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Potentials of Coupled Test Benches

Technological trends, such as electrification and automated driving, result in increasingly complex vehicle development processes. Hereby, distributed development tools can assist in a wide range of applications. In the FVV project “Method Hybrid Testing” (no. 1363) a methodology for a virtual test bench network for hybrid electric drives was developed at the Karlsruhe Institute of Technology accompanied by APL. This allows investigations at system level to be carried out as early as at the component development stage.

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1 MOTIVATION

Hybrid Electric Vehicles (HEVs) are characterized by increased complexity, due to the large number of electronic control units' functions for the drive train consisting of an Internal Combustion Engine (ICE) and an Electrical Machine (EM). This results in a large variety of concepts at both system and component level, which must be validated with appropriate tests. For an efficient development in the design and integration phase virtual product development and integrated toolchains are increasingly being used, such as the methods summarized under the umbrella term X-in-the-loop (XiL) [1]. This also includes engine-in-the-loop (EiL) test benches, in which an ICE is operated together with a simulation of the remaining powertrain, vehicle, driver and environment in order to create test conditions that are as realistic as possible. Three KIT institutes, the Institute of Internal Combustion Engines (IFKM), the Electrotechnical Institute (ETI), and the Institute of Vehicle Systems Technology (FAST), have further developed these procedures with the support of APL by means of a test bench methodology in order to minimize the effort required for the validation of complex systems.

2 FURTHER DEVELOPMENT OF METHODS AND STANDARDS

Common XiL approaches have been expanded in recent years to improve the validity of the results. Previously pure virtual components, such as the EM, are now installed with real hardware on a second test stand and networked with the EiL test bench. This represents an evolution to the co-simulation approach and is referred to as real-time co-simulation. Just as the original co-simulation is supported by standards such as the Functional Mockup Interface (FMI), the Distributed Co-simulation Protocol (DCP) standard was developed as part of the Acosar project to couple hardware [2]. The application of this protocol in this project is intended to create a procedure for networking test benches that is as standardized as possible. This is associated with potential time and cost savings for applications from different areas. A particular focus was on the development of a methodology for implementing virtual coupling. A structured approach allows any number of test beds to be quickly and, above all, safely expanded into a system test bench.

3 REQUIREMENTS AND APPLICATIONS OF NETWORKED VALIDATION

Depending on the structure of the network, the presented methodology can be used in a wide range of applications. **FIGURE 1** schematically shows the temporal shift of individual complete vehicle test cases into the component test phase. The associated time and cost savings can be achieved by networked test rigs. Depending on the test case, various requirements resulting additionally from different boundary conditions have to be fulfilled, such as mechanical, electrical and thermal limits as well as gradients of the test items and test rig technology. Technical properties of drive units such as maximum torque or efficiency maps are determined

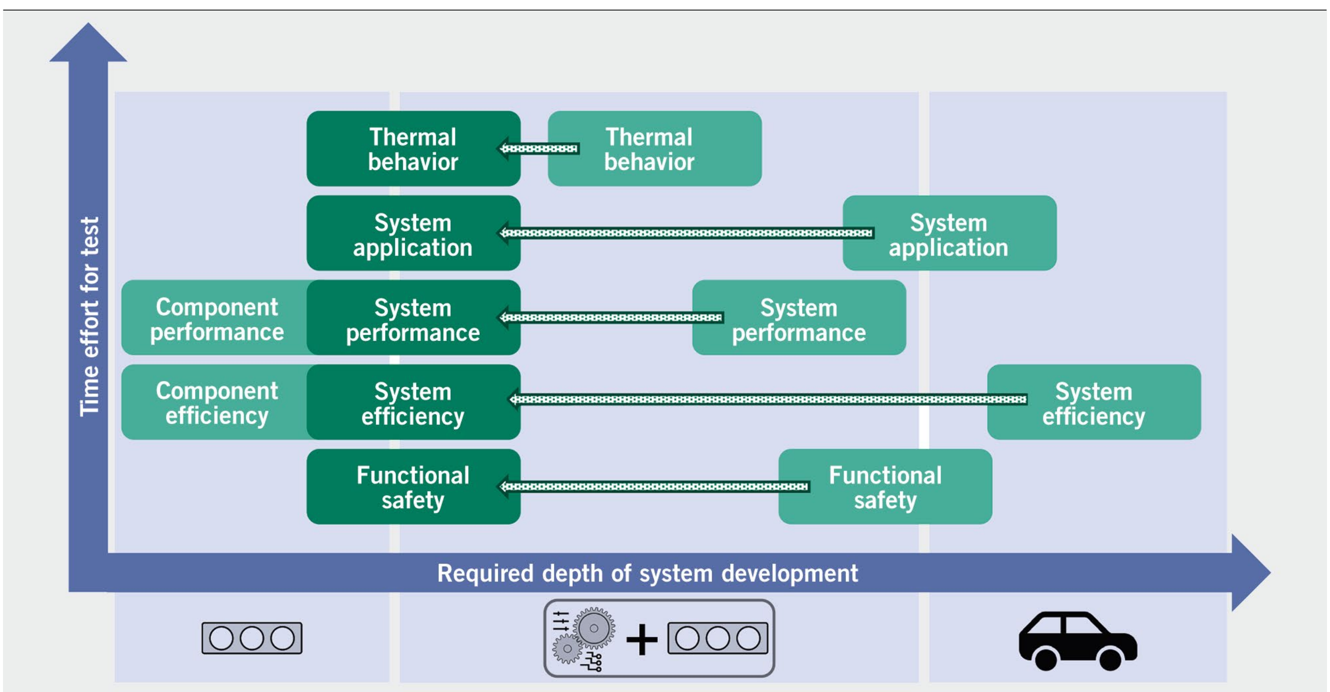

FIGURE 1 Shifting test cases of the complete vehicle test to the component test in order to reduce the time required (© KIT)

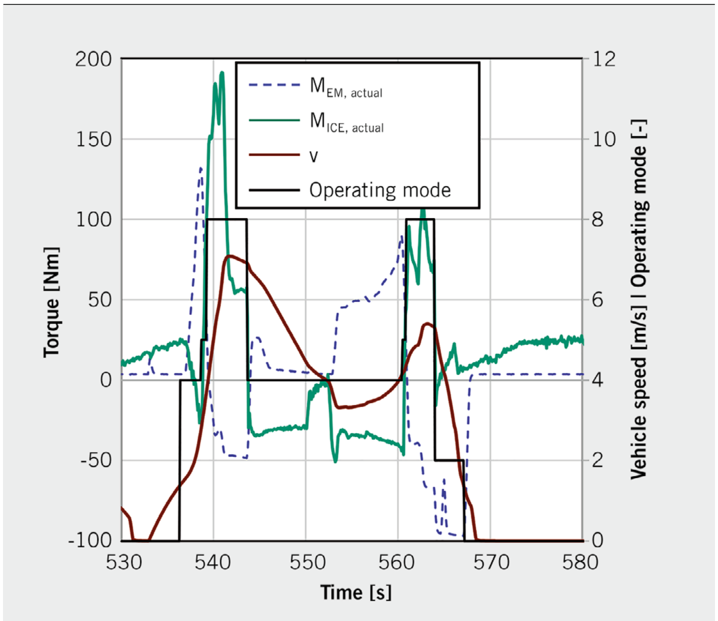

FIGURE 2 Split into VKM and EM torque by changing the operating mode (© KIT)

at temperatures that are as constant as possible. In contrast, the safeguarding of thermal limit cases requires sufficiently dynamic conditioning of the test specimens in order to realistically reproduce the load-related heating and cooling behavior. In addition to appropriately specified conditioning units, temperature models must also be integrated into the test environment. In the case of high dynamic requirements for speed and torque, on the other hand, low latency between the network nodes and fast measurement technology must also be available. If necessary, these can be additionally extended by latency compensation algorithms [3]. Another possibility is the targeted outsourcing of the (partial) models for calculating the dynamic behavior to the corresponding test benches.

The following solutions, among others, were realized in the course of this project to implement the networking setup:
- coupling via the network protocol UDP/IP
- implementation of the DCP standard for simplified commissioning of real-time co-simulation scenarios
- upgrade and integration of suitable conditioning units
- development of functions for torque-controlled operation of the EM, as well as algorithms for different cases of derating
- fast speed/torque measurement for closed-loop operation of the EM within the vehicle simulation coupled via UDP/IP
- creation of a hybrid operation strategy for load sharing and consideration of thermal effects.

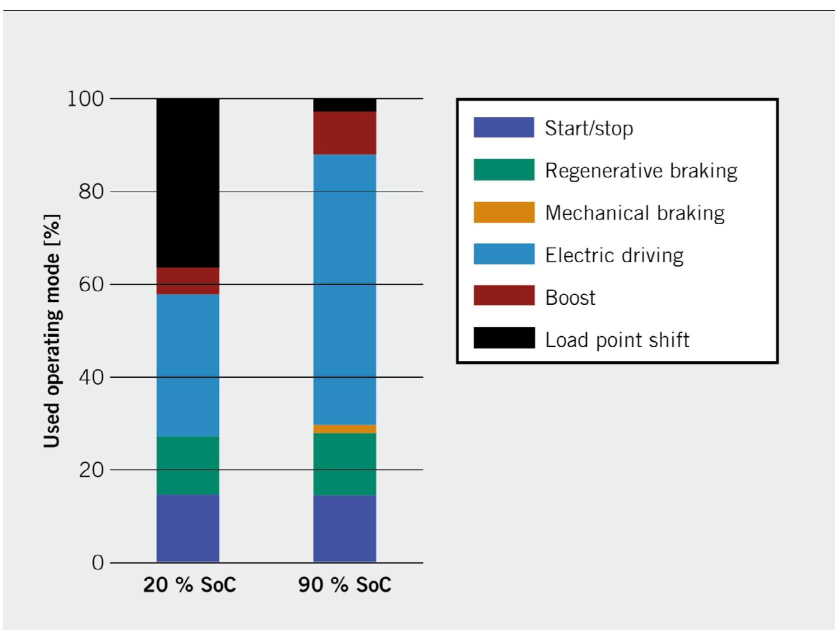

FIGURE 3 Proportions of different operating modes in the WLTC at 20 and 90 % SoC at the beginning of the cycle (© KIT)

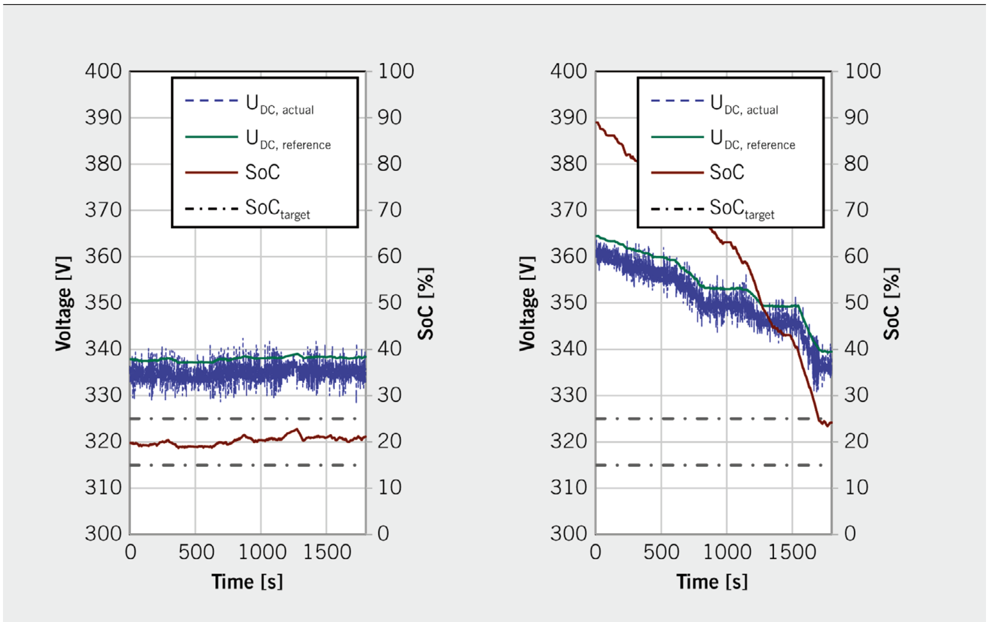

FIGURE 4 DC link voltage and SoC of the battery as a function of the start SoC and the operating mode in CS mode (left) and in CD mode (right) (© KIT)

Further information on the test rig and networking setup was described in [4]. In standardized test cycles, such as the Worldwide harmonized Light-duty vehicles Test Cycle (WLTC), as well as mountain trips with high load requirements, it was thus possible to investigate several of the test cases shown in **FIGURE 1**.

4 CONSIDERED TEST CASES AND RESULTS

In addition to the thermal behavior presented in [4] the topics of system application, efficiency and performance were also considered. In the following, various results with a function-oriented operating strategy are presented as examples, which were summarized under the term system application.

In **FIGURE 2**, the speed(v)- and load-dependent distribution of ICE and EM torque ($M_{ICE, actual}$ and $M_{EM, actual}$) can be seen as a function of the situationally active operating mode. After acceleration from standstill, the vehicle changes from mode "0" (stop) to mode "4" to start up electrically. Shortly afterwards, the ICE is switched on and supported by the EM, mode "5" (boost). The vehicle then switches to mode "8" (load point shift) which is manifested by the negative EM torque of approximately -50 Nm at times and an increased positive ICE torque. During the subsequent braking process, the system switches exemplary back to the electric driving mode. Due to the drag losses incurred by the undisconnected ICE, the EM must provide a positive momentum. If the test bench environment permits decoupling of the ICE from the rest of the drivetrain, regenerative braking (mode "2") can also be used. In the shown case, however, the drag losses caused by the ICE must be compensated by the EM. Regenerative braking is implemented at stronger decelerations, as from approximately second 570.

In **FIGURE 3**, the percentages of the individual operating modes are plotted for two WLTC measurements. Here, the effect of different start values of the battery State of Charge (SoC) is examined, at 20 and 90 %, respectively. While start/stop phases occur with almost the same frequency, a significantly higher proportion of purely electric driving is seen at 90 % start SoC. In contrast, the virtual vehicle is frequently operated in the load point shift modus for WLTC with a lower start SoC. It is also noticeable that at a high start SoC, mechanical braking is also used in some cases instead of regenerative braking. This is due to the fact that regenerative braking was only permitted below a SoC of 85 % in the selected parameterization of the hybrid controller.

For certification-relevant WLTC tests for HEVs, several measurements must be performed. This includes tests in which the vehicle is driven from 100 % SoC in purely electric mode to the lower state of charge limit (Charge-depleting mode, CD). In addition, tests are performed with an empty battery in which the state of charge must be maintained (Charge-sustaining mode, CS) in a target area (SoC_{target}) shown in **FIGURE 4**. In addition to the steady discharge in CD mode (right) and the maintenance of the specified SoC range in CS mode (left), the DC link voltage of the EM is shown. Here, the measured, set value ($U_{DC, actual}$, dashed blue) follows the default value follows the default value ($U_{DC, reference}$, green), which is transmitted via the test bench network from the EiL test bench to the EM test bench. At this point, it should be noted that, depending on the initial situation of the existing control software of the EM, certain functional scopes must be supplemented for coupled operation in the overall system:

- A tracking of the DC link voltage must be considered when calculating the current setpoints for a desired torque.
- Software functions for the field weakening range must be implemented for operation of the EM in high speed ranges.
- To protect the EM from thermal overload, an appropriate power derating must be implemented, if operating ranges in the overload are required.

The functionalities mentioned lead to a reduction of the maximum possible torque according to the operating state, which must be taken into account in the hybrid controller.

In addition to the thermal derating shown in [4], functions for component protection of the EM also include derating as a function of EM speed ($n_{EM, actual}$). An example of the reduction of the maximum permissible torque ($M_{EM, maximum}$) is shown as a function

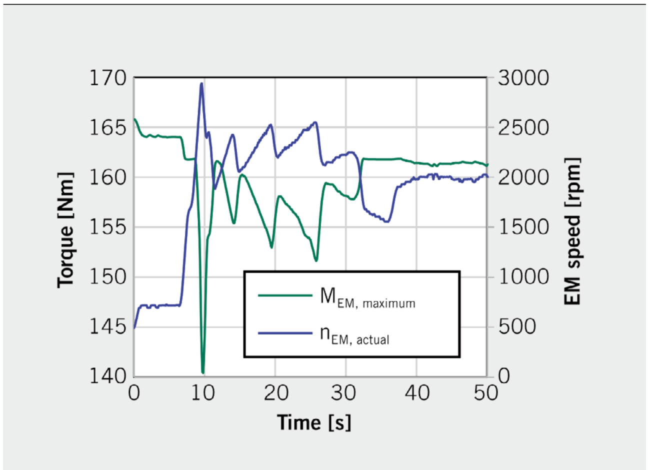

FIGURE 5 EM derating as a function of speed-dependent criteria (© KIT)

of the EM speed in **FIGURE 5**. Hereby, a reduction of $M_{EM,\ maximum}$ from approximately 2200 rpm by approximately 20 Nm can be seen. Gear changes in the transmission reduce the speed requirement and increase the value of the maximum torque again.

5 CONCLUSION

In this article, it was shown how two test stands can be networked and which exemplary measurements can be carried out. Reference was made to the growing importance of real-time co-simulation. Worth mentioning here is in particular the standardization of suitable protocols for these use cases, which are supported by a further development of the functions of the FMI towards the DCP. Depending on the test case, the setup of a networked validation environment requires different adaptations of test bench hardware and software, which were outlined as examples for this project. On the basis of different results, it was explained how the presented development environment can be used for system application. In particular, the validation of different control algorithms in the overall system context can be performed with it.

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