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Integrated design and optimization of a complex nonlinear hybrid electric powertrain including simulations in time domain

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This paper deals with the design and optimization of hybrid electric powertrains. Therefore basic relations of the behavior of hybrid electric powertrain systems and the controller design are introduced. Based on models of typical hybrid electric system components principal optimization approaches with respect to performance parameters like efficiency, availability, lifetime, etc. are shown. Hereby an optimization algorithm based on a global optimization technique is applied. Using the example of a fuel cell based hybrid electric powertrain system the approaches are introduced and compared to each using time-domain simulations integrated in optimization algorithms. The results show that both approaches are appropriate to design the system as well as the controllers.

1 Fuel cell/supercap-based hybrid electric powertrain system

Due to the industrial effort on the electrification of automotive drives the development of hybrid electric powertrain systems has been increased significantly in recent years. In this context the importance of optimization aspects have become an important task in the research of these systems [1]. Hereby one aspect is related to the optimization of the sizing of the power train system components. Classical approaches typically consider only static effects of the system behavior such as the expected measurement levels of the system voltage and current in stationary operation, the maximal motor speed, torque etc. [2]. Another field with increasing significant importance is the development and optimization of powermanagement systems to control the electric powerflows within the powertrain system structure [3, 4]. In this contribution the optimization of both the system component sizing and the control parameters of the powermanagement is discussed using the example of a fuel cell/supercap-based hybrid electric powertrain. The optimization algorithm applied is realized based on a fuel cell/supercap-based hybrid electric powertrain system. The related Hardware-in-the-Loop test rig as well as the topological structure are shown in figure 1 (left and middle figure). Hereby the system components are arranged to a "Range Extender" topology with the fuel cell system as primary energy source and the supercap system as energy storage. Additionally two motors are included to the system. Hereby a drive motor, which is supplied by the components described is mechanically coupled to a load motor which applies external moments equivalent e.g. to friction, inertia, and air resistance to the drive motor during the operation. The load motor is supplied by an external grid. To influence the power flow between the fuel cell system, the supercaps, and the drive motor a controllable DC/DC converter is applied. The dynamic behavior of the system components can be described by nonlinear models. In this context the motor unit is modelled as a Hammerstein model and the supercap system can be described by a nonlinear state space model. Further details about the modeling are described in [5].

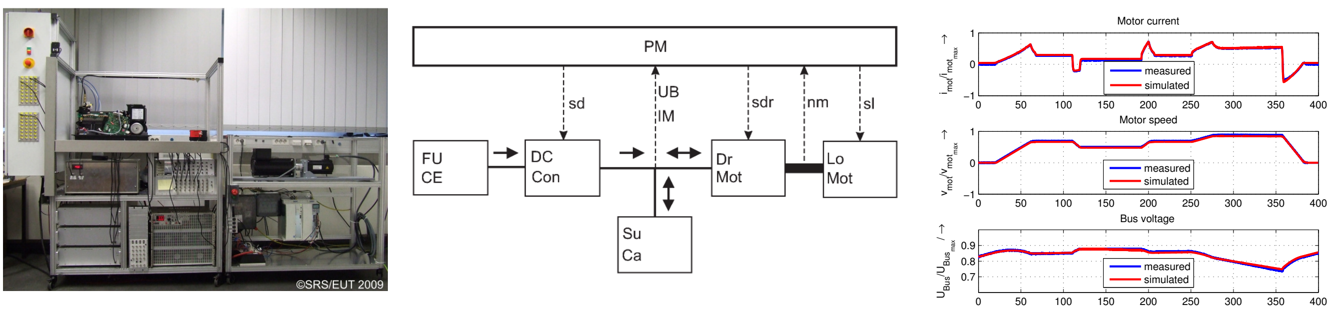

Fig. 1 HiL test rig of the powertrain (left), its topological setup (middle), and the dynamical behavior (measured and simulated) during operation (right)

For the validation of the models the simulation results are compared with measured data of the system. As it can be seen in figure 1 (right) a good coincidence between these values can be observed, which make the system model suitable to be applied for further investigations.

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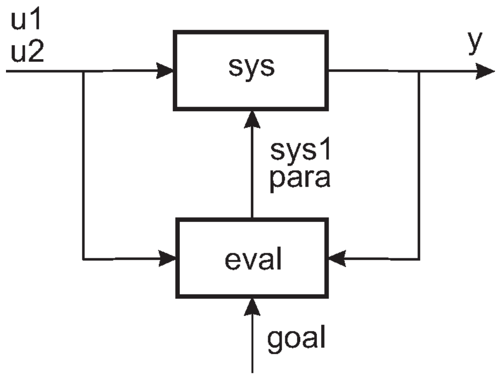
2 Integrated optimization applying an optimization loop structure

Based on the developed system models an algorithm is applied to realize an integrated optimization of both the system component sizes and the control parameters of the powermanagement system.



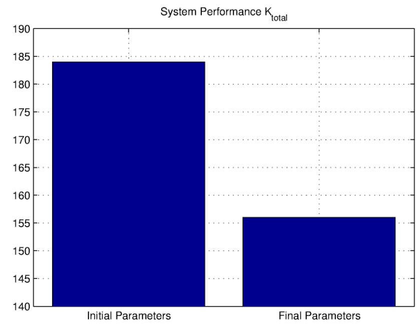


Fig. 2 Scheme of the optimization loop(left) and optimization results (right)

In contrast to known approaches the optimization algorithms described here are realized by the usage of an optimization loop applying a search algorithm based on global optimization techniques. The relating structure of this loop is depicted in figure 2 (left side). The optimization is based on the system evaluation by the parameters K_1, K_2, and K_3 describing specific properties of the system behavior. Hereby the fuel consumption/supercap discharging is described by $K_1 = V_{H_2} + g_1(SOC_{SC,init},\ SOC_{SC,final})$ with the measured fuel consumption V_{H_2} and the supercap's state of charge (SOC) at the beginning and the end of the operation denoted as $SOC_{SC,init}$ and $SOC_{SC,final}$. The system availability with respect to the desired value deviation is described by $K_2 = g_2\left(\int_t |v_{ref} - v_{measured}|\, dt, v_{measured}(s)\right)$ with the reference velocity v_{ref} and the measured velocity $v_{measured}$. The third parameter denoted by $K_3 = g_3\left((P_{FC,filt}(t))\right)$ describes the aging of the fuel cell system caused by high frequent power changes.
For the determination of the total performance these parameters are weighted as

$$K_{total} = \alpha K_1 + \beta K_2 + \gamma K_3. \tag{1}$$

To get an optimal parameter a minimization of this function has to be determined.
Based on these considerations the optimization of the capacity of the supercaps and the controller parameters of the DC/DC controller with respect to Eq. 1 is performed. As it can be seen in figure 2 (right side) for the system performance a significant improvement can be achived by this method.

3 Summary and outlook

In this contribution a method is introduced to optimize both the system component sizing and the powermanagement parameters within an integrated process. Using the example of the optimization of the supercap size and the DC/DC controller parameter it becomes clear that a significant improvement can be achived. Further steps in future wiil be the application of the methods to further system components (e.g. battery systems), system topologies (e.g. full hybrid, extended hybrid topology etc.), and powermanagement structures. Therefor relating models have to be developed and validated and the optimization structure has to be adapted in a suitable way.

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