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A HOLISTIC MODELING AND SIMULATION APPROACH TO OPTIMIZE A SMART COMBINED GRID SYSTEM OF DIFFERENT RENEWABLE ENERGIES

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ABSTRACT

In this contribution, a model-based method for analyzing and designing energy systems comprising the electrical, thermal and chemical domains is presented. Beside the energy generation and consumption, the bidirectional coupling between all energy domains is considered, as well. This method is an adapted variant of the so called Hardware-in-the-Loop simulation where virtual energy components are combined with geographically distributed real energy components. In order to integrate the real components with minimal instrumentation efforts, measured quantities are included as information flows, only, while the physical power flows are connected to local available grid structures. This virtual coupling has the further advantage of a simple scalability so that existing real components can be used for different applications. The virtual energy components are represented by real-time capable models describing their physical behavior. In this contribution, a CHP unit is described as a first virtual energy component. The modeling approach is based on a time domain approach using state variables of the multiple domains to describe the dynamic behavior. Furthermore, the model is scalable regarding the modeling depth and the power ratings which allows an application for different simulation scenarios. Besides the modeling of a standalone CHP unit, its integration into a simulated electrical grid is discussed as well. Afterwards, the overall model is parameterized and validated with data of a medium size CHP unit. Finally, the model is used for simulations of an exemplary electrical grid.

1. INTRODUCTION

The increasing shortage of fossil fuels as well as the continuing climate change leads to an increasing relevance of renewable energy. The current energy system will be transformed from a centralized generation by conventional power plants to a distributed energy system mainly consisting of renewable energy generators, [1], [2]. While centralized energy systems are approved during the past decades, the control and structural expansion of a decentralized energy system are rather different due to volatility of the renewable energy and progressive structural changes.

Small and medium energy suppliers, like municipal energy supplier, are no longer just operators of local grids, but also energy producers for electrical and thermal energy. Furthermore, such small suppliers are already participating in the balancing energy market. Private households and industries are also no longer just consumers of energy, but also energy producers by photovoltaic systems for example. All mentioned parties are taking new roles in the fast changing, highly competitive and legally regulated energy market. From an economic point of view, it becomes obvious that new marketing and remuneration strategies are required to reach the turnaround in energy policy with an increasing participation of the involved suppliers and consumers.

From a technical point of view, efficient mechanisms for compensating the fluctuating energies are required. The direct storage of electrical energy is limited due to geographical, topological and geological boundary conditions (e.g. pumped-storage plants) or high invests and saving costs (e.g. battery based storage). Therefore, other compensating mechanisms are also under investigation and partially already utilized. Beside dynamic controllable power plants in a small-scale, the coupling between various energy grids and the adaption of the consumption behavior by smart grids are promising approaches.

The combined heat and power (CHP) technique is well-established and used for an efficient utilization of primary energy carriers (mostly gas, partially biogas). Especially, small and medium-sized CHP plants are suitable for compensation effects in electrical grids due to their good controllability. Since electricity and heat generation of CHP facilities are coupled, further mechanisms are required for providing an appropriate thermal and electric energy simultaneously. Beside the conversion of electrical energy in thermal energy (Power-to-Heat), the bidirectional coupling between different forms of energy is possible as well as shown in Fig. 1. The conversion of electrical energy into chemical energy using Power-to-Gas technologies is a novel and frequently discussed approach. A very high capacitance is provided when using the widely established gas grid for storing. An efficient reconversion to electric energy is given by CHP units, for example.

An additional option for compensation of fluctuations is a systematic control and adaption of the energy consumption by private households and industry. On the one hand the total energy demand is optimized by energetic optimizations of technical devices while on the other hand the energy peaks are reduced by using controllable loads and buffers which can be disconnected or controlled depending on the available energy. Therefore, the demand-oriented energy supply system is developing towards a smart and coupled energy grid with a strong orientation on the current energy supply.

Based on Sterner [3] an extended version of such a combined grid system is shown in Fig. 1. An energy management is required to operate the smart combined grid system under optimal conditions, [4]. In order to optimize the components and structure as well as the operating strategy, a holistic investigation of the overall smart combined grid system considering all forms of energy as well as technical and economic aspects is required.

For investigating such smart combined grid systems, a scientific approach based on Hardware-in-the-Loop (HIL) simulations is presented in section 2. This approach comprises models describing the investigated energy components in combination with real energy components. In similar approaches, real energy components were electrically connected to electronic loads having same power ratings. The approach presented here is capable of including real components of any power class with minimal instrumentation efforts but does not comprise detailed effects of electrical grids in comparison to approaches with electronic loads.

As a first virtual component, section 3 comprises the modeling of CHP plants with respect to its physical behavior. The model is afterwards parameterized and validated by measurement data of a real CHP facility. Compared to similar modeling approaches of CHP units, this approach is capable of representing the transient behavior but still avoiding too much parametrization effort. This allows a simple scalability of the model regarding different power ratings. Finally, a conclusion is given in section 4.

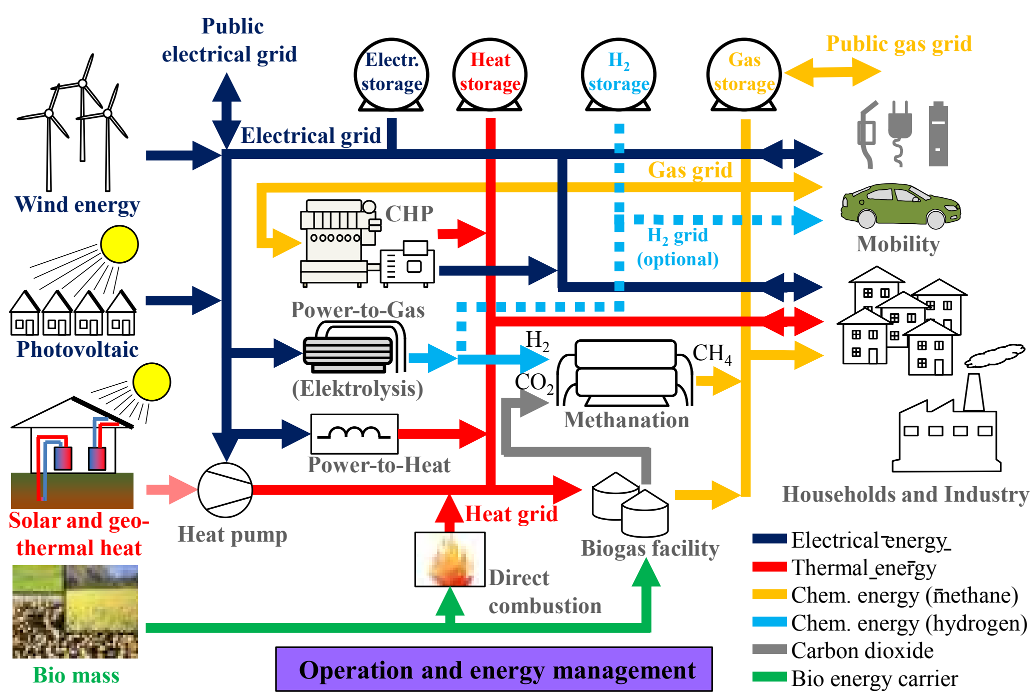

FIGURE 1 SMART COMBINED GRID SYSTEM BASED ON DIFFERENT RENEWABLE ENERGY SYSTEMS

2. SCIENTIFC APPROACH

Different approaches for investigating energy systems have been proposed. Especially, the control of electrical energy systems is currently investigated by HIL simulations. As an example, Rohjans et al. [5] evaluate information and communication solutions like protection and control systems for operating decentralized energy systems. For testing these controllers, a real-time simulator is used which is capable of simulating dynamic models of electrical grids. With the simulation framework Mosaik different simulators are combined for using existing models.

In further approaches, real energy generators and consumers are considered as the hardware under test. An introduction and overview on such approaches is given by Panwar et al. [6]. For a direct coupling of the hardware under test with real-time simulations, electronic loads are required. It is obvious that the investigated hardware is limited to the rated power of this electronic load. Further on, accuracy and stability of the simulation are very important to prevent damages of the physical devices under test. Such experimental facility with a maximum power of 5 MW is placed in the Center for Advanced Power Systems (CAPS) at Florida State University, [7].

The scientific approach presented herein after and schematically illustrated in Fig. 2 is also a variant of the HIL simulation. By this approach, various simulated and real components are combined to a virtual coupled power grid. Virtual coupled power grid means that all components are just coupled via information exchange for balancing their power quantities while the real power flow is connected to locally available grid structures. In contrast to the approaches mentioned before, also spatial distributed and high power facilities can be included without the necessity of electronic loads. However, by electronic loads, detailed effects of electrical grids on the real components (e.g. change in voltage) are represented which allow more detailed investigations in comparison to the presented approach here. Beside electrical, also thermal and chemical components are considered in this approach as shown in Fig. 1.

2.1. HIL simulation

The comprehensive, holistic investigations on combined grid systems are started by offline simulations. First rough results in terms of optimization and concept engineering can be obtained in this phase. Afterwards, more realistic results can be obtained by a HIL simulation where some components of the simulated power system are represented by real or experimental components, [6]. While measurement data are taken into account by real components, only, a free adaptability of the operating state is furthermore given by utilizing experimental components. The basic structure of the overall simulation approach is shown in Fig. 2.

As illustrated in Fig. 2, a simulation manager couples the information flow of these real and simulated components. Furthermore, this simulation manager is capable of scaling the real components regarding their rated power so that an application of existing facilities for different use cases is possible.

The models developed for the offline simulation are used for the HIL simulation, as well. For coupling the real with experimental components, these models need to be capable for the real-time simulation. The previously described part of the approach is labeled as “CampusLab” in Fig. 2. Beside the local available and simulated components representing the

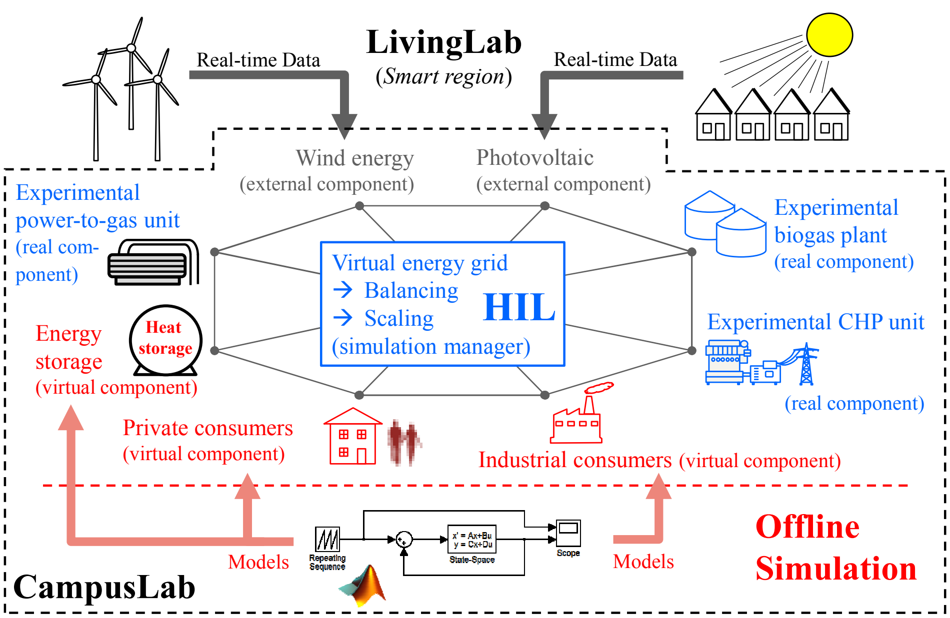

FIGURE 2 STRUCTURE FOR A HIL SIMULATION FOR OPTIMIZING A SMART COMBINED GRID SYSTEM

"CampusLab", an integration of geographically distributed facilities and external data from villages or cities into the virtually coupled energy grid is possible, as well. These external energy components and real data are represented by the term "LivingLab" as depicted in Fig. 2.

As an example for the HIL simulation, an experimental CHP unit could be used as shown in Fig. 3. The CHP unit is controlled by a simulated energy management system based on the demands of simulated virtual consumers. While the generated thermal and electrical energy is physically either used by the university or fed into the grid, the measured values of electrical and thermal energy as well as the gas consumption of the CHP unit are used in the real-time simulation for supplying the virtual consumers. In order to simulate CHP units with different rated powers, the existing experimental CHP unit can be used by scaling the quantities of output power and gas consumption according to the desired rated power.

2.2. Modeling of energy components

In order to describe the virtual components, models are required for the proposed HIL simulation. For modeling of these energy components different approaches are possible. On the one hand, models based on energy flows are possible resulting in a simple parameterization and fast simulation. On the other hand, models based on state variables (e.g. voltage and current) are required for a detailed simulation of both the stationary and transient behavior. Due to the fact that several generation units based on renewable energies are weather dependent and that the behavior of the consumers is unknown, stochastic models describing the weather conditions and consumer demands are required as well, [8]. The combined energy system comprises both: fast and slow subsystems. While thermodynamic processes are comparatively slow yielding slow changes of the state variables. Other components like electric machines, power electronic components and electric energy transducers are comparatively fast. This causes strongly different eigenvalues and therefore stiff systems which have to be handled by appropriate simulation methods, [9], especially in case of a real-time simulation. While high eigenvalues need to be neglected in real-time simulations, they have to be considered for more detailed investigations.

For a general applicability regarding offline and HIL simulations as well as different simulation objectives like optimization of the structure or optimization of the strategy, it becomes obvious that the component models should be scalable with respect to the modeling depth. Furthermore, the component models need to be real-time capable for the HIL simulation.

For simulating the transient behavior of the energetic quantities, MATLAB®/Simulink is used which is capable for an investigation of domain-crossing problems and furthermore enables the use of non-deterministic models. A new component library will be created during our research activities considering the mentioned scalability of the component models.

2.3. Application and validation

Based on the proposed simulation method, a realistic study of smart energy systems is possible. On the one hand, novel structure concepts can be evaluated, for example a combination of the mentioned P2G technique with the CHP technique in addition or in comparison to the usage of bio-gas plants. On the other hand an optimization of existing structures by dimensioning the energy components is also possible. First of all, we start with the offline simulation of different concepts. Afterwards potential concepts will be selected and further optimized and evaluated by means of the proposed HIL simulation. While a validation of the developed models is given by the integration of real components, the overall research approach can be proven by applying it to an optimization study for a new or existing energy system. As a first project, the proposed approach is applied to an existing energy system near by the university. This so called energy village is also representing the"LivingLab" in Fig. 2. As mentioned before, real-time data from generators and consumers of the"LivingLab" will be used in combination to the HIL

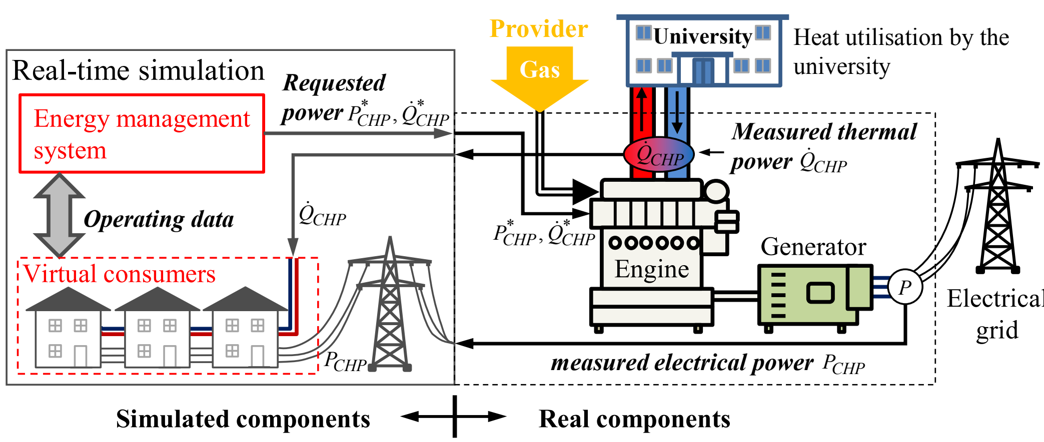

FIGURE 3 EXAMPLE OF A HIL SIMULATION WITH AN EXPERIMENTAL CHP UNIT

simulation.

3. MODELING OF CHP UNITS

As a first model for the proposed scientific approach, the physical behavior of CHP units is investigated. Different approaches for modeling of CHP units have been proposed in various publications. A common approach for µ-CHP units is the model developed by Beausoleil-Morrison and Kelly [10]. This approach is capable of modeling the dynamic behavior of the system temperatures and power outputs by using an empirical approach with over 50 parameters. The parameterization is rather complex and needs much measurement data for a complete identification. After calibration, the model agrees well with measured data of several µ-CHP units [11], [12].

Another approach considering a piston engine is presented by Lee et al. [13]. This physical based model is rather simple but not capable of modeling its dynamic behavior. This model is also validated with a µ-CHP unit.

Furthermore, a data driven modeling approach using artificial neural networks (ANN) is developed by De et al. [14] and trained with data of a gas turbine plant of the upper power class. Especially, the forward temperature showed a very good agreement with a prediction error less than 1%, [15].

Our proposed approach [16] is a physical-based approach and capable of modeling the transient behavior of a CHP unit. In contrast to the approach by Beausoleil-Morrison and Kelly [10], a simpler parameterization is obtained.

3.1. Modeling approach

The CHP unit considered for modeling consists of a piston engine as the aggregate which is mechanically coupled to a synchronous generator for the electrical energy conversion. The thermal energy of the piston engine is comprised in the exhaust gas and engine coolant. For both carrier mediums separate heat exchangers are considered. The total heat is transferred to the consumers through the heat grid. Finally, a local management is required to control the overall CHP unit which comprises the control of the electrical or thermal power as well as the control of the temperatures by variable pumps, for example. The local management itself could be controlled by a central management. An overview of the complete model is given in the functional diagram of Fig. 4.

All components are modeled utilizing the state variables of the chemical, mechanical, electrical and thermal domains. Especially in stability studies, the mechanical domain is highly relevant. Except for µCHP units, the mass inertias of the aggregates I_{PE}, I_G are significant energy storages for the converted electrical energy, [17]. For modeling this effect, a stiff coupling between the piston engine and synchronous generator is assumed. The resulting equation of motion as shown in Eq. 1 represents the rotational speed ω utilizing the torques of the piston engine T_{PE} and the synchronous generator T_G as well as the torque T_f which describes the sum of all friction effects within the CHP unit:

$$\left(I_{PE} + I_G\right) \cdot \dot{\omega} = T_{PE} - T_G - T_f \qquad (1)$$

The torque of the piston engine T_{PE} results from the combustion process. Based on the demanded torque T_{PE}^* this process is approximated by a first order lag, [18]. For modeling the torque as well as the electrical quantities of the synchronous generator, several approaches already exist in literature. In this contribution, a common approach which neglects nonlinear effects like saturation is implemented, [19]. This approach is adaptable for salient and solid pole rotors as well as permanent and variable excitations. Therefore, a good matching for different CHP units is achieved. For modeling the heat flow of

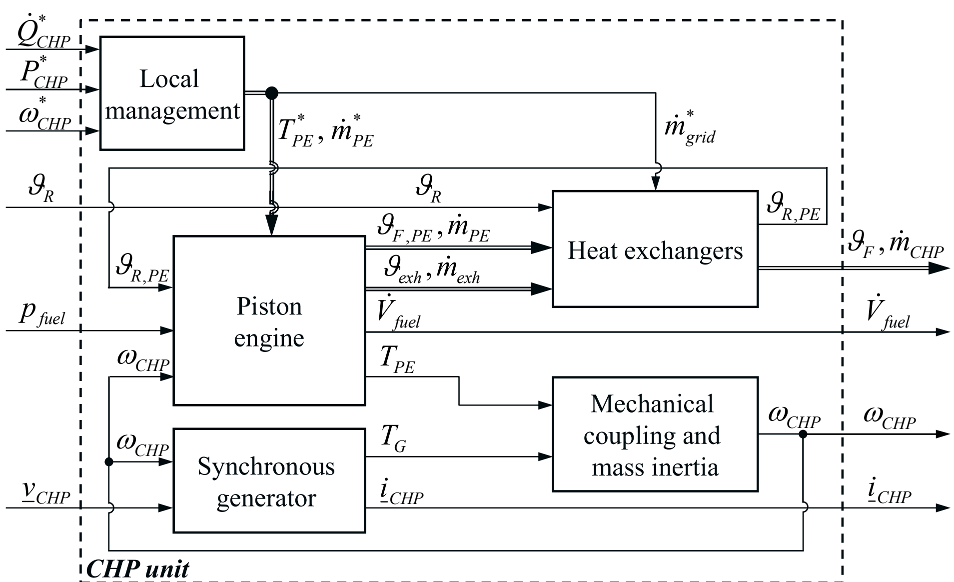

FIGURE 4 FUNCTIONAL DIAGRAM OF THE OVERALL CHP MODEL

the CHP unit, the thermal quantities of the piston engine and heat exchangers need to be modeled. First of all, the overall engine is separated into four elements as shown in Fig. 5.

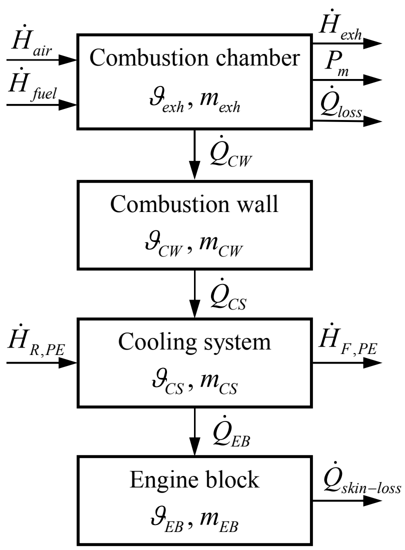

FIGURE 5 THERMAL MODEL OF THE PISTON ENGINE

Beside a detailed representation of the heat transfer, this allows the separated consideration of the exhaust gas and engine coolant for the subsequent heat exchangers. The cooling system itself is discretized by N elements as depicted in Fig. 6. Due to this discretization, the spatial dependency of the coolant temperature is considered. Here, a simple uniform distribution is assumed resulting in equal masses and heat transferring surfaces for all discrete elements.

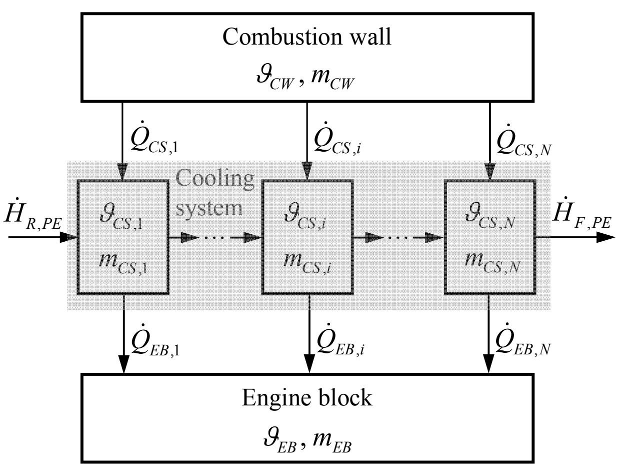

FIGURE 6 THERMAL MODEL OF THE COOLING SYSTEM

In order to represent the dynamics of the thermal quantities, all discrete elements in Figs. 5 and 6 are modeled by the first law of thermodynamics. Considering the enthalpy flows $\dot{H}$, heat flows $\dot{Q}$ and powers P of the combustion chamber, we obtain:

$$m_{exh} \cdot c_{P,exh} \cdot \dot{\vartheta}_{exh} = \dot{H}_{air} + \dot{H}_{fuel} - \dot{H}_{exh} - P_m - \dot{Q}_{loss} - \dot{Q}_{CW} \quad (2)$$

where $c_{P,exh}$ is the specific heat capacity, m_{exh} the mass and ϑ_{exh} the temperature of the exhaust gas.

The heat flows are modeled by heat transfer coefficients and surfaces. Except for the heat flow from the combustion chamber to the combustion wall, these coefficients are assumed to be constant. In this special case, the heat transfer coefficient α_{CW} strongly depends on the actual thermal and mechanical state of the pistons and is approximated by the empirical approach of Woschni [20].

For describing the thermal losses of the piston engine, two heat flows are assumed. While the heat flow $\dot{Q}_{skin-loss}$ describes temperature dependent losses to the environment, the heat flow $\dot{Q}_{loss}$ describes the temperature independent losses like the required power of auxiliary units.

The same approach used for the cooling system is adapted for modeling the heat exchangers. Both, the heat transferring and heat absorbing structure are discretized by M elements to consider their spatial dependency. In contrast to the thermal model of the piston engine, no heat losses are considered for the heat exchangers due to the good insulation. The CHP unit investigated for model validation consists of two heat exchangers, one for the exhaust gas and one for the engine coolant. Both are connected in series as shown in the functional diagram in Fig. 7. First, the cold return water ϑ_R from the consumers is heated up by the heat exchanger of the engine coolant. Afterwards the heat exchanger of the exhaust gas heats up the outgoing water ϑ_{F-exh} to the final value ϑ_F of the water outlet. The outgoing exhaust gas passes to the chimney.

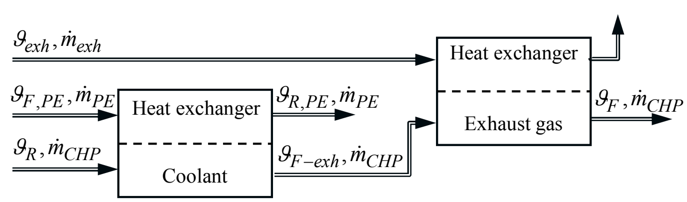

FIGURE 7 FUNCTIONAL DIAGRAM OF THE IMPLEMENTED HEAT EXCHANGERS

Beyond the application for the discussed heat exchangers, this model is adaptable for modeling heat storages as well. In contrast to the heat exchangers, the losses cannot be neglected in case of long storage periods. Therefore, the model of the storage should be extended by a heat flow to the environment, similar to the approach of the piston engine.

Finally, the overall model is completed by implementing the local management as shown in Fig. 4. Beside the torque demand of the piston engine, the mass flow of the outgoing fluid to the grid is usually a manipulating variable. The control for the demanded torque depends on the operation mode. While in isolated operation, the frequency stability needs to be considered, the frequency is fixed by the grid in case of parallel operation. Therefore, a speed control is required in the isolated operation mode. Operating in parallel mode, the electrical or thermal power is controlled.

Regarding the control of the temperatures, the control technique varies between the CHP manufactures. Hence, the controller need to be designed to the specific case and is therefore not further described in this contribution.

A detailed description of the overall CHP model is given in the contribution by Griese et al. [16].

3.2. Grid integration

In order to integrate the model into an overall combined grid system, as shown in Fig. 1, the electrical, thermal and chemical grids need to be modeled. In the scope of this contribution, the integration of the discussed CHP model into a simulated electrical grid is discussed. For modeling the three phase system, the $d-q$ reference frame is used as also applied for the synchronous machine of the CHP model, [16]. A common assumption for modeling electrical transmission lines is to neglect their transients, in particular for grids in a small scale, [19]. In case of a transient change in electrical power of a CHP unit, most of the energy is initially balanced by the inertia of the mechanical domain while the energy stored in the electrical transmission lines is negligibly small. However, solving the partial differential equations of the transmission line, the equivalent π-circuit as shown in Fig. 8 is obtained with a frequency dependent impedance $\underline{Z}_e$ and admittance $\underline{Y}_e$, [19]:

$$\underline{Z}_e = \sqrt{\frac{R'+i\omega L'}{i\omega C'}} \cdot \sinh\left(\sqrt{(R'+i\omega L')\cdot i\omega C'} \cdot l\right)$$
$$\frac{\underline{Y}_e}{2} = \sqrt{\frac{i\omega C'}{R'+i\omega L'}} \cdot \tanh\left(\frac{\sqrt{(R'+i\omega L')\cdot i\omega C'} \cdot l}{2}\right) \quad (3)$$

where R', L', C' are normalized parameters per length for the resistance, inductance and capacitance of a transmission line of the length l.

The frequency ω of the grid strongly depends on the investigated operation mode. While the frequency is assumed to be fixed in grid connected operation, in isolated operation the frequency depends on the transient behavior of the connected generators. Especially in case of rotating machines, the mechanical speed of the rotor defines the electrical frequency.

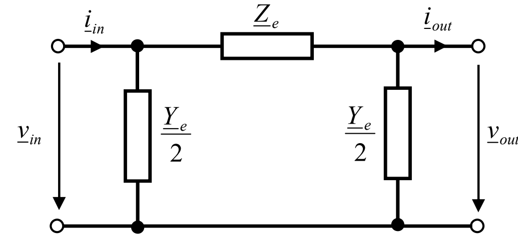

FIGURE 8 EQUIVALENT π-CIRCUIT OF A TRANSMISSION LINE

While each machine is described by its individual $d-q$ frame, a common reference frame $(D-Q)$ is required for coupling all machines including their transient mechanical behavior. Hence, the quantities of each frame are transformed into a defined common reference frame $(D-Q)$, [21]. Such a transformation is illustrated in Fig. 9 and described by Eq. 4 for the transformation of a general quantity $\underline{x}$ from an individual $d_j - q_j$ frame into a reference $D-Q$ frame:

$$\begin{bmatrix} x_D \\ x_Q \end{bmatrix} = \begin{bmatrix} \cos(\delta_j) & -\sin(\delta_j) \\ \sin(\delta_j) & \cos(\delta_j) \end{bmatrix} \cdot \begin{bmatrix} x_{d_j} \\ x_{q_j} \end{bmatrix} \quad (4)$$
$$\text{with} \quad \delta_j = \int (\omega_j - \omega_{ref}) \cdot dt$$

where δ is the angle between the two frames.

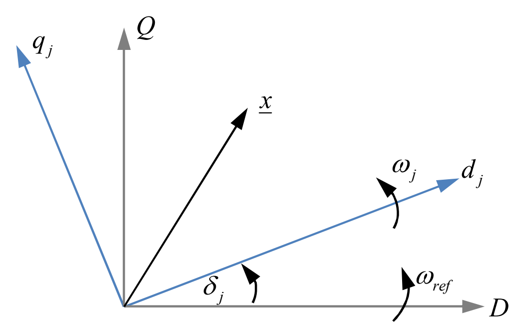

FIGURE 9 TRANSFORMATION OF THE QUANTITY $\underline{x}$ FROM AN INDIVIDUAL FRAME $(d_j - q_j)$ INTO A REFERENCE FRAME $(D-Q)$

In case of an isolated operation, the reference frame $(D-Q)$ can be chosen arbitrarily, e.g. as the frame of any generator. A simple example of an electrical network with a CHP unit connected to a load in isolated operation is shown in Fig. 10a). Here, the reference frame $(D-Q)$ is the frame of the CHP unit. In this case the speed control of the CHP unit is ensuring frequency stability. A model of such a scenario of a micro grid is shown by the functional diagram in Fig. 10b).

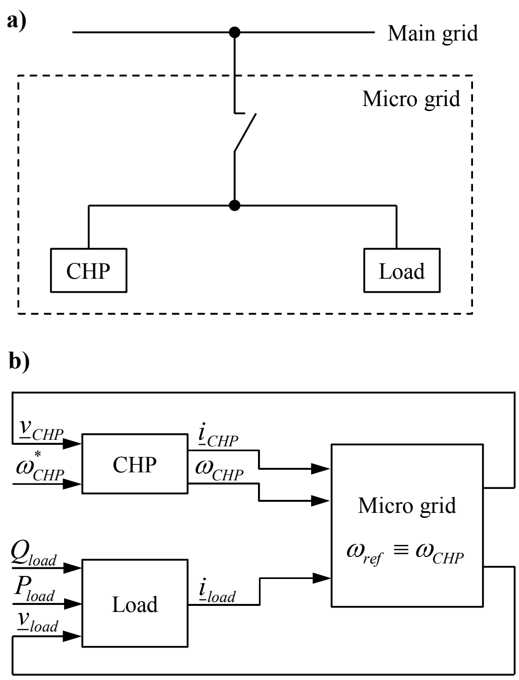

FIGURE 10 STRUCTURE (A) AND FUNCTIONAL DIAGRAM (B) OF A CHP UNIT IN ISOLATED OPERATION

As an example for this scenario, the load is simply modeled as a static load by solving the equations of active and reactive power:

$$
\begin{aligned}
i_{load,d} &= \frac{2}{3} \cdot \frac{v_{load,d} \cdot P_{load} + v_{load,q} \cdot Q_{load}}{v_{load,d}^2 + v_{load,q}^2} \\
i_{load,q} &= \frac{2}{3} \cdot \frac{v_{load,q} \cdot P_{load} - v_{load,d} \cdot Q_{load}}{v_{load,d}^2 + v_{load,q}^2}
\end{aligned}
\quad (5)
$$

where v_{Load} is the voltage, i_{Load} the current, P_{Load} the active power and Q_{Load} the reactive power of the load. Since only one generator is determining the frequency in the scenario in Fig. 10b), the discussed transformation does not need to be implemented.

By including the main grid, modeled as a constant voltage and frequency source, a second frequency determining component is added to the system. In this case, the reference frame $(D-Q)$ can e.g. be given by the main grid while the quantities of the CHP unit are transformed by applying Eq. 4. Such a scenario is shown in Fig. 11a) and modeled according to the structural diagram in Fig. 11b).

In the scenario shown in Fig. 11, the main grid ensures the frequency stability yielding an additional degree of freedom for the control of the CHP unit. Hence, the electrical or thermal power of the CHP unit can be varied while an excess or deficit of electrical power is balanced by the main grid.

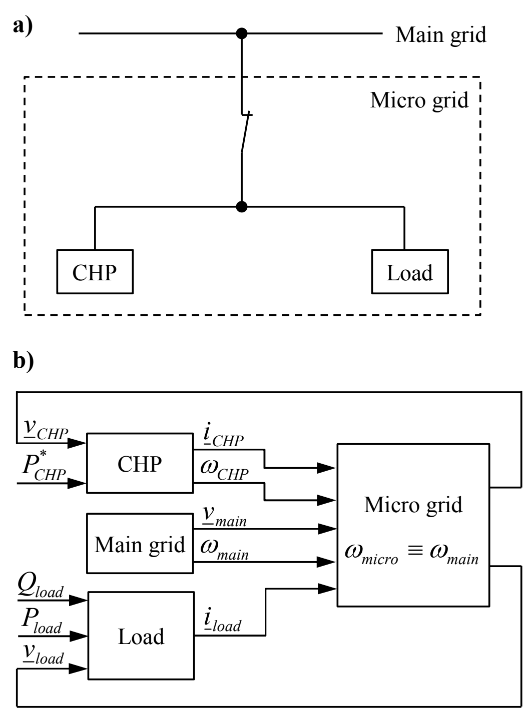

FIGURE 11 STRUCTURE (A) AND FUNCTIONAL DIAGRAM (B) OF A GRID CONNECTED CHP UNIT

4. RESULTS

For parameterization and validation of the model, data of a CHP unit with an electrical power rating of 140 kW are used. On the one hand, datasheet specifications like the cylinder capacity are taken into account for parameterization while on the other hand measurement data of transient responses like thermal equalizations are used. In order to minimize the parameterization effort, the heat exchanger combination is decoupled from the piston engine. Furthermore, the stationary and transient behaviors are analyzed separately which enables an independent identification of the heat transfer coefficients and masses of the corresponding heat flows. A more detailed description of the parameterization is given in [16].

In order to validate the simulation model, transient measurement data of the electrical power P_{CHP} and return temperature ϑ_R, shown in Fig. 12, are taken into account as inputs for the simulation. Furthermore, the mass flows $\dot{m}_{PE}, \dot{m}_{CHP}$ are kept constant as given by the datasheet, specified in Tab. 1.

TABLE 1 SPECIFIED MASS FLOWS CONSIDERED FOR THE SIMULATION

Parameter	Value	Unit
Mass flow of the motor-coolant $\dot{m}_{PE}$	5.95	kg/s
Mass flow of the overall CHP unit $\dot{m}_{CHP}$	2.66	kg/s

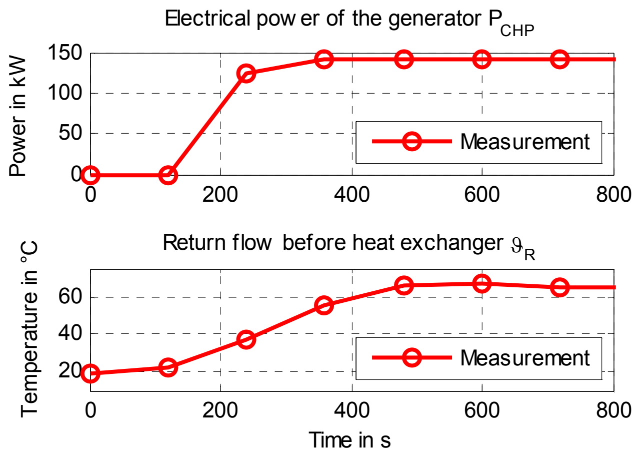

FIGURE 12 MEASURED ELECTRICAL POWER AND RETURN FLOW TEMPERATURE CONSIDERED FOR THE SIMULATION

A comparison of the measured and simulated temperatures of the CHP unit is shown in Fig. 13 comprising the exhaust gas, motor coolant and forward flow to the grid. For the measured exhaust gas temperature in Fig. 13 it can be noticed, that the temperature slightly increases as the measurement starts. Compared to the measured electrical power in Fig. 12, the electrical power starts to increase at 120 seconds after simulation. In the interval before, the piston engine operates in idle mode and friction effects need to be compensated, only, causing a low torque of the piston engine. The subsequent low losses explain the slight increase of the exhaust gas temperature.

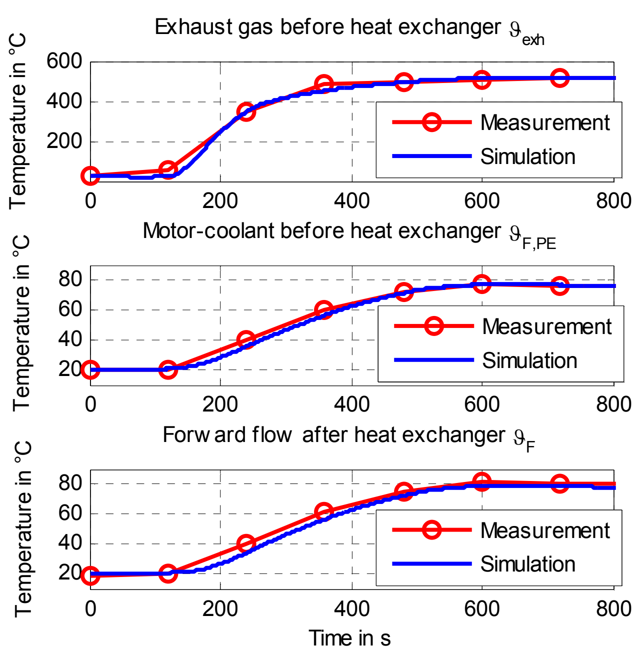

FIGURE 13 MEASUREMENT AND SIMULATION RESULTS OF SEVERAL TEMPERATURES

After starting the synchronous generator and increasing the electrical power, a significant change of all temperatures can be noticed. Comparing the dynamic behavior of all temperatures, Fig. 13 shows that the temperature of the exhaust gas has the highest eigenvalue. This can be explained by the comparably low density and low mass of the exhaust gas, respectively. The temperatures of the motor-coolant and forward flow are similar. It can be derived that the heat exchanging of the motor-coolant is more dominant than the heat exchanging of the exhaust gas. The poor heat exchange of the exhaust gas is caused by its low specific heat capacity.

However, by comparing the measurement and simulation results in Fig. 13 a good agreement can be observed. A short delay time can be noticed during the transient response. One reason for this is that the exact start time of the piston engine and synchronization with the grid are unknown due to the low temporal resolution of the measurement data and differ to the simulation. In comparison to other approaches, the model by Beausoleil-Morrison and Kelly [10] shows better agreement between simulation and measurement. On the other hand this empirical model comprises a very complex parameterization which makes an interpretation and scaling of the parameters more difficult. Therefore, the approach presented here offers a compromise between accuracy and applicability.

In addition to the results of the thermal domain in Fig. 13, simulation results of the electrical domain are shown and discussed afterwards. According to Figs. 10 and 11, two operation modes are possible and considered in this contribution. The results of the isolated operation are depicted in Fig. 14.

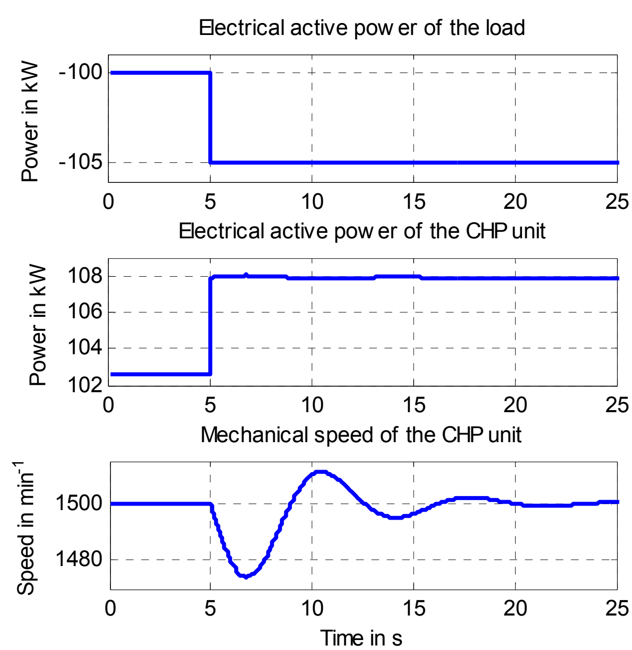

FIGURE 14 SIMULATION OF A CHP UNIT IN ISOLATED OPERATION ACCORDING TO FIG. 10

Beside the electrical power of the load and of the CHP unit, the mechanical speed of the CHP unit is also presented. During the simulation a stepwise change of the active power of the load of 5 kW is simulated. The reactive power of the load is assumed to be zero. It can be noticed that during the transient response, the mechanical speed decreases before the frequency control of the CHP unit interacts by increasing the torque of the combustion engine.

By comparing the stationary values of the electrical power of the load and of the CHP unit, a difference of about 3 kW can be mentioned. These are losses in the transmission line caused by parameters given in Tab. 2.

TABLE 2 SIMULATION PARAMETERS OF THE TRANSMISSION LINE

Parameter	Value	Unit
Resistance per length R'	0.05	Ω / km
Inductance per length L'	1	mH / km
Capacitance per length C'	0.5	$\mu F / km$
Length l	1	km
Nominal voltage v	400	V

When considering the main grid with its quantities $\underline{v}_{main}$ and ω_{main} as inputs for the simulation, the electrical power of the CHP unit is controlled instead of the frequency. The results of such a scenario according to Fig. 11 are shown in Fig. 15 describing the electrical power of the CHP unit and the main grid as well as the mechanical speed of the CHP unit.

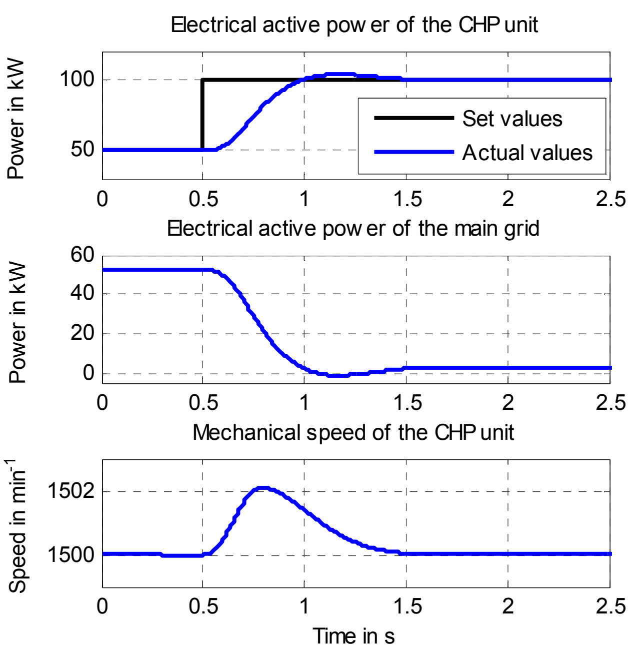

FIGURE 15 SIMULATION OF A GRID CONNECTED CHP UNIT ACCORDING TO FIG. 11

While the active power of the load is assumed to be constant at 200 kW, a stepwise change of the electrical power of the CHP unit of 40kW is simulated. The reactive power of the load is assumed to be zero. During the transient response the mechanical speed increases. As a consequence of the changing mechanical speed, the displacement angle of the rotor of the synchronous machine increases. Hence, the torque increases matching the higher demanded power. In the same manner, the electrical power of the main grid decreases. By comparing the stationary values of both powers, the losses in the transmission line are similar to the simulation of the isolated operation.

5. CONCLUSION

Within this contribution, a scientific approach for optimizing smart combined energy systems is presented. This approach is based on an offline and HIL simulation where real energy components are virtually coupled with simulated models in real-time. For this virtual coupling, a simulation manager is considered which is capable to scale the quantities of the real components as well as the modeling depth of the simulated components. This allows a simple adaption of existing real and simulated components for different use cases. As a first virtual component, a CHP unit is investigated and modeled with respect to the electrical, thermal, mechanical and chemical domains. The overall model comprises the dynamic behavior of the piston engine, synchronous generator and heat exchangers. Besides modeling a standalone CHP unit, also its integration into an electrical grid is discussed. With measurement data of a real CHP unit, the overall model is afterwards parameterized and validated. Finally, the thermal quantities of the CHP model match the measurement data quite well. Further on, simulation results are shown regarding the integration into an electrical grid. The results show the expected behavior of a CHP unit under transient conditions.

Currently, further energy generation facilities like renewable energies are modeled and implemented. Moreover, energy consumers will be described by a model, representing a holistic description of the building, its heating systems and appliances as well as the behavior of the users. By simulating the overall system and utilizing the discussed methods, different smart combined grid systems can be optimized, compared and evaluated with respect to technical and economic aspects.

NOMENCLATURE

Symbols

c_p	specific heat capacity $\left(J/(kg \cdot K)\right)$
C'	capacitance per length $\left(F/m\right)$
$\underline{x}$	arbitrary quantity in $d-q$ frame
$\dot{H}$	enthalpy flow $\left(J/s\right)$
$\underline{i}$	electrical current in $d-q$ frame $\left(A\right)$
I	inertia $\left(kg \cdot m^2\right)$

l	length (m)
L'	inductance per length (H/m)
m	effective mass (kg)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
P	electrical active power (W)
Q	electrical reactive power (var)
$\dot{Q}$	heat flow / thermal power (W)
R'	resistance per length (Ω/m)
T	mechanical torque (Nm)
$\underline{v}$	electrical voltage in $d-q$ frame (V)
$\dot{V}$	volume flow rate (m^3/s)
$\underline{Y}_e$	equivalent shunt admittance (S)
$\underline{Z}_e$	equivalent series impedance (Ω)
ϑ	temperature $(°C)$
δ	angle between two $d-q$ frames (rad)
ω	rotational speed (rad/s)

Subscript and superscript

CHP	overall CHP system
CS	cooling system
CW	combustion wall
d	direct axis
EB	engine block
exh	exhaust gas
f	friction
$fuel$	fuel for combustion (e.g. gas)
F	forward flow
G	generator
i	discretization describing index
in	ingoing quantity
j	$d-q$ frame describing index
$load$	electrical load
m	mechanical
$main$	main grid
out	outgoing quantity
PE	piston engine
q	quadrature axis
ref	reference frame
R	return flow
$skin-loss$	losses over the surface
$*$	set value

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