

Collaborative simulation of a cybernetic energy management system with an automotive power net model

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Abstract

The electric power and energy consumption in automotive power nets has continuously increased. This paper shows a cybernetic approach for an energy and power management system, based on the viable system model from Stafford Beer. The system is able to coordinate the components of the automotive power net in a safe and efficient way. This management system is coupled with an automotive power net simulation, based on the acausal modeling language *Modelica*. The simulation results show, that the cybernetic management system is able to fulfill the requirements and will be investigated in future work.

Keywords: load management, simulation, reliability, energy, efficiency

1 Introduction

The traditional 14 V automotive power net mainly contains three types of components that are connected via a wiring harness and fuse elements. The alternator, that is connected to the belt drive, produces electric energy. The energy storage usually is a lead-acid battery or a li-ion battery in new vehicles. It stores the energy that is needed for the engine start, engine-off operation and for peak power scenarios. In addition, there is a significant number of electrical consumers.

In recent decades the number of electrical components in the automotive power net has greatly increased. In a modern luxury class vehicle, there are more than 100 electrical consumers connected to the 14 V automotive power net. One reason for this is the rising number of comfort and infotainment systems. In addition, there is a trend to replace mechanical driven systems like fan drives or pumps by electric driven systems, in order to benefit from the higher efficiency and better controllability. This results in an increase of the electric continuous power as well as the electric peak power. Transient peak power scenarios can lead to severe voltage drops in the vehicle's power net voltage. This issue can be countered by a correct sizing of the wiring harness, the alternator and the battery [4]. The high level of electric continuous power is a challenge for reaching the efficiency objectives for the entire vehicle, especially due to the fact that all the electric energy has to be produced by the alternator with an maximum efficiency of about 70 %. Indeed, the rising electrification and digitalization generates new degrees of freedom for an energy management system. The digital interface of the new generation of automotive alternators can be used to control the alternator's output voltage that is strongly coupled to the battery current. Furthermore, there are electrical loads like fan drives or heating systems with time constants of several seconds and more. These components can be degraded or switched off for a short period of time, without being noticed by the customer [5]. This fact can be used to implement an active load scheduling in the automotive power net. In addition, a second voltage level of 48 V will be introduced in the near future, connected to the 14 V power net by a bidirectional DC/DC converter. This new system offers even more possibilities for an energy management system at the cost of a significantly increased complexity. When

applied to the challenges of a power net in modern vehicles, an energy management system in form of a viable system model as proposed in [8] can reduce the complexity of the system and the integration afford for new components. Many of the electrical consumers in the proposed system have a localized low level energy and power management system as presented in [5], to stabilize the power net voltage in case of transient power peaks. Furthermore electrical consumers follow guidelines set by a higher strategy. This paper shows an implementation of this cybernetic energy management system simulated with an physical model of an automotive power net and its components.

2 Physical modeling of the components

In order to simulate the automotive power net with the developed energy and power management system a power net simulation is modeled in the *Modelica* description language [12]. *Modelica* is an acausal modeling language, which offers the possibility of modeling physical systems in different physical domains like the electrical, the mechanical or the thermal domain. A self-developed library of the electric producers, storage systems, consumers and wiring harnesses offers the possibility to model a wide range of different power nets.

2.1 Producer

Currently the only producer of electric energy is the automotive Lundell alternator. Basically the Lundell alternator is a three-phase synchronous generator with a three phase diode rectifier. The field winding on the rotor is fed by the battery voltage with two slip rings and carbon brushes. The output voltage can be controlled by controlling the exciting current in the field winding. This is usually done by a pulse-width-modulated power semiconductor combined with an two-level controller. Modern automotive alternators additionally have their own digital interface that allows the energy management to vary the set point for the output voltage or to reduce the alternator's dynamics when the rotational speed of the combustion engine is low. The physical models of the automotive Lundell alternators can be very computationally intensive. Depending on the objective of the simulation scenario, models with different levels of detail for the alternator can be used. For short simulation scenarios of a few seconds, with the attention to the dynamics in the automotive power net, the single phase stationary equivalent circuit or even d-q models provide the best results. For long simulation scenarios of several minutes or even hours, with the attention to the overall system efficiency, table-based models are the better choice.

2.2 Storage

For modeling the battery, the use of an electric terminal voltage model is a widely used method. These models in general consist of a voltage source, which represents the chemical open circuit voltage and an internal resistance. In order to depict the dynamic effects of the battery, the model is expanded by one or more RC elements. The voltage drop over these RC elements represent physical or electrochemical effects like the charge transfer or diffusion processes. The model used in the power net simulation which is pictured in Figure 1 (a) consists of two RC elements. Depending on the use case, different models are used in the power net simulation. The models differ by the parametrization of the components. The parameters can be constant or a function of the actual status of the battery, like the terminal current or the state of charge. The use of state depending parameters offers more degrees of freedom and therefore a more accurate model, but also means an increase of computing time for the simulation. Figure 1 (b) shows the step response of the model after a current step with a 50A step size. The waveform shows the typical behavior of a battery.

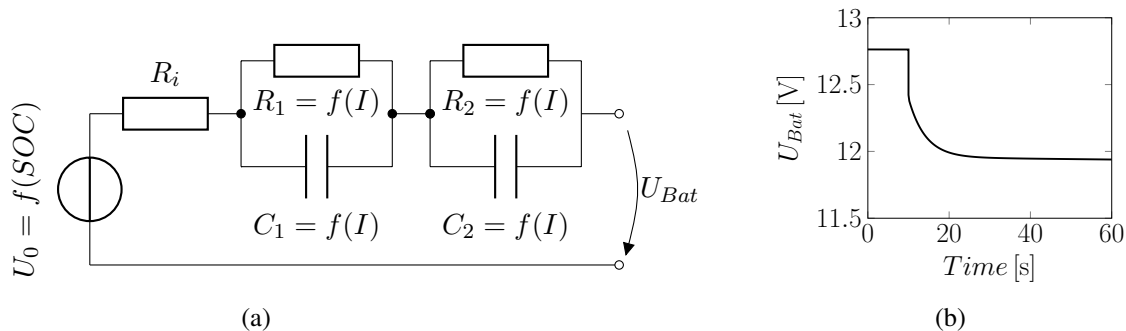


Figure 1: The battery is modeled by the standard equivalent circuit model with two RC-circuits (a) with state-variable parameters. The step response to an 50 A load step is shown in (b)

2.3 Consumer

This subsection presents the used models for two types of components with a very high energetic impact to the automotive power net.

2.3.1 Electronic devices

Most of the electric consumers in a modern vehicle are electronic devices such as the infotainment system, screens or electronic control units (ECUs). From an energetic point of view, electronic devices are a type of consumer that just consumes the amount of power it needs from the power net and usually can't be degraded or switched off by the energy management because of safety or comfort reasons. Most electronic devices have their own power electronic input stage in order to compensate voltage fluctuations from the power net and to supply the electronic circuits with a constant voltage at a lower level, usually 5 V or 3.3 V. A common DC/DC converter topology for the input stage is the synchronous buck converter. The physical model for electronic devices used in the automotive power net simulation is shown in Figure 2 (a). The power stage is connected to the power net's bus voltage V_{in} at its input port and to a current sink at its output port. The power stage uses an average model of a synchronous buck converter as described in [1]. The average model eliminates the need to simulate every single switching cycle of the power semiconductors which would increase the simulation effort. Instead it uses a transfer equation system considering the conduction losses as well as the switching losses in the power semiconductors. The efficiency of the DC/DC converter is mainly a function of the actual load current, as shown in Figure 2 (b). The load current $I(t)$ is set by the simulation environment and can be either constant or time variable depending on customer actions or environmental parameters. The system's current consumption depending on the power net's bus voltage is shown in 2 (c).

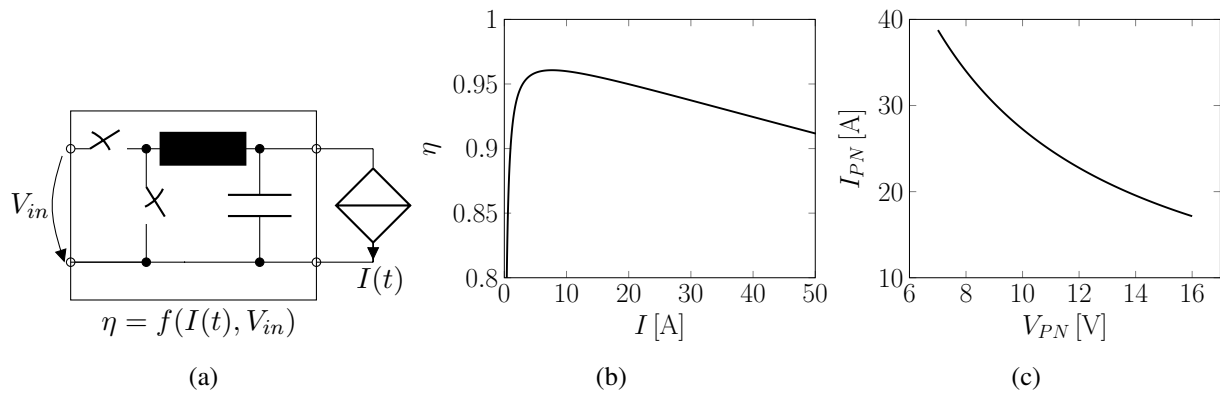


Figure 2: Electronic devices are modeled by an average model of a synchronous buck converter with an time-dependent current sink (a). The efficiency of the converter is primarily a function of the load current (b) and the input current depends on the input voltage (c).

2.3.2 Heating systems

The type of component with the highest energetic impact in the automotive power net are the heating systems, like the seat heating or rear window heating. Their combined power consumption can exceed 2kW. Figure 3 (a) shows a schematic of a simple model for a heating system. It basically consists of a heating resistor which is connected to the automotive power net via a switch. This switch is usually realized as a MOSFET or relay in older vehicles. The emerging heating power at the resistor effects a model of the thermal system that is connected to the heating resistor. This thermal system consists of two thermal capacities and three thermal conductors. The heat flow is emitted via heat conduction, convection and radiation to the environment. The current of the seat heating system is mainly dependent on the power net's voltage and the heating resistance that is a function of it's temperature, having a positive temperature coefficient. As a result, the current of the heating system also depends on the actual temperature of the seat. Figure 3 (b) compares the simulation result of the current waveform with a measured waveform during a heating period of 90s. The simulation can reproduce the real waveform very well. The seat temperature rises from 20 C to nearly 30 C during this period.

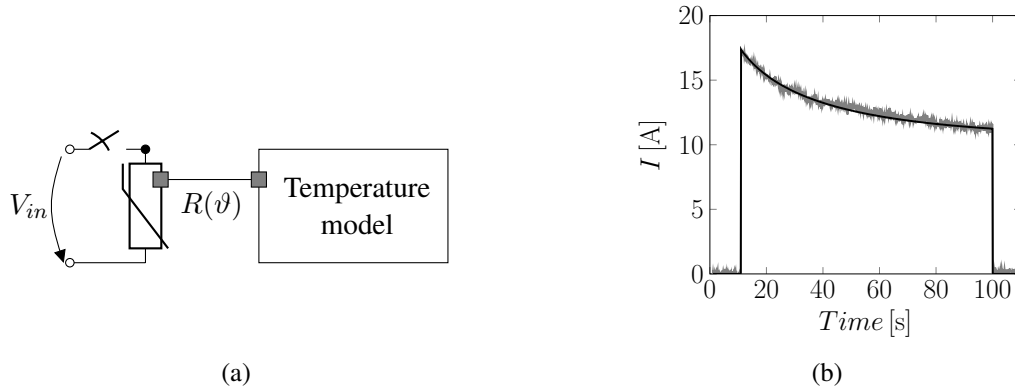


Figure 3: Heating systems are modeled by an temperature-dependent resistor with a co-simulated thermal network (a). The plot (b) shows the current consumption of the model compared to the measurement of a real seat-heater over a 90s heating period.

3 Cybernetic Energy and Power Management

The increasing complexity of the control of electric energy and power flow in modern premium vehicles requires a management system with an intrinsic behavior to reduce complexity. The cyberneticist Stafford Beer analyzed the structure of animals especially of mammals. He found out that the organic structure of these animals can be modeled with his viable system model (VSM) [14]. This model is used in the business management by Fredmund Malik described in [15]. Another transformation is made by Kohler for a predictive power management system [13]. For an energy and power management system the model is transformed in a similar way to the flexible Energy and Power Management called fEPM. This transformation from the VSM to the fEPM is shown in Figure 4. The first implementation of the fEPM for series production was rolled out in the BMW 7 series in 2015 and called ConnectedPower-Management [9].

3.1 The basic model of the fEPM

Like Beer's VSM the fEPM features 5 system levels:

- System level 1 contains the system values, the physical connection, control and the steering functions.
- System level 2 condenses the system values into operating figures and has to combine the level 1 functionalities in a fast way.
- System level 3 determines the operating figures and tendencies with deposited knowledge into system states. Tendencies mean the analysis of the variation in time of the system values and the operating figures. This level contains the autonomous, state based system modifications for the purpose of system stabilization. Compared to the biological system it works like a reflex system.
- System level 4 combines the internal system states and diagnostic information from the system itself with the external system states based on environmental information. The modification instruction of a higher hierarchy level is included here. The coupling of the environment information is made of filtered, relevant information out of the system specific environment.
- System level 5 contains the operating strategy. Compared to the biological system it works like the conscious behavior. In this level the regulation values, the so called modifiers, are calculated. Some important modifiers are the energy availability and the energy generation modifier.

The information flow between the system levels can be divided into two directions. Bottom up, from level 1 to level 5 the information gets more and more abstracted and compressed, from physical values to operating figures to system states. Top down, the modifiers get more and more specific from general suggestions into precise commands for the components.

3.2 The recursive model approach

The fEPM features additionally a recursive approach in order to manage a more complex system. Therefore the basic model is used in different hierarchy levels. The lower hierarchy level include the components and their local management behavior. The upper hierarchy level represent the management system

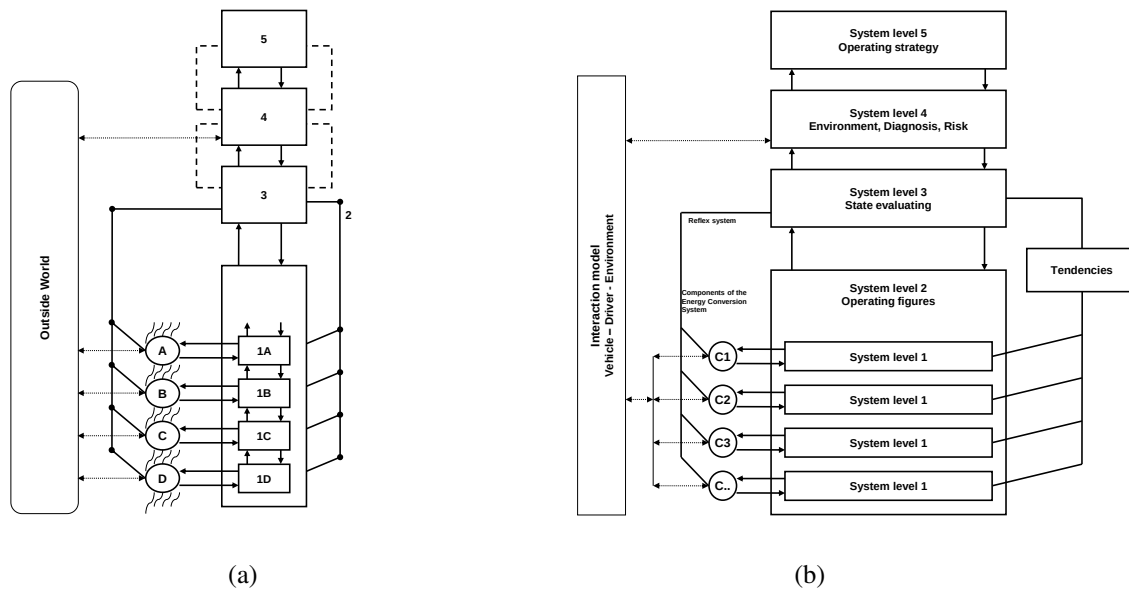


Figure 4: Transformation from Beer's Viable System Model (a) [14] to the flexible Energy and Power Management (b) for use in automotive applications.

of the coordination instance of the power supply system itself. At the current development stage, three recursions of the viable system model are used. They called hierarchy level and ordered as follows:

- *Component level*: The individual components of the automotive power net. The main task of the components is to fulfill the function they are designed for, but every component has an interface to the fEPM and provides information about the actual and maybe the future power consumption. Some components are even able to reduce their power consumption (degradation) if the energy availability is low or they are equipped with autonomous functionality like the autonomous load shutdown mechanism proposed in [3].
- *Component Group level*: The individual components are grouped into three component groups for electrical producers, consumers and storage systems. This way the data is further concentrated for the next hierarchy level. Furthermore the decision which components should be involved in actions to reach the component group's goal can be kept on this level.
- *12V Power Net level*: The 12V power net is created out of the three component groups. In a conventional 12V power net, this the highest hierarchy level.

With the cybernetic model of the fEPM, it is possible to create a managed power supply system with more than one voltage level, more than one power source or storage system and a huge number of functional systems which need electrical energy. The aspects of resiliency are discussed in [8].

4 Automotive Power Net System Simulation

This section explains the composition of the automotive power net system simulation consisting of the cybernetic energy management system and the physical models of the power net's components. The system simulation is implemented in the *Modelica* modeling language. Initially the physical models are extended with a generic wrapper in order to homogenize their interfaces. Subsequently the power net simulation can be constructed from generic components and linked to an implementation of the fEPM.

4.1 Generic Interfacing

Section 2 has shown examples for the different physical models used in the automotive power net simulation. It can be seen that the models are quite heterogeneous and depending on a large variety of parameters and variables. In order to simplify the handling of the models and to be able to support an automated export to a real-time environment as described in [2] it is advantageous not to have each component its own input/output signature. As the models are implemented in the *Modelica* modeling language two types of connections have to be differentiated. The physical connections on the power net

level are acausal physical connectors containing one *potential* and one *stream* variable. Environmental parameters like the velocity or temperatures are also physical values, but for the purpose of an automotive power net simulation they only serve as boundary conditions so they can be treated as causal signals just as control signals from the power management or customer interactions.

For homogenizing the interfaces of the different physical models, they are used with a generic wrapper as shown in Figure 5. The interface of this generic wrapper consists of the acausal physical connectors and one common bus interface containing all causal signals. There is only a need for a separate generic wrapper if a component has a new combination of acausal connections. So, all electrical consumers and storage systems are using the same generic wrapper as they only have electric connectors to the power net. Instead the alternator models are using their own generic wrapper as they have a second physical connection to the rotational-mechanical-system of the belt drive. The common bus interface consists out of four vectors as shown in definition 1. The environmental input vector $\vec{e}$ contains information about the current environmental conditions of the vehicle, like the velocity or the ambient temperature. The passenger input vector $\vec{p}$ holds information about the interaction between the passengers and the vehicle's comfort and infotainment systems. The interface to the energy management system is composed of the vectors $\vec{m}$ and $\vec{s}_i$. The management vector $\vec{m}$ contains global values of the energy management system like the degradation coefficient whereas the status vector $\vec{s}_i$ is specific for each generic component and holds information like the current utilization or the energy demand of the component.

$$\vec{e} := \begin{pmatrix} \text{velocity} \\ \text{temperature} \\ \vdots \end{pmatrix} \quad \vec{p} := \begin{pmatrix} \text{comfort} \\ \text{infotainment} \\ \vdots \end{pmatrix} \quad \vec{m} := \begin{pmatrix} \text{generation} \\ \text{degradation} \\ \vdots \end{pmatrix} \quad \vec{s}_i := \begin{pmatrix} \text{utilization} \\ \text{demand} \\ \vdots \end{pmatrix} \quad (1)$$

The wrapper itself is separated into two layers. The physical layer of the component is directly connected to the electric connectors and contains the whole physical description of the model including it's basic functionality like low level control loops. Furthermore, the physical layer is connected to the signal bus to provide the models with the environmental boundary conditions they are depending on. The control layer serves as an interface between the physical layer and the abstracted vehicle's IT. It receives $\vec{p}$, $\vec{m}$ and $\vec{e}$ as input information and contains all energy management related functionality as well as reactions on passenger's actions. The interface between the physical layer and the control layer is highly specific for each type of component. It is composed of the control vector $\vec{c}_i$ and the feedback vector $\vec{f}_i$ as can be seen in definition 2. Using the example of a seat heating, $\vec{c}_{SH}$ would contain information of the switches position and $\vec{f}_{SH}$ gives feedback about the current consumption, the local voltage or the actual temperature.

$$\vec{c}_i := \begin{pmatrix} \text{controlsignal1} \\ \text{controlsignal2} \\ \vdots \end{pmatrix} \quad \vec{f}_i := \begin{pmatrix} \text{feedback1} \\ \text{feedback2} \\ \vdots \end{pmatrix} \quad (2)$$

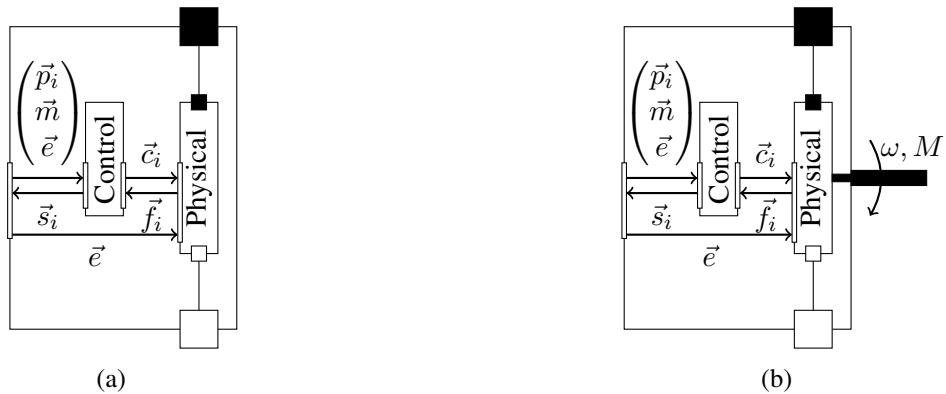


Figure 5: Interface concept of the generic wrapper. The models are separated into one control layer for the implementation of the logic and one physical with acausal connections the power net simulation. The wrapper (a) has a connection to the electrical domain, wrapper (b) has an additional connection to the rotational-mechanical domain.

4.2 System simulation

With all components using the generic interface wrapper, the system simulation can be constructed from these generic components containing the physical models. A simplified diagram of the system simulation is shown in Figure 6. It consists of two parts, the automotive power net simulation at the lower part of the diagram and above the cybernetic energy management, called fEPM. In the automotive power net simulation, the generic components are interconnected via the wiring harness and the common interface bus. The physical model of the wiring harness includes models of the wires, connectors, fuses and the resistances of the car's body. The common interface bus connects the components to the energy management system and to the environment. The driving cycles needed for this type of simulation are not just simple speed profiles. In addition the customer interaction with the vehicle and environmental parameters have to be defined. This information is fed into the simulation by the scenario block that basically is a set of timetables for these values.

According to the equi-structural design of the cybernetic energy management the components of the power net are grouped into producers, consumers and storage systems. At the current stage of expansion, the consumer group is the only component group with more than one component. It contains up to 40 models of electric consumers as described in section 2. The producer and the storage group instead contain currently only one element each, the alternator and the battery. Nevertheless the whole system simulation is prepared to be extended up to a multi-producer-, multi-storage-, multi-domain-simulation environment.

Regarding the cybernetic energy management system, it can be seen that the structure of the management system is based on the topology of an automotive power net with its three basic types of components. At the current development stage, three recursions of the viable system model, also called hierarchy levels, are used. The lowest hierarchy level is the component level that controls the component itself and is implemented in the control layer of the generic wrapper. It defines the reaction of the individual component to the modifiers received from the component group level. The 12 V power net level is composed of the three component groups *consumer*, *producer* and *storage systems*.

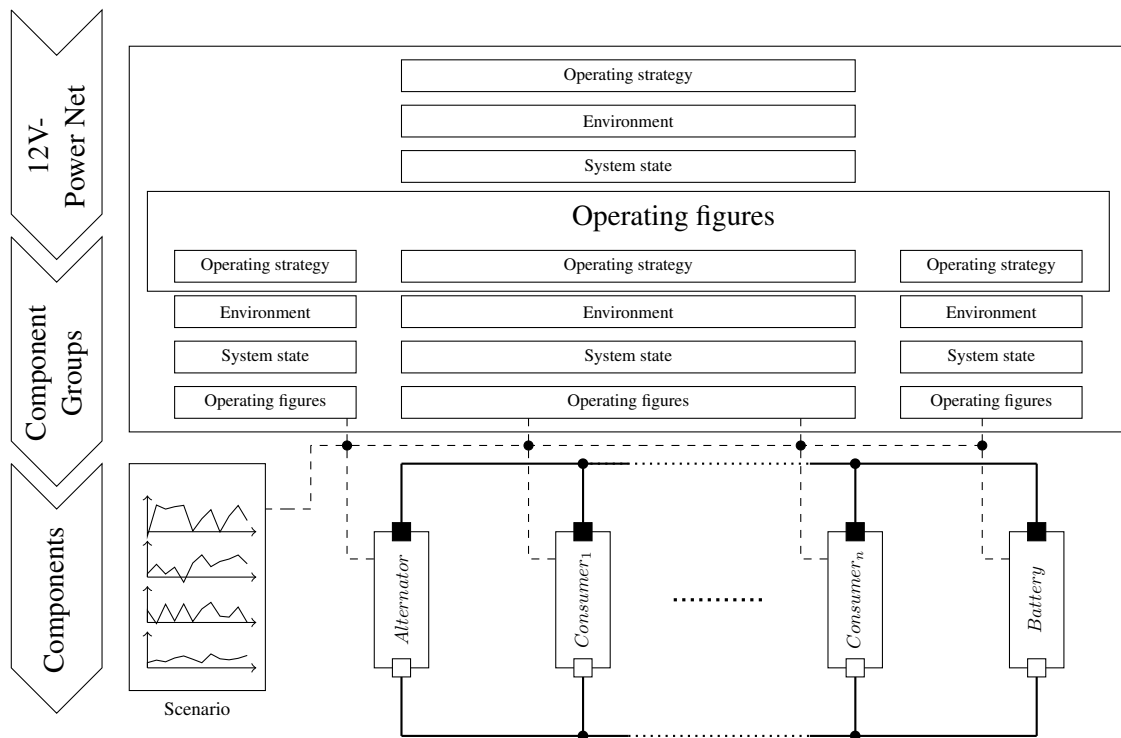


Figure 6: The system simulation is the collaborative simulation of the physical model of the automotive power net and the implementation of the flexible Energy and Power Management.

5 Simulation

This section shows the simulation results of two exemplified generic scenarios. It is pointed out, how the fEPM interacts with the automotive power net simulation in order to ensure an efficient and safe operation.

5.1 Scenario 1: High demand, low production

In the first scenario the behavior of the system will be examined in a situation in which the consumption of electric energy is higher than the maximum possible energy production. A typical example for such a scenario is when the combustion engine is running in idle speed and many consumers are active. Due to the low rotational speed of the engine, the alternator cannot deliver its nominal output power. For a short period of time such situations have no negative impact because the battery can compensate the difference between energy production and energy consumption at the cost of a decreasing state of charge. So, obviously, the energy management has to react if the SOC falls below a defined level. This situation can be solved by two types of interventions. The first possibility is, to reduce the energy consumption down to the level of production for example by the degradation of the heating systems. For short periods of time this could be an option, since the thermal constants of the heating systems are very high and the customer would not notice a degradation of several seconds. But for longer durations this solution would be a loss of comfort for the customer. In the scenario of engine idle operation there is a second option that can be chosen to improve the boundary conditions for the alternator. The energy management can request an increase of the idle speed. Figure 7 shows the simulation results of the explained scenario.

Two simulations were done with the same settings. At an initial SOC of 70 %, the rotational speed of the combustion engine in idle-mode is set to 800 rpm and the electrical load of the power net is set to 250 A. At 800 rpm the alternator can deliver a maximum current of 175 A, so the difference of 75 A has to be compensated by the battery. As expected the SOC decreases and crosses the line where the system state changes from *stressed* to *critical* at 65 % as indicated by the dotted line in the plot. In order to prevent oscillations, the state change logic in the energy management features a hysteresis of 5 %, so the internal state change occurs at an SOC of 62.5 %. It can be seen that the fEPM decides to intervene in two different ways in this scenario. It requests an increase of the idle rotational speed of the combustion engine from 800 rpm to 1500 rpm so that the alternator is able to deliver its nominal current of 230 A. Additionally the energy management decreases the energy availability modifier with the result that some heating systems degrade their power consumption. As a result of this intervention the system is able to produce more energy than dissipated by the electrical loads, the SOC increases and leaves the critical state.

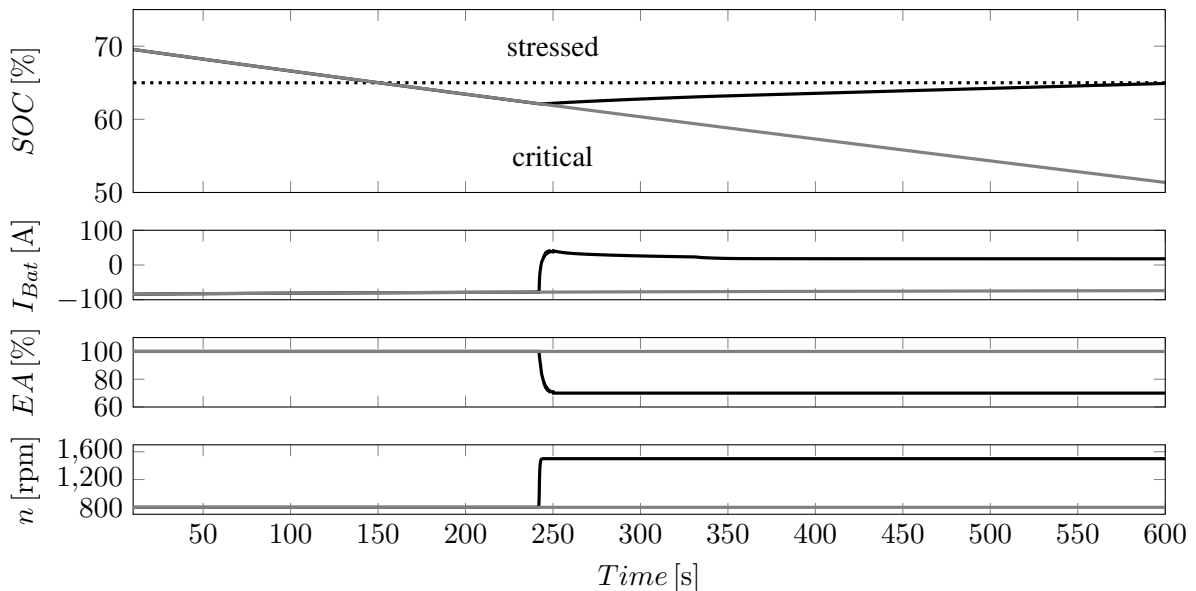


Figure 7: Simulation results for the first scenario with high demand of electric power and low production due to the idle state of the vehicle. If the SOC falls below a certain level, the energy management request an increase of the engine speed and degrades low priority consumers.

5.2 Scenario 2: Active load scheduling for efficiency increase

The second scenario shows, how the cybernetic energy management supports the implementation of efficiency optimization strategies. Even in conditions with no slope, the production cost of electric energy for the automotive power net is highly dependent on the operating point of the involved components, in particular of the torque and rotational speed of the combustion engine and the alternator. An interesting vehicle state for the production of electric energy is the coasting. During this state, the combustion engine is driven by the kinetic energy of the vehicle, but there is no fuel injection. The only cost for the production of electric energy is a slight increase of the decelerating torque. An energy management can use the information of the route prediction and schedule the low priority parts of the electric load to states of low energy production costs [10].

Figure 8 shows a generic scenario of a vehicle passing a small hill with a height of 100 m. The upper plot shows the height profile. The positive slope starts at 60 s. The car needs one minute to climb the hill and another minute to go down to the original height. The energy management in system level 5 controls the system by the two modifiers *energy availability* (EA) and *energy generation* (EG). In order to prepare the energy storage it reduces both modifiers as long as the vehicles is in the section of positive slope. As a result, the low priority consumers like heating systems reduce their energy consumption, the alternator completely stops the energy production and the SOC decreases slightly. As long as all system states like the SOC or the power net voltage are out of the critical state, there is no need for system level 3 to intervene. When the vehicle reaches the section of negative slope it starts coasting. The EG-modifier is set back to 100 % and the EA-modifier is set to 120 % as the production cost for electric energy are very low in this part. As a result, the SOC increases and the heating systems compensate their lack in thermal energy from the section before.

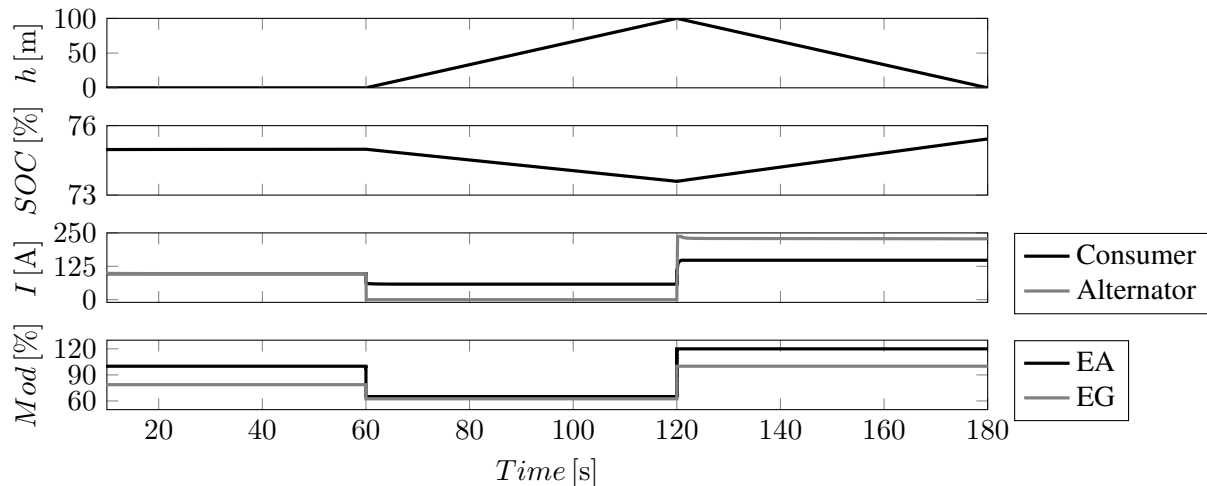


Figure 8: Simulation results for the second scenario. With the knowledge of the route, the energy management can schedule low priority loads to states with low energy production costs, like coasting.

6 Conclusion and Outlook

This paper describes the coupling of an automotive power net simulation with a cybernetic energy and power management system. It is shown how the cybernetic approach helps to meet the ever growing complexity of systems and that it can operate the automotive power net in a safe and efficient way. In future work, the system presented here will be coupled to a multi-criteria optimization in order to adjust the parameters of the energy management. Furthermore, the cybernetic approach will be expanded to the new 48 V power net and different energetic domains like the thermal or the mechanical domain. The vision is a cross-domain energy management for the entire vehicle.

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