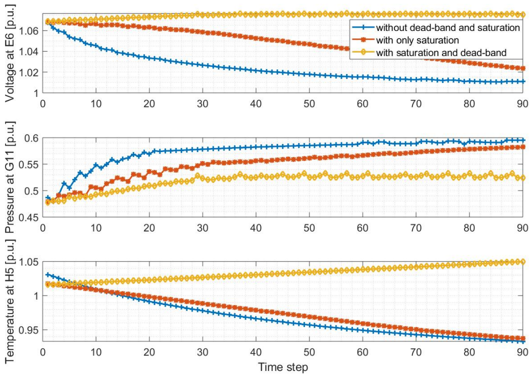

Fig. 12. Comparison the voltage at E6, pressure at G11 and temperature at H5 in MES under 3 agent conditions: without dead-band and saturation, with saturation and with dead-band and saturation.

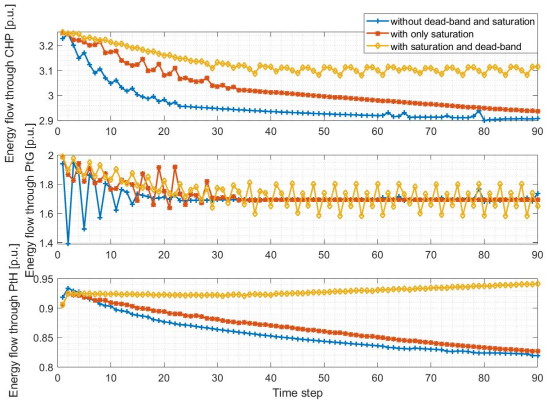

Fig. 13. Comparison the energy flow through CHP, PtG and PtH in MES under 3 agent conditions: without dead-band and saturation, with saturation and with dead-band and saturation.

the effect of each agent separately, the expected response of every agent is revealed. The same process shows the expected effect of the parameters gain, dead-band and saturation. By activating more agents simultaneously, an oscillatory behavior emerges because of interaction between controllers. Observing this behavior requires specific observer in every case. The results show above all that MESs have some characteristics of CASs, therefore the paradigm of CAS can be used for more studies. The presented results pave the way for designing proper agents to identify expected from unexpected behaviors of the MES.

The proposed methodology for analyzing MESs using CAS-paradigm must be equipped with *emergence recognition* methods for networks with a big number of nodes with considering the desired degree of abstraction. All concerns about the controller design will be discussed in the following works under the concept of simulation drive as shown in (Nieße and Shahbakhsh (2018)).

The outlook of the work at hand comprises a wide horizon including: 1)defining new observers and combining observers to build a *key performance index*; 2)Using varying load profiles for MESs; 3)Specifying the transient behavior of the MES between two sequential time points and 4)Changing the reaction time of agents. Moreover all these analysis can be used for finding a solution to operate the energy system more resiliently and optimally. For instance, a solution is to set up a *multi agent system* from the group of autonomous agents as depicted in Fig. 1, so that agents can communicate, cooperate and coordinate to reach a specific goal.

REFERENCES

Borshchev, A. and Filippov, A. (2004). From system dynamics to agent based modeling: Reasons, techniques, tools.

Codd, E.F. (2014). *Cellular automata*. Academic Press.

Dekkers, R. (2017). *Applied systems theory*. Springer, Cham, 2nd edition edition.

Gilbert, G.N. (1995). *Artificial societies: The computer simulation of social life.*

Holland, J.H. (2000). *Emergence: From chaos to order.* Oxford Univ. Press, Oxford, 4. printing edition.

Holland, J.H. (2014). *Complexity: A very short introduction*, volume 392 of *Very short introductions*. Oxford Univ. Press, Oxford, 1. ed. edition.

Macal, Charles M and North, Michael J (2005). Tutorial on agent-based modeling and simulation.

Müller-Schloer, C., Schmeck, H., and Ungerer, T. (2011). *Organic Computing — A Paradigm Shift for Complex Systems*. Springer Basel, Basel. doi:10.1007/978-3-0348-0130-0.

Nava Guerrero, G., Korevaar, G., Hansen, H., and Lukszo, Z. (2019). Agent-based modeling of a thermal energy transition in the built environment. *Energies*, 12(5), 856. doi:10.3390/en12050856.

Nieße, A. and Shahbakhsh, A. (2018). Analyzing controller conflicts in multimodal smart grids - framework design. *Energy Informatics*, 1(S1), 1. doi:10.1186/s42162-018-0041-3.

Shahbakhsh, A. and Nieße, A. (2019). Modeling multimodal energy systems. *at - Automatisierungstechnik*, 67(11), 893–903. doi:10.1515/auto-2019-0063.