Heterogeneous Modeling: A Need To Model Future Energy Systems

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***Abstract*—Flexible infrastructure of the grid system is needed for more power utilization efficiency and use of renewable energy systems. This is because of increase in enviornmental awareness to get free clean energy and also on the other hand depreciating fossil fuels. One promising approach of attaining such are "Microgrids". These sustainable grid systems needs robust new control algorithms and a redesign of existing grid infrastructure to enable integration of distributed power generation. The difficulties for attaining such diversity in microgrid infrastructure is the freedom needed to batch up power generators, storages and loads as plug and operable devices. This concept complicates the development of the realistic models for microgrids. Therefore a model centric approach using heterogeneous modeling is presented in this paper. The heterogeneous modeling process is elaborated which enables precise simulations through combination of specified modeling tools for specific tasks. With this approach, microgrid system containing two different renewable energy sources are modeled in Modelica and coupled together with a control designed in Simulink. The simulation results identified some design aspects on control and physical models of microgrids.**

***Index Terms*—Renewable Energy Systems, Model Centric Design, Microgrid, Heterogeneous Modeling.**

I. Introduction

The growing demand of energy with depreciating fossil resources drive the political and public awareness towards using distributed renewable energy resources (RES). For integrating these RES, large scale changes are needed in the existing infrastructure of electrical power supply system. Future energy systems rely on such changes, which enables the exchange of power from generators to consumers more efficiently and in environmentally friendly manner. One concept capable of providing this flexibility and sustainability is "Microgrid". By distributing the power generation into small local intelligent energy systems, connected through a bidirectional power grid, high level of flexibility can be achieved. But on the other hand this flexibility introduces high complexity. Compared to the traditional one-directional power system, the bidirectional power exchange systems imposes many big challenges to the control side as mentioned in [1]. In order to design such control algorithms new development processes capable of handling complexity correlatively to the new system design are needed. Considering local power system, active power balancing among energy sources and consumption in real-time needs to be realized. And on a larger scale interaction strategies between the energy systems consisting power networks need to be realized to match the power demand and supply in case of failure or over/under power generation.

This paper is divided and discussed in two steps. In first step, a model centric approach is elaborated in section II using component based heterogeneous modeling capable of combining specified development tools for the simulation of flexible power system. In section III interfacing solutions between development tools are given and in section IV model centric hetrogeneous modeling with hardware in the loop (HIL) is discussed. In second step two hetreogeneous modeling of microgrid is discussed in section V. Discussed Microgrid consists two energy systems each consisting of main three physical components which are intermittent power generator, storage and load. These physical components are modeled in Dymola Modelica. The two energy systems within microgrid vary in the storage capacity, load behavior and integrated renewable energy source. Further a control side is realized in Matlab Simulink consisting of local control, protecting the battery of over or undercharg and regional control, coordinating the power exchange between the two energy systems in microgrid. For simulation and evaluating, the two energy system models are connected through S-functions whereas other integration possibilities are also explored. These types simulations will be beneficial for the power systems designers to visualize forecasted holonic as well as local level power consumption/generation patterns. The simulation results are discussed in section IV, in which obtained results enabled us to analyze the behaviour of the microgrid and the benefits offered by the heterogeneous modeling approach.

II. Heterogeneous Model Centric Development

The model centric development approach is already common in the electronics design automation (EDA) and mechanics computer aided design (CAD). Fast simulations without endangering any hardware is clearly offering a lot of advantages. A model-centric development method "to develop efficient solutions to complex engineering problems" are discussed in [2]. In this process stepwise transformation from a pure model to a real hardware prototype is percieved as given in see [3]. By continuous testing during the design process the development efficiency and reliability of the product is increased. These problems addresses the flexibility problems in future energy systems. A lack of data and knowledge on the system behaviour complicates the straight forward development. Without a clear idea about the system redefining and rethinking the first drafts of the models are mostly indispensable.

Another challenge which is addressed in this paper concerning future energy system is the diversity of tasks spread over nearly every technical discipline. Designing the storage, load and generation is only a small part. Intelligent control algorithms, bidirectional power exchange, forecasting, safe data transmission and many more functions need to be taken care off. It is clear that for these different tasks and domains specified tools and software's are needed during the design process. Therefore heterogeneous models are required which can then be embedded in model centric approach to get the desired system behaviour. The combination of several specified tools for each task enables more flexibility during the development process. Through coupling or interfacing of these tools for a faster and preciser development is possible. To develop future energy systems, information about the behaviour need is to be gathered to improve and validate the models necessary for better and more efficient control and communication algorithms integrated with physical models. In [4], it is mentioned that "modeling and gathering practical experiences using prototypes must go hand in hand". To create realistic modeling environments and models for future energy systems, the need of data and validation of components is essential. New structures need to be tested in a simulation environment offering a behavior equal to the network in which they will be included to design related reliable control

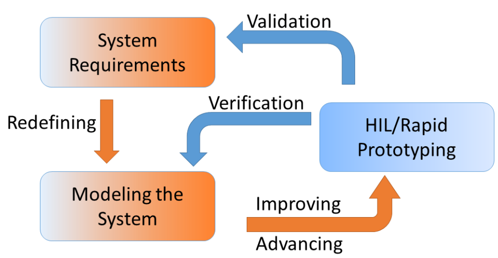

Fig. 1. Model Centric Approach

algorithms. These informations can be provided by prototypes through hardware in loop (HIL) testing and rapid prototyping. The standard model centric approach is adapted to address the problem in modeling future energy systems by using the cyclic process instead of sequential, as shown in fig 1.

Future energy systems are composed of electromechanical components such as generators, loads and energy storages, and they have embedded software giving them intelligence to improve the efficiency and reliability. For the development of such interdisciplinary systems specialized tools and methods are needed. Combining different modeling environments and development tools offers a preciser solution for each task and therefore better models and results. The combination not only of different development techniques but merging diverse highly specialized software is called heterogeneous modeling. It enables the use of the best fitting program or tool for each task and therefore a more powerful model. In section V model is developed using simulator coupling and the advantages and disadvantages are discussed.

III. Interfacing Solutions

Realizing the connection and interaction between developing tools can be done in three different main ways.

A. Single Framework

The single framework approach for heterogeneous modeling uses tools or software capable of simulating models of different domains in one framework. These frameworks can combine tools for certain specific problems, for example modeling of a heat pump and a wind generator in one development environment, or they can combine tools for specific modeling methods, for example causal and acausal. The combination of different modeling methods has been realized for example in Scilab offering XCos, or in Matlab offering Simulink and Simscape. Simulink for causal modeling and the Simscape library for acausal, work in the same software and are capable of interacting with each other. Merging causal and acausal in one tool enables heterogeneous modeling in one framework, so called "multi-porpose" software tools [5].

B. Simulator Coupling

Unlike the single framework approach, simulator coupling not uses one development software but connects at least two simulator. This enables an interaction between specialized development programs. To use the simulator coupling approach both software's must have the same interfaces. Interfaces such as Functional Mock-up Interface (FMI) or System-Functions (S-functions). With the S-function, Dymola model can be implemented in a Simulink. The interaction between the acausal modeling tool Dymola Modelica and the causal tool Simulink will be elaborated more in a later section and is used for the development of discussed microgrid models.

C. Interfacing Tools

Tools like The Assert Set of Tools for Engineering (TASTE) are offering one single framework to manipulate the overall system but do not provide specific modeling tools. Functions and connections can be defined in the framework but modeling and algorithm design is done in specialized designing tools. The interfacing tools offer only the possibility to merge standardized code and models in one framework and start simulations. TASTE [6] uses a C-compiler and a standardized C-file structure to merge and run different models that have been compiled into C and structured as recommended. It is not important which software creates the C-file as long as the needed structure for the compatibility with the C-compiler and fixed interfaces are provided. Therefore the interfacing tool is the most powerful solution because it is not limited to certain programs.The advantages of such interfacing tools are pretty clear. Using specified tools, connecting the software parts in one framework and enabling faster simulation with discrete and inline functions. But on the other hand the variety

of tools offered, causes the need of working into each of these programs and is enlarging the groundwork needed before starting to model.
It can be imagined that coupling and interfacing possibilities discussed in this section needs clear realization about what is needed to be modeled. If a single framework approach is sufficient then there is no need to add unnecessary complexity problems in modeling by using an interfacing tool and several standalone programs.

IV. Heterogeneous Modeling of a Microgrid

In this section a microgrid systems composed of two different energy systems shown in figure 2 is discussed. The physical components of the energy systems are modeled in Modelica discussed in [7]. It is the state of the art acausal modeling language for multi domain systems. On the other hand to model causal control algorithm of microgrid and energy systems Matlab Simulink is used as it is a common tool for continuous, discrete system controls or for data manipulation.

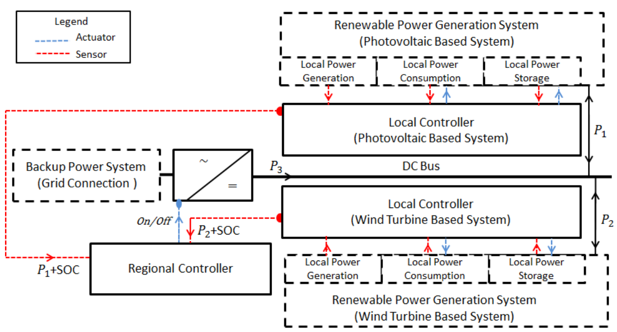

Fig. 2. Scematic View of Discussed Microgrid

A. Acausal Models of Physical Systems in Microgrid

The main difference between the two energy systems within microgrid is the power generation sources. One is based on photo-voltaic and the other on wind energy generation. Besides the different generations, a variation of the storage capacity and in the consumption trajectory is present in both micrograds. For the development, different libraries are used and the integration of already approved and tested models are focused.

1) Battery Model: In the discussed microgrid energy storage is realized with lithium ion batteries. A library providing an accurate model given in Electric Energy Storage [8] is used. Figure 3 shows the battery component ready to be connected with a load, a renewable energy source (the charge pins) and a generator. In this case the generator is the grid connecting the two energy systems enabling a power exchange if the microgrid is no more capable of satisfying the needs of the load. Two switches are part of the model, one controlling the connection to the renewable energy source and one controlling the connection to the grid. These switches are manipulated through boolean signals from controls outside the component.

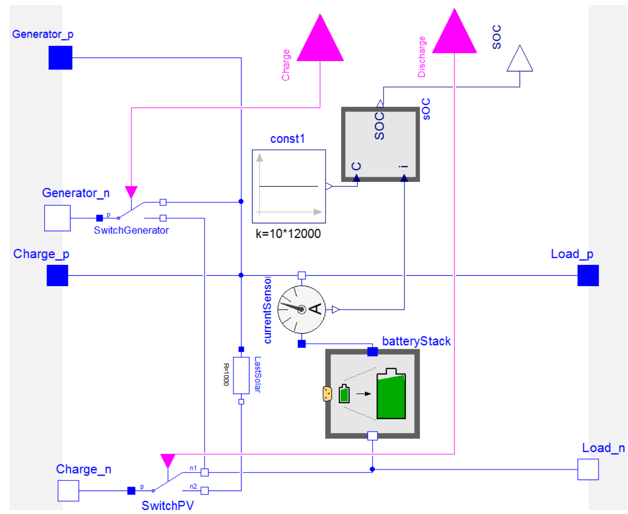

Fig. 3. Battery Model

2) Solar Panel Model: To model solar panel the Photovoltaics Modelica library has been used. It provides simple solar cells based on diodes. The current produced by each cell depends of the irradiance and the temperature input.

3) Load Model: The simulation of an adjustable load has been realized using Modelica Standard Library. The electrical power stored in the battery and produced from the solar panel is consumed in a variable ohmic resistor. By changing the value of the resistor the power consumption of the system follows a trajectory given.

4) Connecting Devices Models: For the connection between solar panel and battery an ideal DC converter with MPPT has been realized with the Dymola standard libraries, which are also used for connecting loads with batteries.

5) Wind Turbine Model: The wind turbine model is based on the WindPowerPlants Library which is elaborated in more details in [9]. The wind turbine model transforms a wind speed input into mechanical power respecting the design of the wind turbine and the pitch angle of the blades. Model of the wind turbine is shown in figure 4.

6) Rectifier Model: Same as the DC converters in the photovoltaics systems. The rectifier for the wind energy is modeled as ideal. An ideal model of the electronic would slow down the simulation without any benefit. Therefore an ideal transformation of the power from the wind generator side to the electronic battery side is realized.

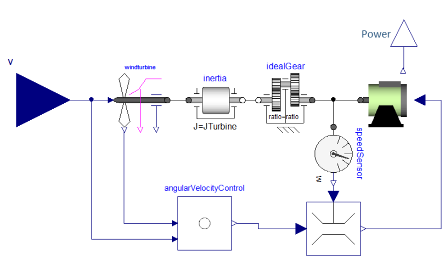

Fig. 4. Wind Turbine Model in Modelica [9]

B. Photovoltaic Based Energy System

The overall system model is given in figure 5. The corresponding connectors are directly included in the four main subsystems, generator, load, grid connection here represented by a current source, and the battery. Also part of the model are six inputs and outputs. The two pink boolean inputs control the switches connecting or disconnecting the battery from the grid or the renewable energy source. The blue real input interface controls the signal current exchange between the microgrids. The three white real outputs give the informations about the SOC of the battery stack, generated and consumed power to the control side.

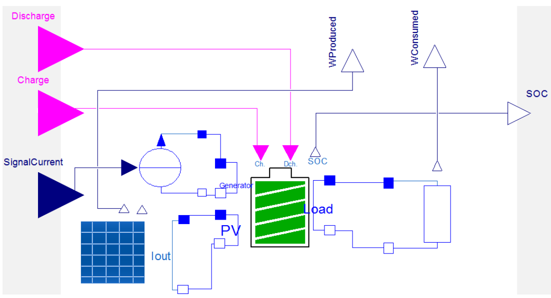

Fig. 5. Photovoltaic Based Energy System

1) Wind Turbine Based Energy System: To model the wind turbine based energy system, the battery and the load model designed in the photovoltaics based energy system are imported. The capacity of the energy storage has been adapted to the production of the wind turbine and the load power consumption curve has been changed. The overall wind turbine based energy system is given in fig 6. In figure four main parts can be identified as battery in the middle, then load with an variable consumption curve, current source connecting the energy system to the microgrid and wind turbine. Considering the wind turbine subsystem which follows four steps. In first step the real data input is fetched which is in our case wind speed to the system. Whereas in second step the data is transformed in the speed adapter to match the wind turbine specifications like hight or landscape. Third step gives power by transforming the wind speed into mechanical and electrical power and in fourth step rectifier passes the power to the battery.

C. Causal Model of the Control Algorithm

After modeling the physical system of the two energy systems, a status control for exchanging and providing reliable energy is needed. As mentioned before Matlab Simulink which is considered as state of the art causal modeling tool is used. The control side is separated in two control levels which are local and regional. Local control take care of individual energy systems within microgrid whereas regional control is responsible for the interaction between several microgrids on regional level. In figure 7 integrated control model is shown. The different components have inputs for the status of the state of charge (SOC) of the battery from the energy systems.

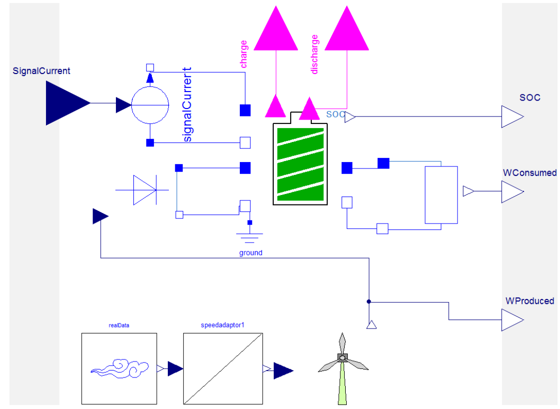

Fig. 6. Wind Turbine Based Energy System

The local controls have outputs for controlling the switches, which are used to connect and disconnect the RES. The regional control is in charge of the power exchange between the systems realized through adjustable current sources. The controls implemented in the subsystems are based on state control commands. At certain values of the SOC, the switches are engaged and the grid react depending on the control commands implemented.

D. Connection through Simulator Coupling

To connect Dymola Modelica to Matlab Simulink, two approaches are explored. One approach is to use S-Functions, a tool dependent interface offered by Matlab. In [10] the configuration and initialization process is explained. Through C-file export of the Dymola Model and utilizing S-function import. Modelica model can be used in Matlab within the Simulink environment represented as a DymolaBlock icon. Changing the model can be done in the DymolaBlock GUI or directly in Dymola Modelica. The alternative approach to the S-functions

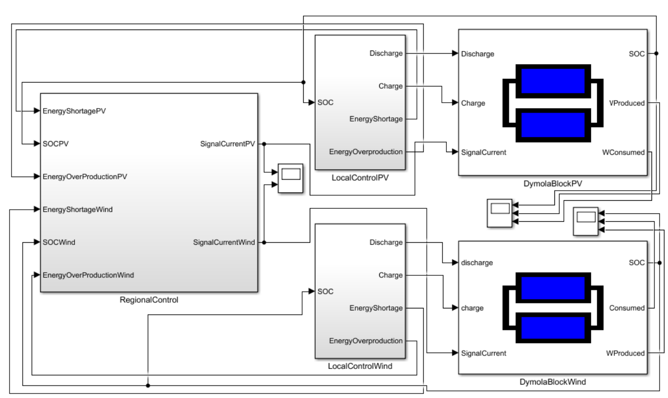

Fig. 7. Heterogeneous Model of Microgrid

is the funtional mock-up interfaces (FMI) presented in [11]. It is a tool independent standardized interface for co-simulation or model exchange. The FMI offers a lot of possibilities that tool dependent exchange software are not offering because solutions on a larger scale are intended. The FMI is not focused on one Software like the S-functions for Matlab but rather for a big contingent of modeling tools. The FMI tools differs between two coupling methods which are model exchange and the co-simulation. The big difference between the exchange and the co-simulation is the solving process. For the model exchange mode, the differential, algebraic or discrete equations are solved numerically in one tool and for the co-simulation these equations are solved individually in their modeling tool. For the co-simulation discrete communication points are arranged and between these points the different tools are solving the models equations based on there special solvers. Then at each time step the data is exchanged for the next solving process. Although the FMI is an interesting and sustainable tool, there exists only a pilot support package for Matlab which is still in developing process. So tests have been made for the FMI coupling but because of reliability, S-functions are used for the Dymola and Simulink coupling. The final microgrid system is shown in figure 7.

V. Simulation

During simulations it is observed that results are gathered much faster. If we consider the simulation computational efficiency and compare FMI with S-fuctions then FMI are faster. On the other hand no expensive hardware or time consuming measurements are needed. Similarly control can be changed without the physical connections between physical models. Along with this behaviours of the two energy systems without and with grid connection are also evaluated to monitor the exchange of power. Some plots are shown and used in the next paragraphs to elaborate the behaviour of microgrid.

a) Energy Generation:: In left side of fig 8 produced energy over one day is plotted. The two curves differ strongly not only in amplitude but in other characteristics. The curve of the wind turbine is based on real data and the curve of the solar panel is based on a model of the irradiance emitted by the sun. A round shape with a peek at noon is exactly what the irradiance at a sunny day would look like. On the other hand in the wind curve, no real form can be found. Random wind gusts during the day are generating the power produced by the wind turbine. The comparison of these two curves underlines the need of correct models in which fluctuations caused by weather is also taken into account for the development of control algorithms.

b) Energy Consumption:: The consumption curves are given on the right side in fig 8. The curve of the photovoltaics system is based on the average energy consumption of family households whereas the curve of the wind turbine system is representing the more constant consumption of a twenty four hour working industrial plant. It is observed that not only the generation based on RES has various curves but also the consumption. A big spectrum from family households to commercial and finally to the industrial sector needs to be considered for the design of the control. For the microgrid, this observation is also of interest because it can be used to match similar load with similar production curves.

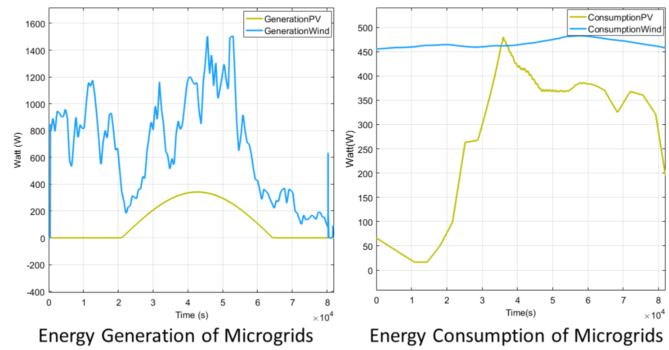

Fig. 8. Power Generation and Consumption of Energy Systems

c) Energy Systems without Grid Connection:: First in order to analyze of the individual energy systems without grid connection. The SOC values of the energy systems are evaluted which are given in fig 9. On the left curves of fig 9 the fluctuations in the wind power generation can directly be identified in the blue curve. The SOC of the big battery stack is slowly wandering around the 0.55 value depending on the consumption and the generation of wind turbine based energy system. whereas photovoltaics based energy system has a smaller battery therefore the fluctuations of the SOC are more rapid. In the morning the generation of the photvoltaics is near zero so only the consumption of the households are influencing the system. Later during the day the photvoltaics panels are producing high amounts of energy in fact too much for the battery stack so the connection to the panel is cut until the SOC reaches a certain state of SOC beneath 0.95. Than the panel is reconnected until the SOC is reached 0.98 and so on. The energy overproduction and the resulting switching are causing the sawtooth waves during the day. In the noon the power generation stops but still the consumption is going on. Until midnight the SOC has fallen down to 0.15, which is a critical value. With this amount of energy left in the storage, the photvoltaics based energy system wont be able to provide energy for the next morning. Although during the day enough energy has been produced but not stored. Clearly an exchange of power with other energy systems or bigger batteries are needed.

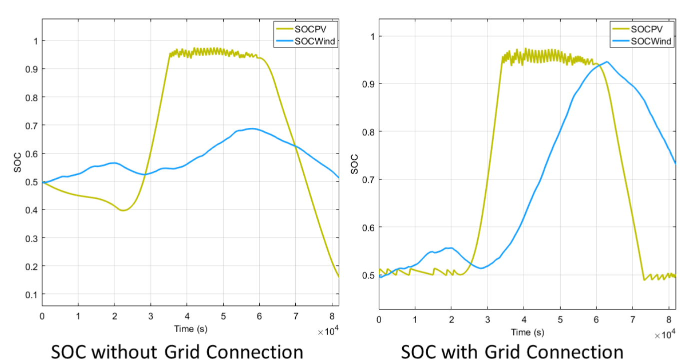

Fig. 9. Energy systems With and Without Grid Connection

d) Energy Systems with Grid Connection:: The connection between the two energy systems is ensured in this configuration and the regional control enabled the current exchange between the systems. In figure 9 on the right side the new SOC curves of the energy systems are plotted and in figure 10 the current exchange between the microgrid and main grid is represented. In the morning where the last mentioned SOC curve of the photovoltaics system was decreasing, here in this system configuration an sawtooth wave curve appears due to a state controlled exchange of energy between the energy systems. If the SOC of one systems is lower than 0.5 the other system is giving and balancing the energy. This exchange can be seen in the energy exchange plot showing as pulsed trade off in the morning. During the day, the solar power generation is still causing a sawtooth wave but the overproduction of energy goes to the wind turbine based energy systen storage stack as shown in the exchange plot by a rectangular form during the day. Also by comparing the wind turbine system SOC with and without grid connection, it can be seen that the SOC increases more strong than before. In the evening when the solar panel is not generating any energy the wind turbine system is again supplying energy for the other photovoltaic system. This exchange provides a reliable energy supply and more efficient use of the renewable sources and storages.

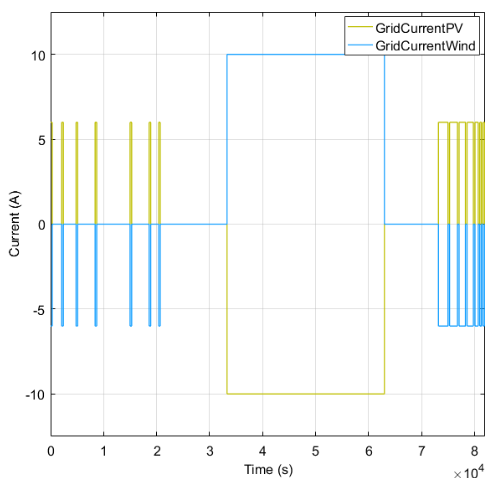

Fig. 10. Microgrid with Grid Connection

VI. Conclusion And Future Work

In this paper, an intermediate step is take to present a modeling approach for future energy systems by using a cyclic model-centric development process with continuous redesign and validation through HIL testing. Flexible modeling structures which are needed for the future energy system can be developed. To handle the complexity and diversity of the needed tasks the advantages of heterogeneous modeling have been explored. Further in a small case-study an heterogeneous model of a microgrid system has been designed by combining two modeling frameworks and simulating two types of energy systems. The need of heterogeneous modeling for embedded systems and then on a larger prospective of considering microgrids has been elaborated and shown on the basis of combining causal and acausal design tools.

To enable different modeling frameworks, software coupling methods have been illustrated and discussed such as the S-functions or FMI. On the other hand, by evaluating the simulation results, some design aspects on control and physical models of the microgrids are identified. Considering the control side, the need of intelligent and forecasting controls are realized which helps in flattening the energy storage curves and enable a more efficient power management within the microgrid systems.

The next development steps in question for future work is, how the SOC and power curves can be manipulated for better matching to the load and the fluctuations of the RES? The sawtooth wave signals in the SOC curves could be flatten by forecasting the generated and consumed power. The possibility of ”playing” with the curves in the simulation environment for testing forecasting methods and load control algorithms is a big advantage offered by the model centric heterogeneous development approach for microgrids.

References

[1] Y. Yoldas, A. Onen, S. Muyeen, A. V. Vasilakos, and I. Alan, “Enhancing smart grid with microgrids: Challenges and opportunities,” *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 205 – 214, 2017.

[2] M. Ahmadian, Z. J. Nazari, N. Nakhaee, and Z. Kostic, “Model based design and sdr,” in *2005 The 2nd IEE/EURASIP Conference on DSPenabledRadio (Ref. No. 2005/11086)*, pp. 8 pp.–, Sept 2005.

[3] J. C. Jensen, D. Chang, and E. A. Lee, “A model-based design methodology for cyber-physical systems,” in *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*, pp. 1666 – 1671, July 2011.

[4] J. M. Molina, X. Pan, C. Grimm, and M. Damm, “A framework for model-based design of embedded systems for energy management,” in *2013 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES)*, pp. 1–6, May 2013.

[5] E. Widl, P. Palensky, and A. Elsheikh, “Evaluation of two approaches for simulating cyber-physical energy systems,” in *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, pp. 3582–3587, Oct 2012.

[6] P. Maxime, C. Eric, D. Julien, S. André, and T. Thanassis, *TASTE: A Real-Time Software Engineering Tool-Chain Overview, Status, and Future*, pp. 26–37. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012.

[7] H. Elmqvist and S. E. Mattsson, “An introduction to the physical modeling language modelica,” October 1997.

[8] M. Einhorn, F. V. Conte, C. Kraland, C. Niklas, H. Popp, and J. Fleig, “A modelica library for simulation of elecric energy storages,” 2011.

[9] P. Eberhart, T. S. Chung, A. Haumer, and C. Kral, “Open source library for the simulation of wind power plants,” September 2015.

[10] Dassault Systems AB, *Dymola Dynamic Modeling Laboratory User Manual Volume 2*.

[11] T. Blochwitz, M. Otter, M. Arnold, C. Bausch, C. Claus, H. Elmqvist, A. Junghanns, J. Mauss, M. Monteiro, T. Neidhold, D. Neumerkel, H. Olsson, J.-V. Peetz, and S. Wolf, “The functional mockup interface for tool independent exchange of simulation models,” Dassault Systems, Lund, 2011.