© KIT

Development Method for Electric and Hybrid Powertrains

Internal combustion engines are still most commonly used for driving mobile machinery. Electric drive units win because of their high efficiency, their possible recuperation and operation with renewable energies is becoming increasingly important. From a customer perspective, however, affects the limitation of labor input by the portable energy supply. By including a second power source, however, the possible energy expenditure on a mobile machine can be increased significantly. At the Chair of Mobile Machines at the Karlsruhe Institute of Technology, the model-based development of electric hybrid drive systems and their operational strategies for mobile machinery is explored using extended XiL methods therefor.

AUTHORS

Dipl.-Ing. Christian Pohlandt
was Research Assistant
at the Institute of Vehicle System
Technology of the Karlsruhe
Institute of Technology (KIT)
in Karlsruhe (Germany).

Lars Brinkschulte, M. Sc.
is Research Assistant
at the Institute of Vehicle System
Technology of the Karlsruhe
Institute of Technology (KIT)
in Karlsruhe (Germany).

Prof. Dr.-Ing. Marcus Geimer
is Director of the Institute of Vehicle
System Technology of the Karlsruhe
Institute of Technology (KIT)
in Karlsruhe (Germany).

MOTIVATION

In the area of powertrains of off-highway machines, the market is dominated by vehicles having an internal combustion engine and in particular a diesel engine. This is due to the fact that the engine components are comparably inexpensive, the use of known design methods, safe management of the technology, and the trivial control expenditure. However, stricter environmental regulations and emission limits are associated with increasing requirements that may only be met by electric drive technologies. Reduction of noise emission, parallel increase of driving and working comfort, enhanced productivity, and reduced system-inherent mechanical loads due to reduced vibrations of the engine are often neglected advantages of electric powertrains, which justify today's costs. Design of components, use of representative load cycles, and integration of suitable components into existing vehicle architectures lead to higher requirements on the design process, including product validation. To ensure traceability and detectability over the design process, extensive methods are needed for the holistic implementation of electric powertrains with specific hardware and software development environments.

The V-model approach [1] used in the private car sector may be transferred to off-highway machines, provided that specific modifications are made. Apart from the driving function, various working functions of off-highway machines have to be considered. The corresponding add-on parts lead to extensively branched and highly complex powertrain topologies. Often, every part is equipped with a control software of its own. Hence, an elaborate control (ECU) strategy is required for optimum coupling of software modules. Energy recovery by recuperation, for instance, largely depends on route topology and the use of the vehicle. Working functions of off-highway machines frequently reach higher recuperation.

Investments in batteries of sufficient capacity are required to cover the complete scope of applications of off-highway machines. Lacking knowledge of this scope and of the application behaviours result in reduced customer acceptance. Consequently, a range extender concept is applied. The electric powertrain topology is complemented by an additional combustion engine of small power that increases the energy content available by potential charging of the battery. The article describes a model-based development of electric hybrid powertrains and their operating strategies for off-highway machines, including extended XiL methods.

MODEL-BASED DEVELOPMENT

Any development process covers hardware, software, and system design as well as application, verification, and final validation of the product developed. The design process represents an iterative process on the system level. In conventional design processes, sub-systems are designed separately of each other and are then integrated into the total system with defined interfaces. Frequently, the V-model approach is used, **FIGURE 1**, where design statuses are allocated to specification and testing phases. The design process consists of five steps. First, requirements to be met by the product are defined. To meet these requirements, sub-system solutions are designed, developed, and then integrated into the total system. In case of successful validation, a product is obtained in the end.

This approach is extended by model-based development in the early stage of the design process. Physical components are developed based on virtual simulation models. To describe the logical and physical behaviour of the system, mathematical models are applied. It

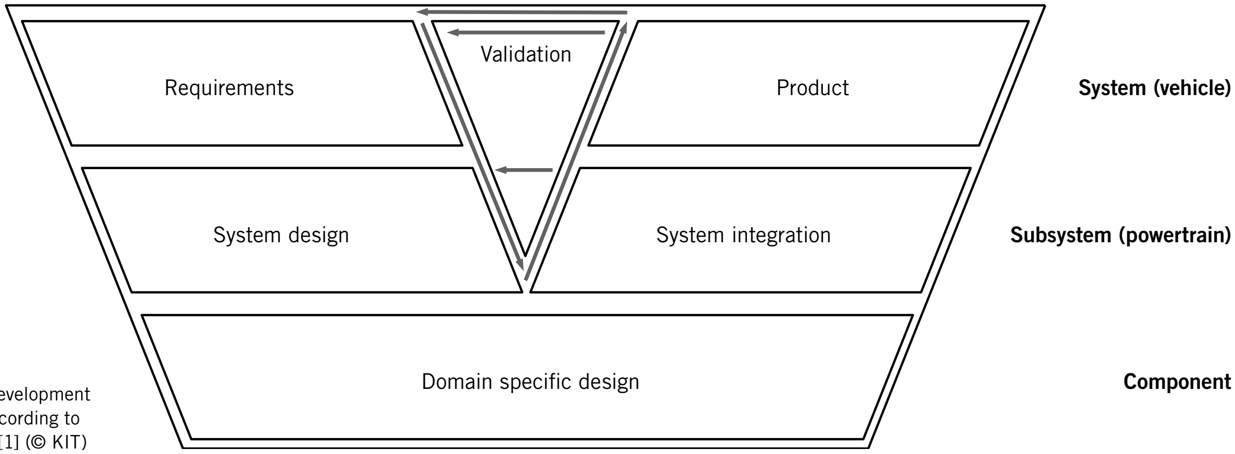


FIGURE 1 Development process according to VDI 2206 [1] (© KIT)

is aimed at making statements about the system before the hardware proper is available. Model-based development facilitates model variation and integration for new functionalities of the product. Early validation and subsequent adaptation of the virtual models may be considered a continuous improvement method in product design.

Design of algorithms for control systems and operation strategies requires models of the control module with defined interfaces. The vehicle model describes physical behaviour of the car in a real world. With these models, the complete system can be analysed holistically on the system level and the behaviour and interactions can be described at an early stage.

While car manufacturers frequently use virtual testing and simulation tools for testing and process integration, such tools have hardly been applied by manufacturers of off-highway machines so far. Combination of real-world test vehicles with virtual driving simulators would have considerable advantages. Due to cross-linked control architectures in electric and hybrid powertrains, vehicle complexity is increasing. Model-based development enhances the traceability, efficiency, and quality of the design process, including integration and testing of adaptive control algorithms.

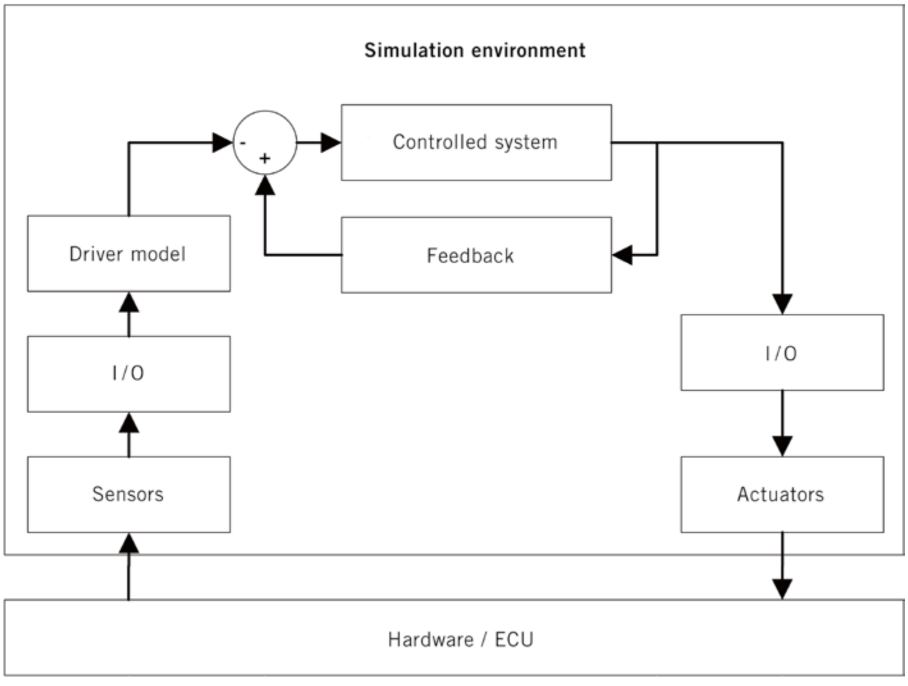


FIGURE 2 Schematic representation of a XiL environment (© KIT)

TRANSFER OF THE XIL APPROACH TO OFF-HIGHWAY MACHINES

A model-based design method is used to design the electric powertrain and to implement an efficient control strategy. This methodological simulation approach is suited for the development of electric/electronic components, but may also be extended to cover holistic system design on the vehicle level. The goal is to design an energy-efficient powertrain technology and an effective operation strategy to optimally support the working process. To consider individual components and sub-systems in various development stages and to make statements with respect to their suitability at an early stage, the verified system design, e.g. the simulation model of the target hardware, is validated using the X-in-the-Loop (XiL) approach, **FIGURE 2**.

The term XiL was originally coined by automotive industry. Virtual integration of individual components into a virtual vehicle simulation allows information on the system behaviour and relevant interactions to be obtained even before all necessary hardware components exist. Depending on availability, simulation models and control software are used or real components and control systems are applied in test benches. In addition to the simulator and the hardware to be tested, physical interfaces (I/O) are needed. They ensure communication and data transfer between vehicle simulation and the component to be integrated.

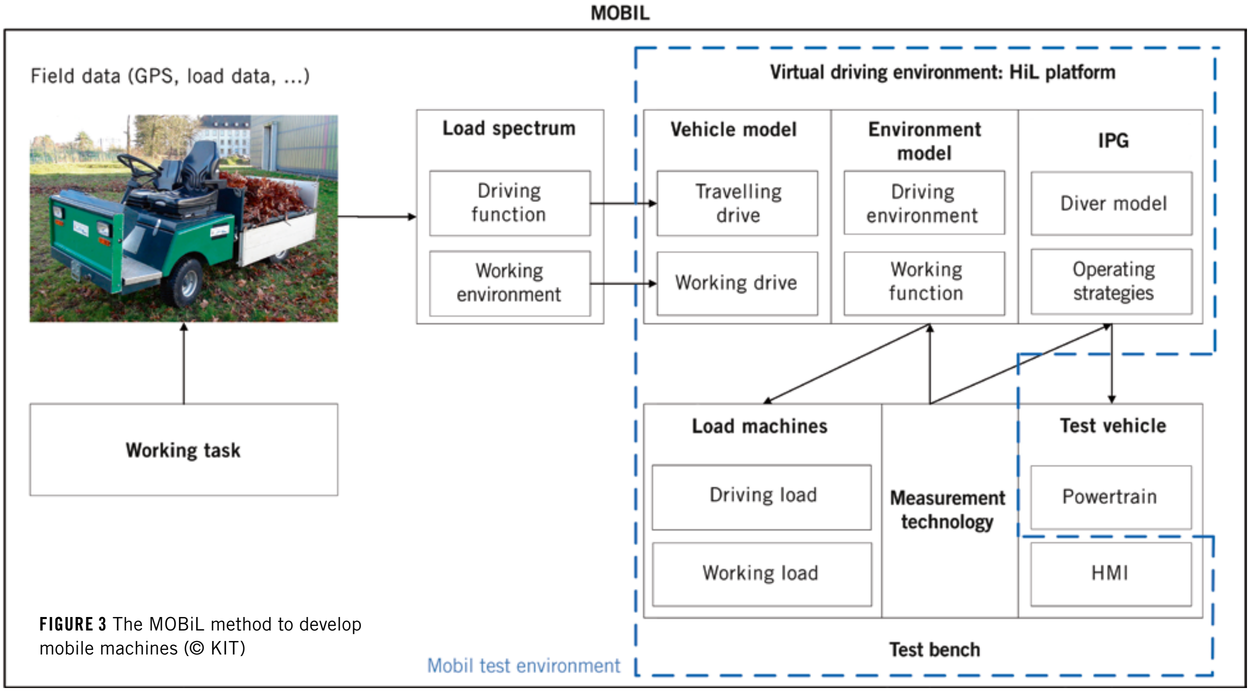


FIGURE 3 The MOBiL method to develop mobile machines (© KIT)

The limit of XiL is the correct modelling of physical relationships. Exact modelling of physical behaviour is hardly reasonable. From the point of view of the control system, a plausible behaviour can be applied. If more complex models are required, the real-time capability of the model can be hurt. According to systems theory, a system is real-time capable, if it responds within a defined time span.

As the XiL methodology is designed for applications in automotive industry, it needs to be adapted to off-highway machines. This resulted in the so-called MOBiL method, **FIGURE 3**. It is based on a dynamic simulation model of the powertrain that can be integrated into an open integration and testing environ-

FIGURE 4 Driver intervention options for performing virtual test manoeuvre (© KIT)

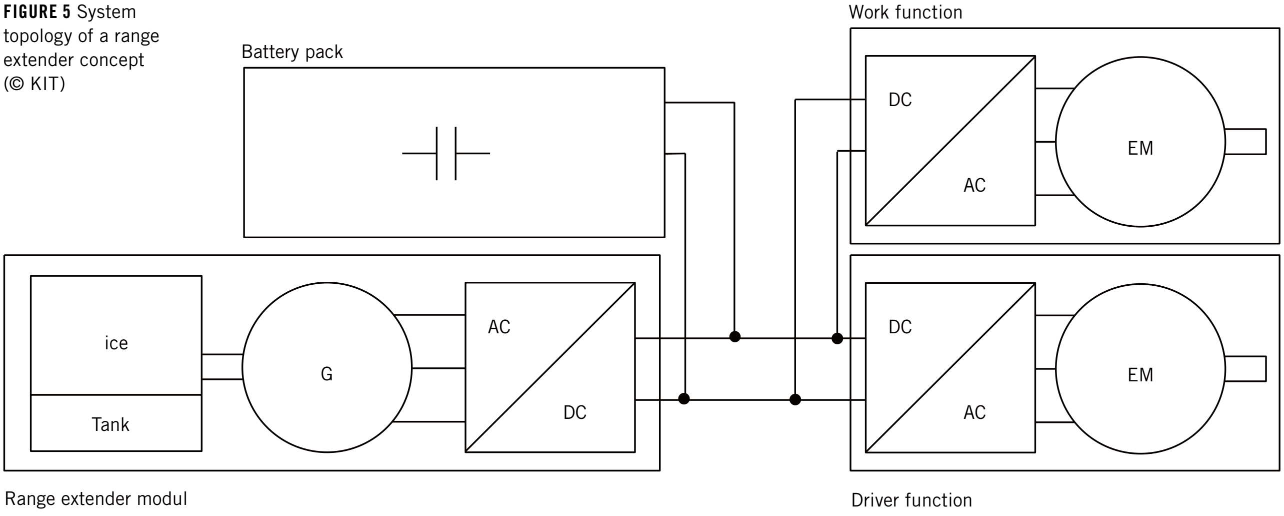


FIGURE 5 System topology of a range extender concept (© KIT)

ment, such as IPG-TruckMaker, by appropriate interface definitions and specific extensions. The virtual platform based on C-code is adapted to off-highway machines, such as work drives, route topologies, modified wheel-ground contacts and material interactions. For this purpose, complete simulation model libraries are made available.

Depending on model complexity, vehicle behaviour can be simulated in real time to derive information on power flows and their dependence on operation strategy. Simulation models are successively replaced by real components and control systems in the test bench. Load cycles standardised for a certain type of vehicle exist in special cases only. Often, however, field data from customer scenarios are available. Hence, operation strategies are validated by virtual manoeuvre-based test drives instead of complex and cost-intensive field tests. Even in case of the same vehicle type, off-highway machines are subject to various loads and power outputs. Hence, a working task has to be defined in addition to load cycles. As the way of fulfilling the working task is determined by the driver, the vehicle can be controlled by an automatic driver – the working task is fulfilled optimally – as well as by manual driver intervention. For the latter, human-machine interfaces are applied.

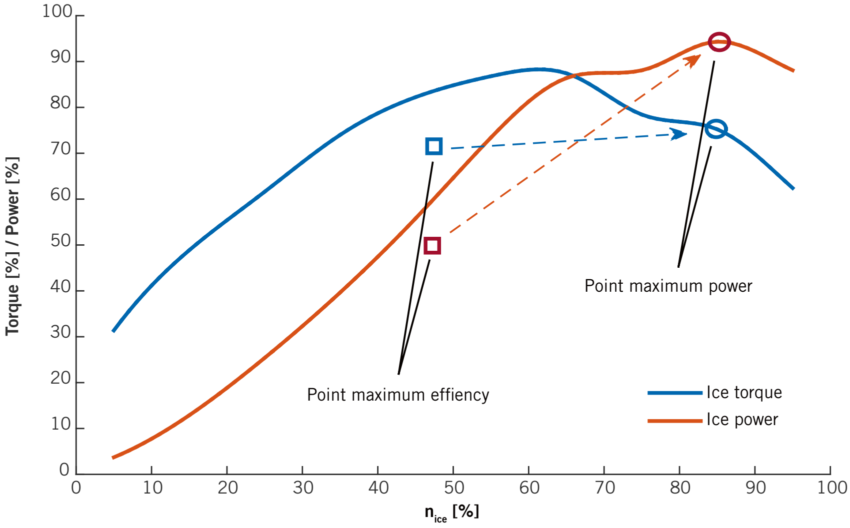


FIGURE 6 Implemented operating strategy of the range extender module with highlighted modes (© KIT)

TEST ENVIRONMENT

Apart from a simulation environment, a test bench is needed [2]. The key components of the MOBiL test bench are three asynchronous motors of 130 kW nominal power each. These motors can be positioned variably on two test benches of 20 m^2 each. These machines are supplied by three water-cooled DC/AC converters connected to a DC-bus with a power supply unit with integrated energy recovery. This test bench topology ensures energy-efficient power circulation among the motors.

The basic simulation structure (vehicle, environment and driver) with defined interfaces is supplied by the virtual IPG-TruckMaker tool. The driver's acceleration is used as speed or torque set point for the unit to be tested. The loads applied to the vehicle in the test bench originate from simulation. For complete integration of the vehicle or vehicle components into the method, the speed signals measured are used as input data for simulation. To analyse the influence of the operator, a human-machine interface (HMI), **FIGURE 4**, can decouple the driver from simulation and be integrated into the environment as a direct control unit of the vehicle.

RANGE EXTENDER SYSTEM TOPOLOGY

According to definition, the range extender topology belongs to the group of serial hybrid powertrains. The vehicle is

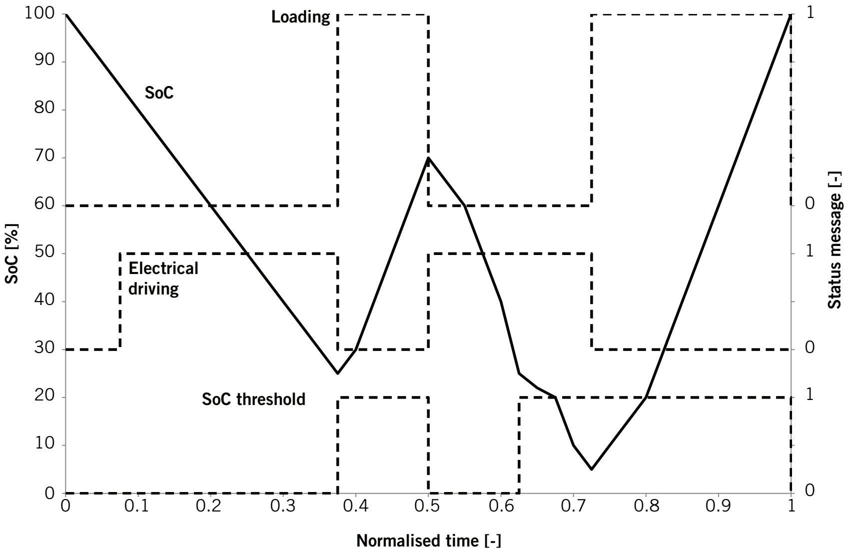


FIGURE 7 State variables of the operating strategy (© KIT)

driven always and exclusively by the electric engine. A potential system topology is shown in **FIGURE 5**. The range extender consists of an internal combustion engine that drives an electric generator (ice) with the corresponding power electronics. The electric energy supplied can be stored in the battery of the vehicle or used in one of the electric motors for driving the car. There is no mechanical coupling between the range extender module and the powertrains. The only connection is an electric cable to the battery via power electronics. Hence, the combustion engine can be operated at the optimum operating point independently of the current driving and working state.

When using the range extender concept, the power of the combustion engine installed in the vehicle differs from that of a serial hybrid. While the latter is equipped with a small battery and a high-performance combustion engine in relation to the output power, the frequency of usage and performance of the combustion engine are reduced considerably when using the range extender concept. This relationship may be described by the degree of hybridisation HG [3].

Eq. 1

$$HG = \frac{P_{\mathrm{EL,max}}}{P_{\mathrm{ice,max}} + P_{\mathrm{EL,max}}}$$

Here, $P_{\mathrm{ice,max}}$ is the power of the combustion engine and $P_{\mathrm{EL,max}}$ the power of the electrical machine.

There is no clear boundary between a serial hybrid and a range extender. While powertrain topologies with hybridisation degrees of more than 80 % are considered range extenders in automotive industry, the degree of hybridisation of off-highway machines may be even higher as a result of the high power installed for driving and working. The power of the combustion engine installed is adapted to the application of the machine.

OPERATION STRATEGY

A range extender can be operated in various modes:

- Zero emission: As a result of the environment (indoor operation, noise reduction), the vehicle is to be driven purely electrically.
- Best-point operation: To increase fuel efficiency of the range extender module, the operation points of the combustion engine are shifted towards minimum fuel consumption, **FIGURE 6**.
- Maximum power operation: To increase the power of the range extender module, the operation points of the combustion engine are shifted towards maximum power, **FIGURE 6**.
- Recuperation of kinetic and potential energy from the driving and working powertrain: As a result of bidirectional power flow in the electric powertrain, excessive energy can be stored in the battery in the form of passive loads, e.g. when slowing down the driving or working power. It is also possible to regenerate energy by making it available directly to another consumer. For example, deceleration energy can be transferred directly to a working function.
- Emergency operation with reduced power: To prevent deep discharge and, hence, damage of the battery, maximum power to be taken from the powertrain is limited when the state of charge of the battery is low.

The operation modes are implemented using a heuristic operation strategy. The share of the range extender module in power consumption is related to the state of charge of the battery module SoC, the maximum power required P_{tot} and the external boundary conditions (zero emission):

Eq. 2

$$u(t) = f(\mathrm{SoC}, P_{\mathrm{tot}}, \mathit{Zero\ Emission})$$

Depending on the state of charge, four operation ranges are defined with variable power flows in the electric powertrain:

- range extender charging mode: u = 1*
- range extender emergency operation: u = 1
- range extender best operation: 0 < u < 1
- battery-electric operation: u = 0.

In the range extender charging mode, the battery of the vehicle is charged up to a threshold value at zero output. In the emergency operation, power is output primarily by the combustion engine and made available to the driving and working systems via the generator. In this way, the vehicle can also be used when the state of charge is very low. To prevent deep discharge of the battery, power consumption for driving and working is reduced to a maximum value below the power supplied by the combustion engine. In this mode, the combustion engine is run at maximum power. In the range extender best operation mode, the combustion engine charges both the battery and the powertrains. This mode occurs rarely, as the power consumed has to be below the power output by the combustion engine at the best operation point. Battery-electric operation is characterised by the use of battery energy only. The range extender module is switched off. Except for the range extender charging mode, recuperation can be performed in all operation modes. To control combustion engine power, various status

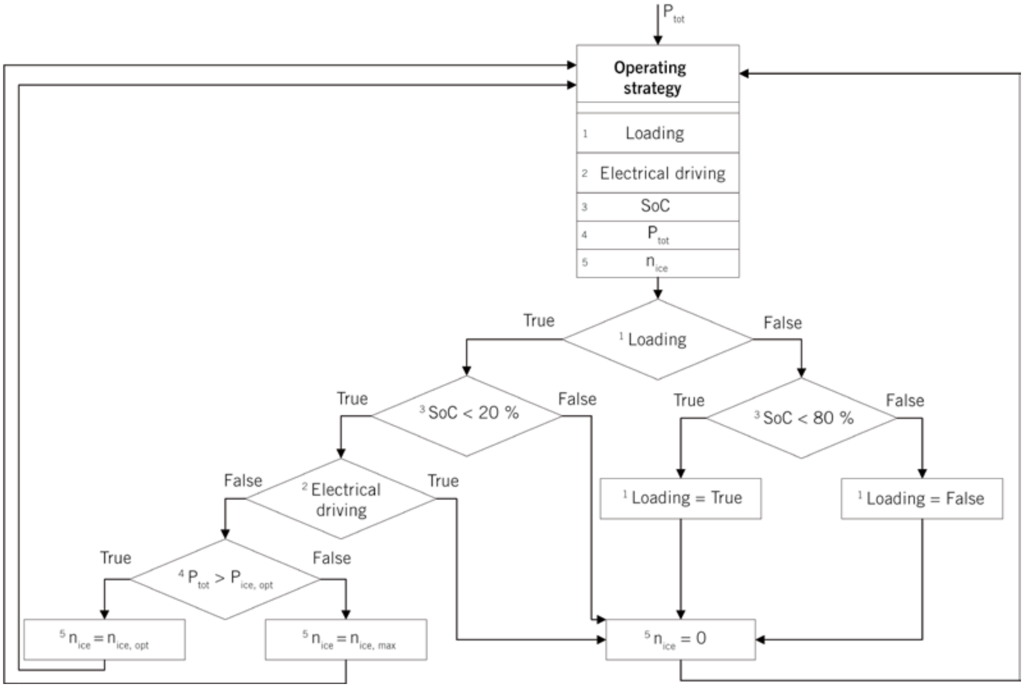


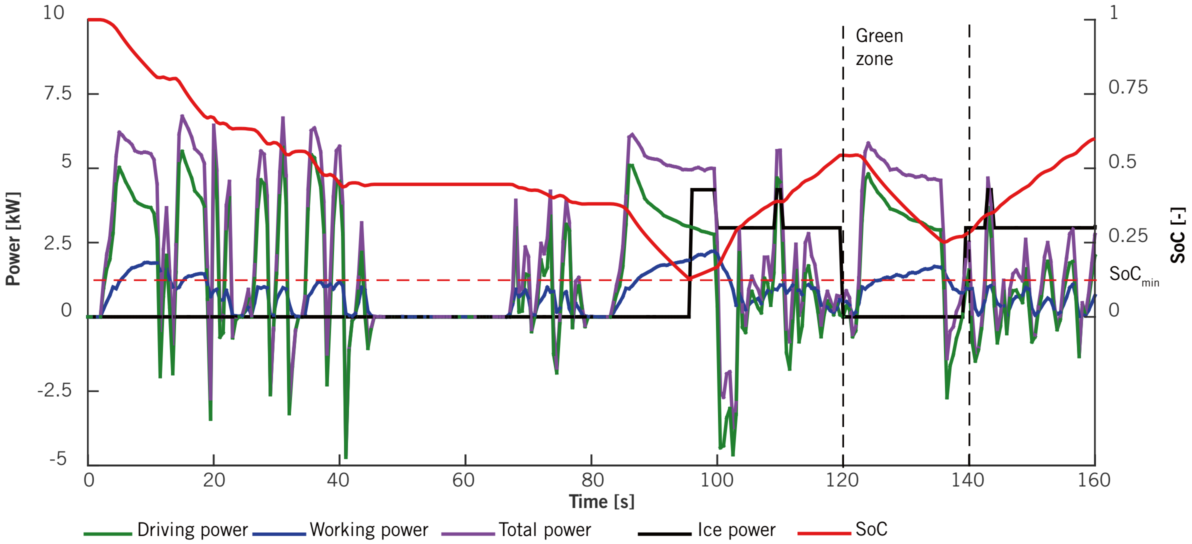
FIGURE 8 Recursive flowchart of state checks for the operating strategy (© KIT)

messages are required. To define the operation strategy, the following input data are needed:
- charging process: loading
- zero emission: electric driving
- state of charge of the battery: SoC
- total power required: P_{tot}
- speed of combustion engine: n_{ice}.

FIGURE 7 shows the status parameters for switching logics. The recursive status data collection process for the operation strategy is shown in **FIGURE 8**. In the beginning, for example when starting the vehicle, the status of the charging process loading is determined. When this status is set, the state of charge of the battery SoC is measured. As long as the maximum threshold value is not exceeded, the combustion engine is set to the active status when activating the zero emission combustion modes. When the total power required exceeds the power of the combustion engine in the optimum mode, speed of the combustion engine is increased to maximum power. When reaching the maximum state of charge of the battery or when activating the purely electric driving function, the internal combustion engine is switched off. This state is kept until all requirements for a renewed charging process are fulfilled. This process is repeated iteratively in the time interval defined $t_{cycle} = 0$ to 10 s. This operation strategy then has to be tested and validated using a test vehicle.

FIGURE 9 Performing a work task on the test bench according to the MOBiL method (© KIT)

FIGURE 10 Power flows from the battery pack and the range extender module based on SoC (© KIT)



SYSTEM APPLICATIONS

The MOBiL method is typically applied to an electric municipal vehicle that is to be equipped with a module for extending the range. Typical applications of such a vehicle are the maintenance of parks and gardens and the transportation of objects and bulk material. To obtain a sufficient database, specific load data are recorded and evaluated in large field tests. Among these data are power flows for driving and working as well as GPS coordinates, driving speeds, and the working task to be performed. Then, the vehicle is integrated into the test bench by coupling of the drive shafts mechanically to the test bench motors. By mathematical comparison of simulation and test results using the least squares method, the mathematical model of the vehicle is parameterised and integrated into the virtual driving environment. Having implemented the MOBiL test environment, any test scenarios can be performed for the working tasks to be fulfilled, **FIGURE 9**.

RESULTS

FIGURE 9 shows a typical case of vehicle operation. The driving cycle represents the cleaning of company grounds. This task includes the cleaning of outdoor areas as well as the cleaning of a hall. Charge control of the vehicle, size of the energy storage system, and the power of the combustion engine are adapted to the application of the vehicle. **FIGURE 10** shows the relationships and interaction of charging modes of the range extender. Based on the working tasks defined and the measured and simulated load data, further test cycles are performed and evaluated to analyse various storage system dimensions and charge levels of batteries to ensure low-defect behaviour. The measurement data collected are evaluated statistically to determine an optimum degree of hybridisation of the vehicle for a mean application. This degree of hybridisation is found to be much higher than typical values in the car sector. This is due to the large power variations of powertrains used for executing a working task.

SUMMARY AND OUTLOOK

By means of the MOBiL method developed, it is possible to make statements on the functionality of components of off-highway machines and their interactions at an early state of the development process already. The real purpose of use of the machine can be implemented easily and effectively in the test bench by using standardised load cycles and field measurements. In this way, powertrain topologies can be defined and operation strategies can be optimised for vehicle application without having to carry out expensive field tests. As a result, the number of iterative development cycles is reduced, development time is shortened, and development costs are minimised. Complex control algorithms can be studied, optimised, and validated for any test scenarios. It is now planned to transfer the MOBiL method to other powertrain topologies. Based on the findings gained, it will then be possible to compare systems depending on the application spectrum.

REFERENCES

[1] VDI Richtlinie 2206: Entwicklungsmethodik für mechatronische Systeme. 2004

[2] Pohlandt, C.; Haag, S.; et al.: Dynamic Text Bench for Electric Drive Systems. In: ATZoffhighway (2014), issue August, p. 72–76

[3] Hoffmann, P.: Hybridfahrzeuge: Ein alternatives Antriebssystem für die Zukunft. Vienna: Springer, 2014

THANKS

Parts of the project are work products of a collaborative project. Supported by the Federal Ministry of Economics and Energy based on a decision by the German Bundestag. The authors are grateful for the support.