Functional Simulations of Power Electronics Components in Series-Hybrid Machinery for the needs of OEM

Matti Liukkonen, Ari Hentunen, Jussi Suomela and Jorma Kyyrä

***Abstract*— This paper proposes method for rapid control prototyping of the series-hybrid transmission system. The rapid control prototyping needs simulation submodels from all system components in order to develop supervisory control software. The same simulation models can also be used to optimize the drive train. The target framework for the rapid control prototyping method is the original equipment manufacturer (OEM), where the objective is to build devices from subcontractor's components. The machinery industry, as a target group, uses high power ratings for the creation of motion, which leads to high voltage and current values used in the system. Therefore, prototyping is started with careful simulations. This paper also seeks to create a general idea about the structure of the series-hybrid power transmission and assists the start of the process for designing the supervisory control.**

***Index Terms*—functional simulation, power electronics, series-Hybrid drive train**

I. INTRODUCTION

HEAVY machinery such as harbor straddle carriers, loaders for underground mines and forestry harvesters are conventionally powered with the internal combustion engine (ICE). The ICE is traditionally connected to the mechanical or hydraulic power transmission. Work cycles of such machinery are often such that the fuel economy of the machine could be increased considerably by hybridizing the drive train. Buffered electric power transmission allows energy regeneration and optimization of the diesel operation.

The driving force behind the hybridizing of heavy machinery is the fuel economy. As a side-effect, better fuel economy results in lower emissions and equipments life-cycle costs. In some cases, it is also possible to downsize the engine, because the engine no more has to be sized for peak-power [1]. Another important aspect is the drastically increased amount of available electric power. In the heavy machinery there often exist subsystems which could benefit from the on-board electric power plant and electric energy storage. For example, the belt-driven cooling fan could be replaced with an electric motor driven fan. The speed of the fan could then be adjusted freely, because there is no mechanical coupling between the ICE's shaft and the fan. When cooling is not needed, energy could be saved by shutting the fan off. Additionally, the electric power transmission provides better traction and actuator control than the traditional power trains.

A hybrid electric vehicle is drive-by-wire by nature and needs a sophisticated vehicle control system. The control system collects data from subsystems, and based on the data and driver's requests, it gives control references to the subsystems. Because of the complexity of the system, model-based software development is widely adopted in the industry.

Model-in-the-loop (MIL) simulations provide fast and flexible development of the system level power management. Simulations provide also useful information in the concept design phase and can be used in the component selection of the subsystems.

In order to perform model-in-the-loop (MIL) simulations for the vehicle control system, functional models of the subsystems are needed. A functional simulation model describes the basic behavior and operational limits of a component or a subsystem. The models should have the same I/O interface as the real components. The models should also simulate real variables, such as voltages, currents and engine speed, with enough accuracy. Too high accuracy results in very slow model execution, and too low accuracy results in inaccurate data, thus corrupting the simulation results. Therefore, a good balance between accuracy and model execution time is desirable.

In this paper, functional models of the main components of the series-hybrid system are presented. MATLAB is used as a modeling environment. The framework of the study and development is the heavy machinery original equipment manufacturer (OEM) industry [2].

II. SIMULATION OF SERIES-HYBRID SYSTEM

The series-hybrid drive train connects primary energy sources to energy storages and loads via the dc voltage link. Therefore, power electronic devices are needed to separate

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different voltage potentials between energy storages and to control the power flow through the drive train. Furthermore, power electronic devices are needed for motion control with the electric motors.

Figure 1 represents possible components used in the series-hybrid drive train. The internal combustion engine or the fuel cell stack is used as a primary energy source. As a secondary energy storage can be used, for example, ultracapacitor module, battery, fly-wheel or a combination of these, depending on the application. Methodologies for designing appropriate power transmission system are presented in papers [1], [3] - [6].

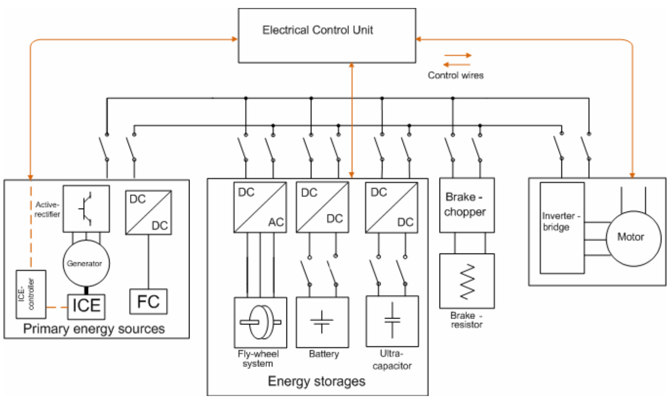

Fig 1. The layout of the series-hybrid drive train

The connection from the generator-set to the dc voltage link is made with an active rectifier, which enables adjustment of the output voltage in the dc voltage link part. As a result, it is possible to force the generator-set to work along the maximum efficiency line, in co-operation with the speed control and the active rectifier control [7]. The connection from the fuel cell stack to the dc voltage link is made with a unidirectional dc/dc converter. In contrast, the battery and the ultracapacitors are connected to the dc voltage link using bi-directional dc/dc converters [8]. The fly-wheel is connected to the dc voltage link through an inverter.

The simulation models presented in this paper are made with the MATLAB/Simulink software. Further, the simulation libraries SimPowerSystems and Stateflow are used to generate the simulation subcomponent models of the series-hybrid system. The SimPowerSystems library components are used for modeling the hardware in the series-hybrid drive train, and the Stateflow library is used for producing the control logic of the subsystems in the simulation model.

Modeling of the series-hybrid power transfer system should reach 20 Hz-bandwidths accuracy, which is enough for the system level control design. The accuracy is ensured by using correct capacitance and inductance values in the interfaces of power electronic component submodels. With regard to the transferred current levels, this bandwidth carries electrical transients caused by capacitors, inductors and the equivalent series resistances. The bandwidth enables the power electronic switches to be left out from the submodels, and the models are built over the current control loop. The functioning of the power-semiconductor switches is taken into account with the PI-regulators, which limits the maximum value of control signal. In additionally, the simulation models are run with a discrete solver of the MATLAB/Simulink, in which the sampling time of the models is close to the switching frequencies of the power electronic devices.

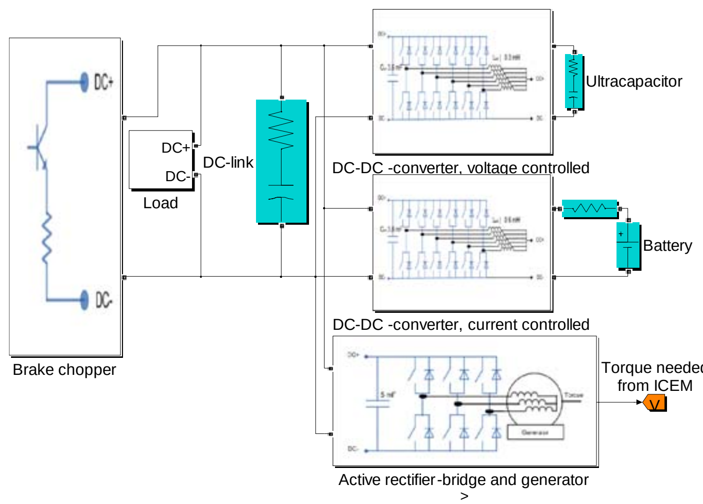

Fig. 2. The series-hybrid system simulation model realized with the SimPowerSystems and Stateflow library components.

The simulation model of the series-hybrid system includes submodels of the current and the voltage controlled dc/dc converters, the brake chopper, the load consumption data and the active rectifier-generator combination. Accurate simulation model from the internal combustion engine have been left

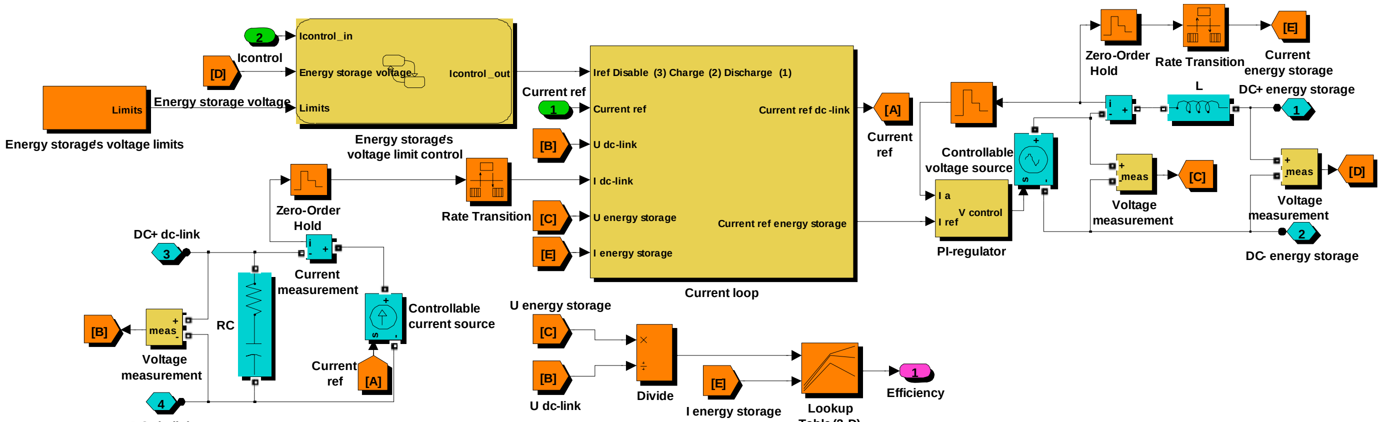

Fig. 3. The simulation model of the current controlled dc/dc converter

out of study for the simplicity. Therefore, the simulation model solves the required torque from the internal combustion engine, which gives information from the rating necessary.

A. Modeling of the Current Controlled DC/DC Converter

Modeling of the dc/dc converters is based on the current control loop. The dc/dc converters are presumed to transfer the current ideally from one voltage level to the other, because the consideration of transfer losses in transferred current would be difficult. The current control loop in the dc/dc converter simulation model will be as follows.

1. Given current reference is generated to the wanted direction
2. Transferred power is measured
3. Solved current is taken from the opposite direction

The difference between current transfers can be neglected because of a short sampling time in the simulations.

The interfaces of the dc/dc converters are modeled using the capacitance and the inductance components found in the SimPowerSystems library. The current reference coming from the superior control is generated and directed through to the inductance port with the controllable voltage source connected to PI-regulator.

Superior to the current control loop, the dc/dc converter has Stateflow block, which contains the voltage value limits of energy storage. If either the maximum or the minimum limit overpasses, then the signals coming from the superior control are disabled. The maximum voltage level is defined by the nominal voltage of the energy source and the minimum voltage is determined by the point at which the power transfer efficiency in the dc/dc converter collapses.

Information of the power transfer losses in the dc/dc converter

Information of the dc/dc converter's transfer losses is based on the measured efficiency map. The dc/dc converter's efficiency is defined by the transferred current and the conversion rate of the voltages between upper and lover voltage levels. The efficiency map is included into the simulation model as a lookup table, which gives the state of the power transfer at the time.

B. Modeling of the Voltage Controlled DC/DC Converter

The voltage controlled dc/dc converter is used in fast low level control/stabilization of the dc-link voltage. This converter is typically used with ultracapacitors [4]. The simulation model from the voltage control has been implemented between the current control and the superior control of the system. This control has been made using the Stateflow block.

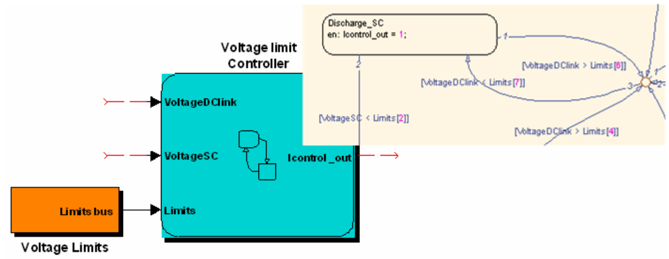

Fig. 4. The voltage control limits build on top of the current control loop with the Stateflow block.

In addition to the voltage limits in energy storage side, the voltage controlled dc/dc converter has a tolerance-band control in the dc voltage link port. The dc-link's tolerance-band control ensures that the dc-link's voltage does not collapse or increase in sudden load transients. After the voltage changes to the maximum or the minimum control value, the current is transferred via the dc/dc converter to stabilize it. The current direction depends in which, maximum or minimum, limit value dc-link's voltage overpasses. The current transfer stops after the voltage overpasses the hysteresis of the limit in question. The voltage controlled dc/dc converter enables the smooth loading of other energy sources, which is suitable for their operation. Therefore, other energy sources should be controlled to remove loading from the voltage controlled converter and to maintain the dc-link's voltage within its voltage tolerance band [9].

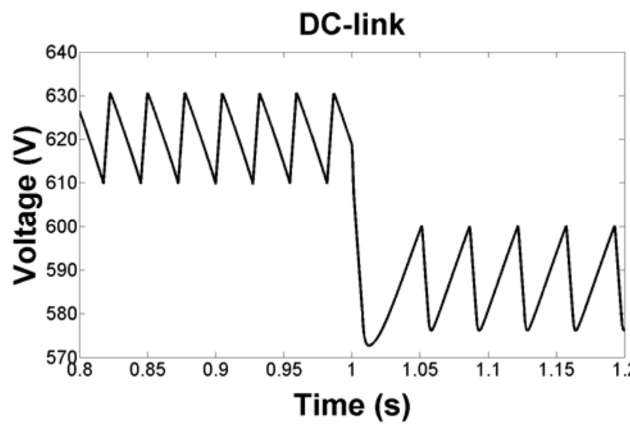

Fig. 5. The voltage control limits illustrated with constant current reference.

C. Modeling of the Active Rectifier

The active rectifier allows controlling of the output voltage of the dc-link's port. The active rectifier is modeled in a similar way as the dc/dc converters, which includes the ideal power transfer, the interface capacitance and the controllable current source. The output in the dc-link's port is voltage regulated, and the output voltage is calculated using the internal combustion engine's speed state value and also the voltage reference, which come from the superior control. The transferred power to the dc-link is measured and the necessary torque to maintain the speed reference of the internal combustion engine is solved. The generated transfer losses will be modeled using the efficiency data inside the lookup table.

Permanent magnet generator

The permanent magnet generator is modeled by taking into account the approximate efficiency value and the inertia of the rotor. The efficiency of the generator increases the torque value necessary from the internal combustion engine. The inertia of the rotor affects the speed states of the internal combustion engine.

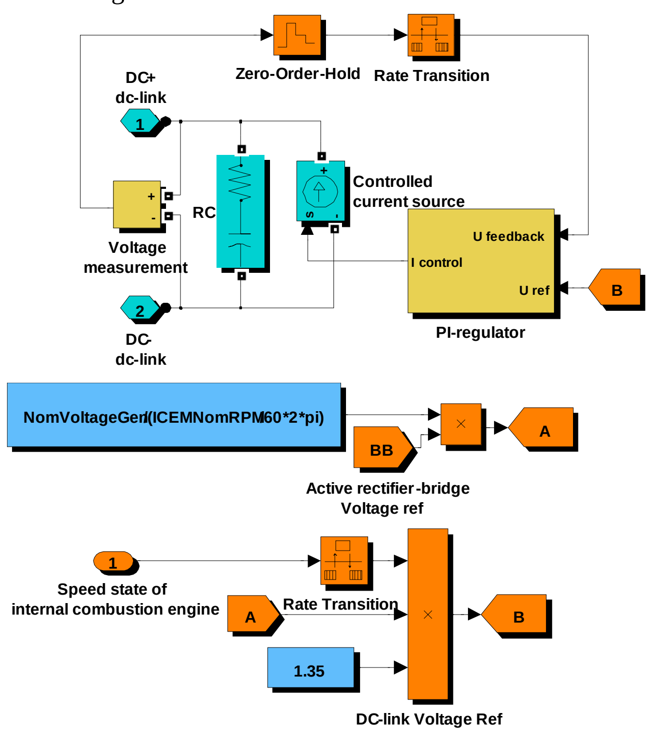

Fig. 6. The simulation model of the active rectifier

Solving the needed torque from the internal combustion engine

Modeling of the internal combustion engine is problematic because it operates behind its own electrical control unit. Therefore, the model of generator-set is superficial and includes only the inertia of the internal combustion engine and the speed control loop from which the required torque is solved. The torque is solved from the transferred power and from the speed state of the internal combustion engine and up rated with the efficiency value of the generator. The speed control loop, with the P-regulator, adjusts the required torque with the production of inertia as well as with the speed state adjustment signal.

D. Modeling of the Inverter load

The loading of the series-hybrid system is modeled using the recorded power consumption data. The heavy machinery's power consumption data can be recorded from the parameter values of the inverter in the machinery, which has electric drive train. The real power data gives information from rating of the secondary energy storages, the dc/dc converters as well as rating of the ICE. If the apparent power is used instead of the real power, the simulation offers information also from the necessary dc-link capacitance. The measured data can be driven out from the dc-link with the controllable current source. The inverters real power data is needed designing a supervisory control for different power flow directions and operation points. The other approach for the simulation of the load is to generate an approximate load curve with the signal builder block.

E. Modeling of the Brake chopper

The brake chopper is modeled using the current source parallel with the dc-link. The current source is controlled with a PI-regulator which is controlled with the dc-link voltage. As a functionality of the brake chopper, the current sources power transfer is limited by the maximum power, which can be dissipated into the brake resistor. The brake chopper enables when the dc-link's voltage overpasses the activation limit.

F. Modeling of the Power Sources

The ultracapacitors and the battery are modeled simply with an internal resistance, capacitance and with the energy storages initial condition. In reality, the equivalent circuit is more complex, but for the OEM needs this modeling level is sufficient. The supervisory control of the series-hybrid power transmission does not necessarily need information from voltage balance between subcomponents of the energy storage [10].

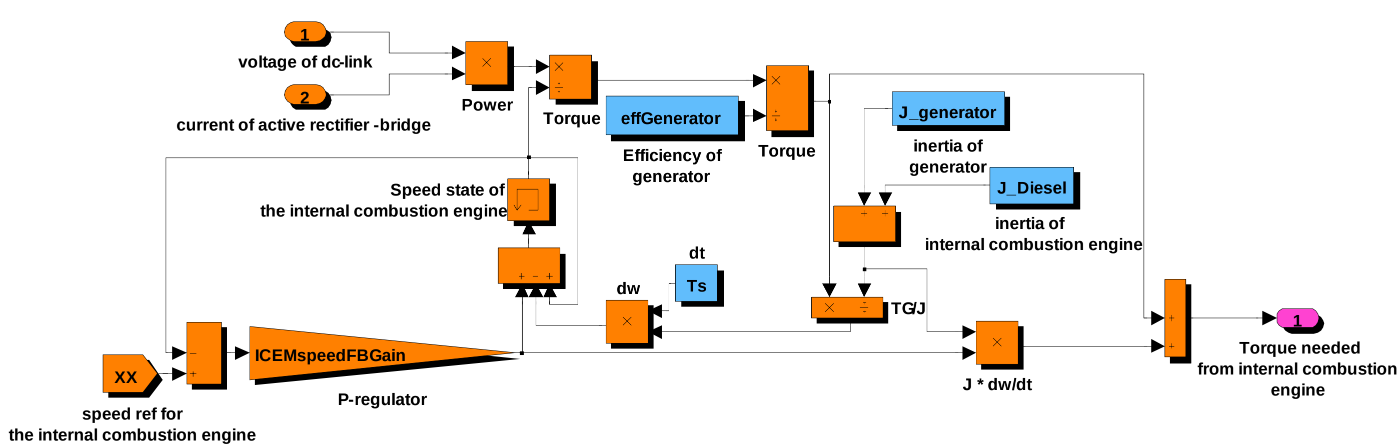

Fig. 7. The simulation model of the generator-set in the series-hybrid system

G. Converting the Simulation Model to S-function

The simulation model of the series-hybrid system is realized using the SimPowerSystems as well as the Stateflow components, which do not belong to basic Simulink libraries. Therefore, it is worthwhile to generate the S-function from the simulation model with the MATLAB/real-time workshop. The S-function belongs to the basic Simulink library, and after compilation, no other Simulink libraries are needed. This is an advantage because then the OEM does not necessarily need to have the same Simulink libraries as the university.

III. SYSTEM LEVEL POWER TRANSFER CONTROL

The power transfer in the series-hybrid system is realized through the dc voltage link. The first, requirement is to create algorithms for controlling the energy storages with the dc/dc converters and the internal combustion engine within the allowable control limits. For example, with the dc/dc converter, the voltage drop over the energy sources series resistance enforces the down rating of the current while operating near the energy sources maximum and minimum voltage levels [9]. Furthermore, the energy storages maximum voltage and power transfers efficiency's collapsing defines these voltage limits.

The second, requirement is to create algorithms and control logic for transferring power through the dc-link with stabilized dc-link voltage. Control with a stabilized dc-link voltage leads to minimized losses in the internal resistance of dc-links capacitor bank. It should be possible to transfer power from any source to any secondary energy storage. Information about the suitability of the controls is also gained from the torque curve of the ICE.

The third, requirement is to create the supervisory control for the series-hybrid power transmission. Several control strategies have been presented in the latest research papers. Simple control strategies are torque boost, in which an ultracapacitor module is used as support while accelerating and as storage while decelerating. Another simple control strategy is peak shaving, which smoothens loading from the ICE during continuous run with the ultracapacitor module. The need for slightly more complicated supervisory control strategies arises when a battery is included in the drive train. More sophisticated supervisory control strategies are presented in papers [6], [7], [10] and [11]. One interesting strategy, for example, is the Equivalent Consumption Minimization Strategy (ECMS) [7].

IV. TEST BENCH

The supervisory control for controlling the hybrid power transmission needs to be tested with the corresponding test setup. The testing is made with the test bench built in the automotive laboratory. The test bench includes an active rectifier-bridge (P_{cont} 310 kW) connected to a power grid, which can be used to simulate the active rectifier connected to the generator-set in the hybrid drive train. The dc/dc converter (P_{cont} 90 kW) and the ultracapacitor module (17,8F, U_{nom} 390V) are used for energy buffering in the test bench. The loading of the dc-link is created with an inverter (S_{cont} 120 kVA), which is connected to the induction motor (P_{cont} 67 kW). The induction motor is used against the dynamometer, which transfers power back to the power grid. The dynamometer has a continuous power limit of 120 kW. Parallel to the dc-link is the brake chopper, for which the power dissipation is rated as 60 kW. At the moment, the series-hybrid power transmission test bench is lacking Li-ion batteries as the

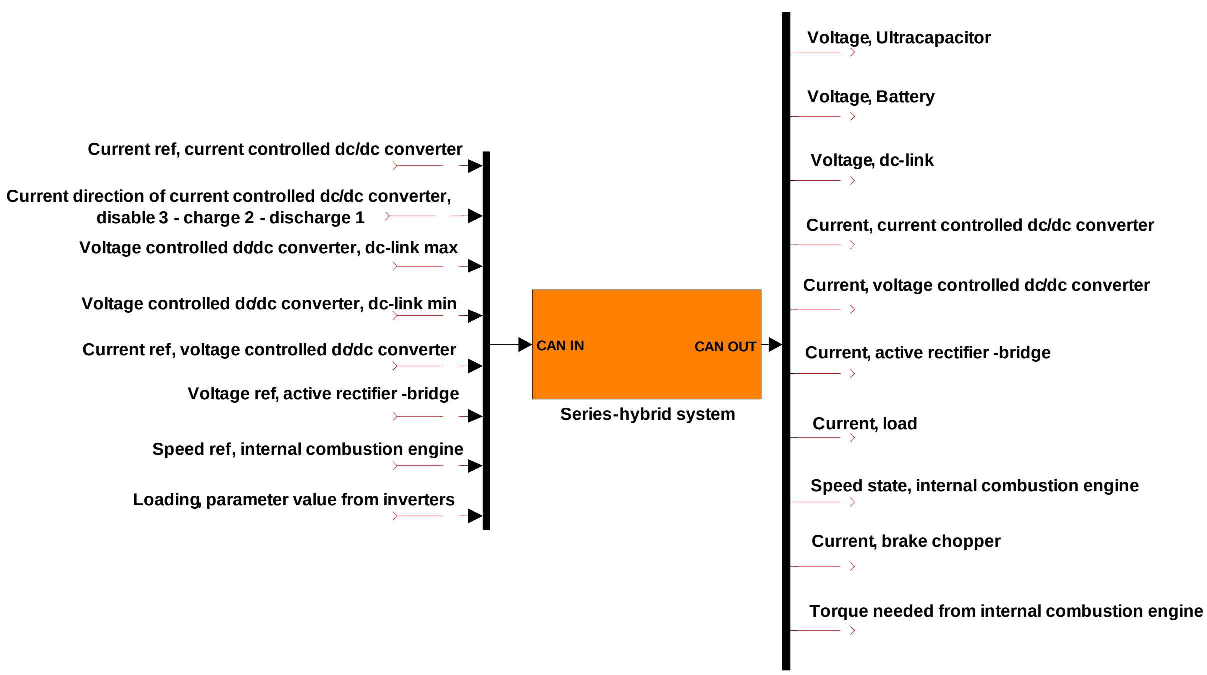

Fig. 8. S-function generated from the series-hybrid transmission simulation model and its control interfaces.

other secondary energy storage.

The series-hybrid power transmission system's components are connected to CAN-bus to Beckhoff industrial I/O interface, which is controlled with the dSPACE prototyping hardware MicroAutoBox. The dSPACE MicroAutoBox can be used to compile the Simulink models to C-code and also as the software platform [12].

Fig. 9. The test bench in the automotive laboratory

V. Simulation Examples

The simulation model is introduced with the control principle, where an ultracapacitor module is used for the power generation in fast load transients, whilst the battery current is ramped up to support the internal combustion engine [4]. The active rectifier is used for raising the dc-link voltage over the voltage controlled converters control limit. After disabling the ultracapacitors, the load current is supplied from the active rectifier and the battery.

The voltage controlled dc/dc converter is used with a 580 V minimum voltage level with 20 volts of control hysteresis. Its current is controlled with the quadratic function of the dc-link voltage. The current controlled dc/dc converter, which controls the battery, has a linear current reference as a function of the dc-link voltage, starting from the same dc-link voltage limit as the voltage controlled converter. Likewise, the control of the active rectifier is started from the same control limit and the voltage reference is ramped up as a function of the dc-link voltage.

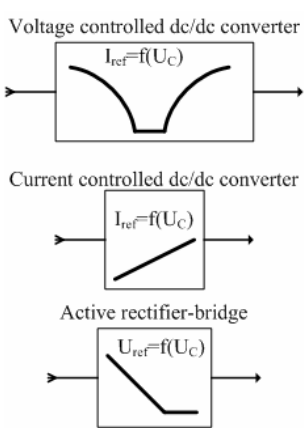

Fig. 10. The control functions in the example simulation

VI. Future Work

In the future, the series-hybrid power transmission systems control algorithms generation will be continued and the testing of the control logics is started with the hardware.

The test bench will be finalized with the lithium-ion battery energy storage connected via the current controlled dc/dc converter to the dc-link of the series-hybrid system's test bench. The active rectifier connected to the power grid is replaced with a combination of the generator-set and the active rectifier.

Efficiency measurement results from the dc/dc converter and from the inverter are included in the simulation model. As a result, the simulation model gives information for the rating of the liquid-cooling system.

Different supervisory control strategies will be simulated and tested in the test bench. In particular, strategies based on the inverter's power transfer parameter will be considered. Strategies with one and two current controlled energy sources, both voltage and current controlled energy sources are also investigated. Furthermore, it is possible to test different kinds of predictive control strategies, if proper data from the machinery's working cycle is available.

VII. Conclusions

This paper proposed a way to model the functionality of power electronic components in the series-hybrid drive train. For the generation of the simulation models the MATLAB/Simulink software with SimPowerSystem and Stateflow libraries were used. The model targeted to 20 Hz-bandwidths accuracy. The simulation models aim is to provide the possibility for early phase software design in the series-hybrid power transmission system, and is also a way to optimize the ratings of the secondary energy storages.

The construction and the operation principles of the sub-model components were presented and the route for the supervisory control generation was briefly described. The operation of the series-hybrid drive train was introduced with the control principle in which ultracapacitors were used for fast transient buffering while the battery and the internal combustion engine were used during steady state loading.

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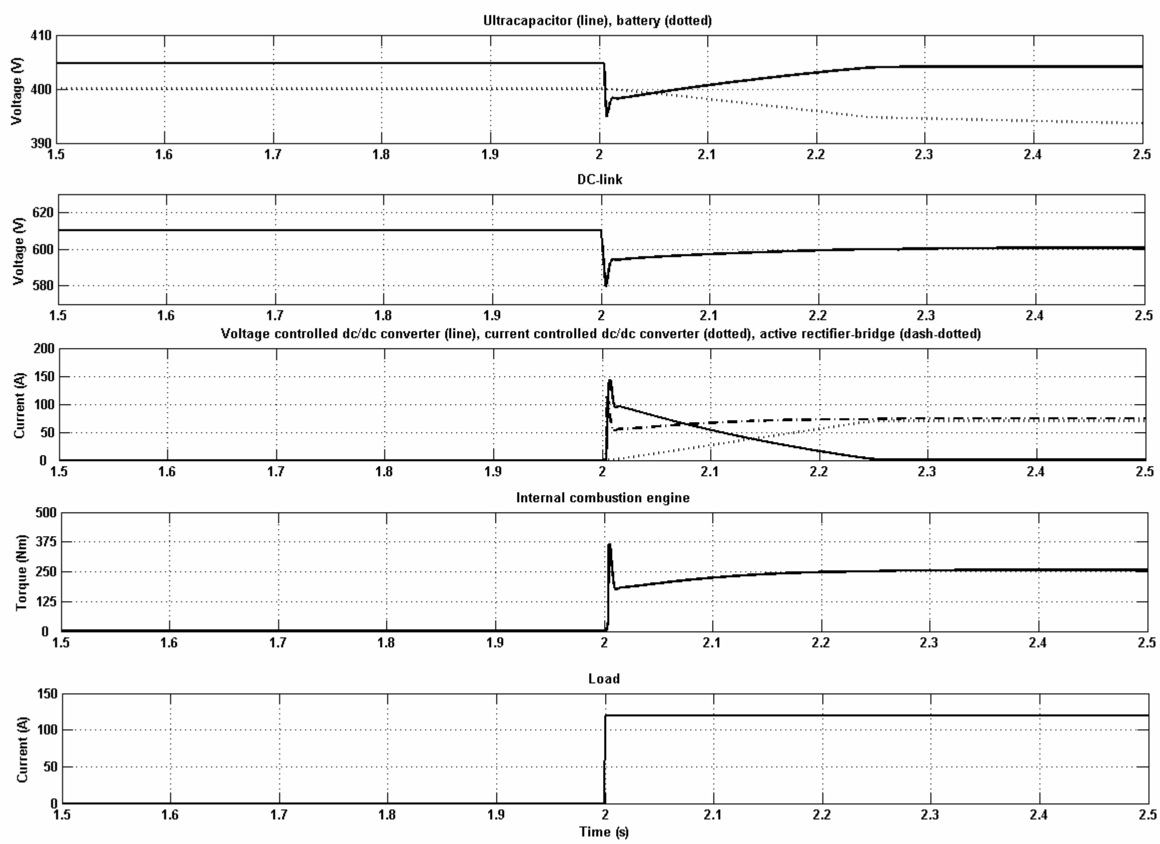

Fig. 11. Simulation results with the represented control principle.