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Building a Highly Dynamic, High Power Test Bench for Electric Powertrains

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Summary

As the automotive industries' focus is shifting towards the development of BEVs (battery electric vehicles), the requirements for powertrain testing and powertrain testing methods have also changed considerably. Differences in powertrain behaviour like high rotational engine speeds, available torque output or harmonic distortions in the power electronics, but also new powertrain concepts like wheel hub drives create new requirements towards components and testing methods. In order to fulfill these requirements, a multitude of challenges have to be overcome and new test benches, dedicated to electric powertrains, have to be built.

Keywords: hardware-in-the-loop (HiL), testing processes, transmission, powertrain, research

1 Introduction

The HEP (High-Power Electric Propulsion Lab) is a single axle, three machine powertrain test bench for EV (electric vehicle) powertrains, which supports a multitude of different drivetrain/powertrain geometries and test setups. Using the wide knowledge base acquired during the construction, commissioning and over 10 years of productive operation of the MKP (Multi Configuration Motor Test Bench), the FKFS (Research Institute for Automotive Engineering and Vehicle Engines) is building the HEP as general contractor. The MKP is a two-axle, five machine powertrain test bench for ICE (internal combustion engine) and HEV (hybrid electric vehicle) powertrains mainly used for providing testing of powertrains/drivetrains and/or powertrain components to original equipment manufacturers (OEMs). Also, multiple researchers have successfully written or still are writing their PhD thesis on subjects surrounding the MKP and powertrain testing.

Fig. 1 shows the test bench's three machines – one input machine and two wheel machines – fastened to the HEP's clamping plate on their bases. The auxiliary measurement system consisting of measurement equipment in a pivotable case connected to a swivel arm can also be seen in the picture, as well as the underslung crane and the switching cabinet (located on the wall in the back) used for selecting the vehicle energy system's (VES) active outputs. The testing room's walls are fitted with soundproofing cladding to keep the noise level in the neighboring test bench control room down to an acceptable and safe range.

Figure1: The HEP test room

1.1 Requirements for electric powertrain test benches

In this Chapter, the main physical requirements regarding planning and design of the HEP will be explained. Some components of test benches for ICE or HEV powertrains like fueling systems and combustion air conditioning are not needed in test benches dedicated to electric powertrains. The cooling system can also be less sophisticated due to the greater efficiency of electric powertrains.

1.1.1 Dynamics

Since the rotors of the commonly used synchronous- and asynchronous electric motors have a smaller moment of inertia than ICEs of similar power, higher speeds as well as higher speed gradients can be achieved. This has to be accounted for by using a high-speed, highly dynamic input machine. To make use of such a machine, an inverter with a high switching frequency and a real-time control system with low latencies and a high update rate is also required.

1.1.2 Energy input

The power electronics and the electric motor of the Device Under Test (DUT) have to be supplied with energy in a variety of the possible test configurations. This means that the feed-in capacity of a test bench for electric powertrains has to be significantly larger than the one of a test bench for ICE or HEV powertrains of comparable power. The difference can be several hundreds of kW, depending on the planned application of the test bench. Also, the commonly used lithium-ion battery, has a great influence on the characteristics of an electric powertrain. In order to reflect this influence, a powerful, highly dynamic DC source, capable of HiL simulation of battery models is needed.

1.1.3 Mechanical frequencies

The most prominent mechanical frequencies which occur during the operation of combustion driven powertrains typically lie between 10 Hz (correlating to 600 1/min) and 150 Hz (correlating to 9,000 1/min). The mechanical frequencies which occur during the operation of electric powertrains on the other hand lie in a wider band, spanning from < 1 Hz to > 300 Hz (correlates to 18,000 1/min). As a result, these powertrains and the vehicles they are used in are designed in a way that their resonant frequencies don't get excited at any time during normal operation. Test benches have to reflect these design choices to ensure a safe operation at any bias point [1].

A way of avoiding the excitation of resonant frequencies of an electrical machine is applying band-rejection filters to the respective 4 kHz torque command signal. In order to do this, the machine's resonant frequencies need to be determined first. This can be done by hitting the rotor of the machine's torque sensor with a rubber hammer, resulting in an excitation over a wide range of frequencies, similar to the Dirac delta function. After each hit, the system will continue to oscillate with its resonant frequency. To avoid aliasing in the 4 kHz measurement, a lowpass filter with a cutoff frequency of 2 kHz is used on the torque sensor's signal.

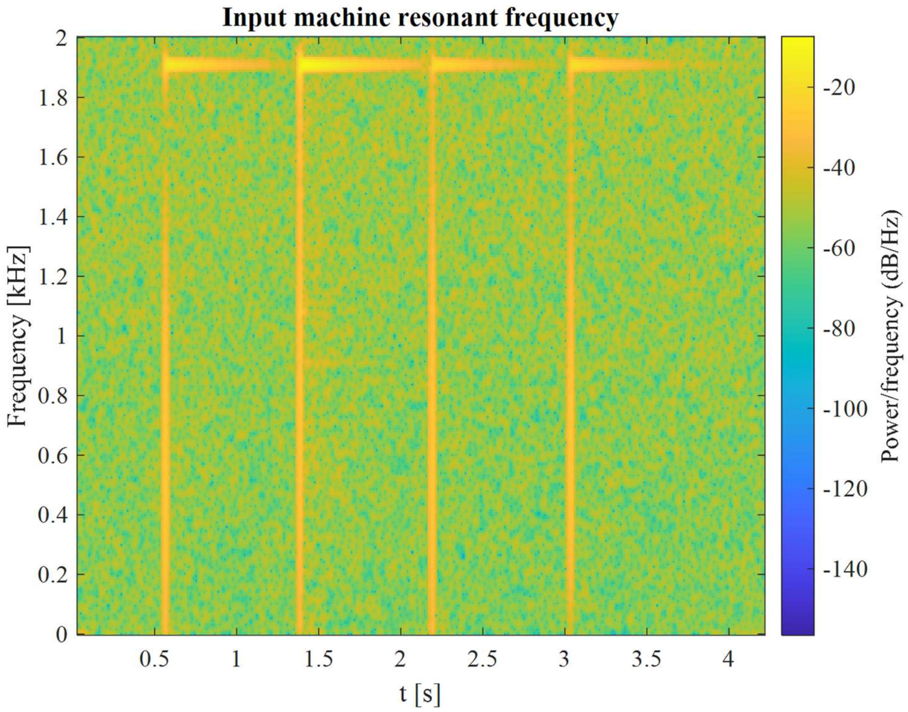

Figure2: Spectogram of the Input machine's torque sensor signal

Fig.2 contains an estimate of the short-term, time-localized frequency content of the input machine's torque sensor's signal, also called spectrogram [2]. The rubber hammer hits are represented by the four vertical lines and the system's resonant frequency can be seen as horizontal lines after each hit. In case of the input machine, the resonant frequency is 1.92 kHz.

2 Test bench components

2.1 Clamping Plate

Since the whole weight of the DUT and the test benches equipment has to be secured to a clamping plate during operation, it is an important component of a test bench. The clamping plate of the HEP is 3.5 m wide and 5.8 m long and has a weight of 22.4 tons. T-slot grooves as defined in DIN 650 – 22H12 [3] are milled into the clamping plate 250 mm apart from each other to ensure a compatibility with a variety of differently sized groove stones. Another important property of a clamping plate are its resonant frequencies, of which there ideally should be as few harmonics as possible, ideally at high frequencies.

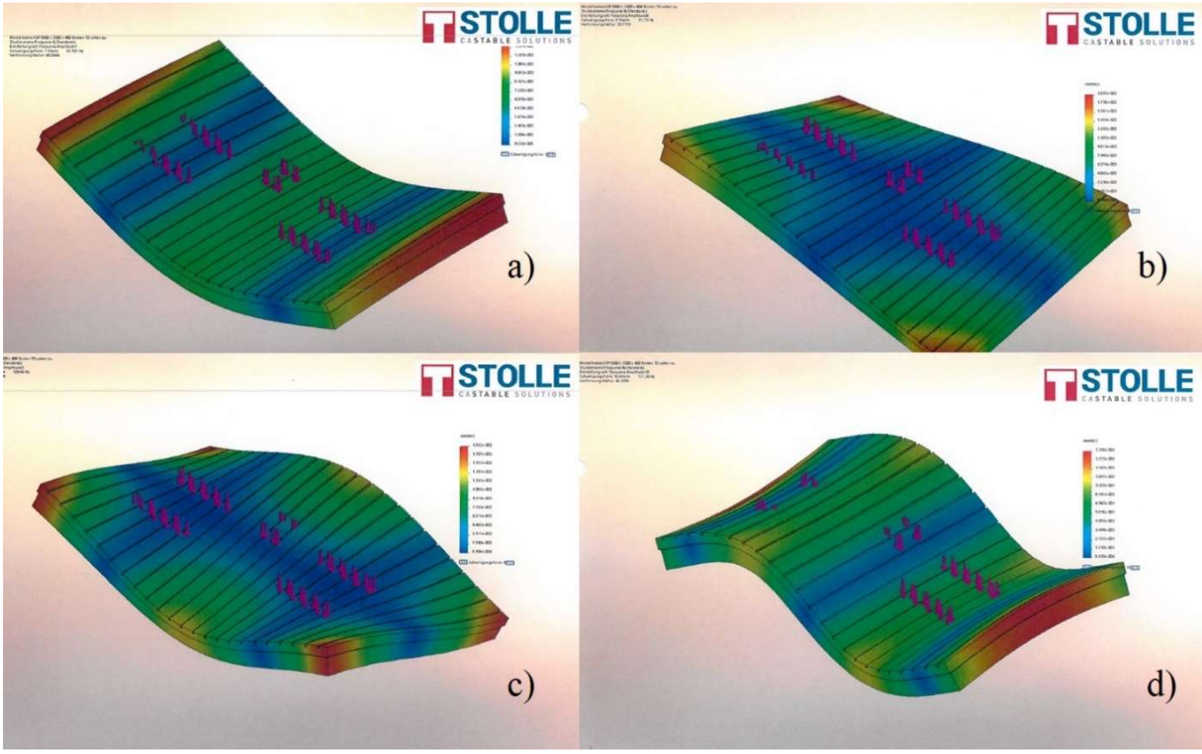

Figure3: The clamping plate's first four resonant frequencies

Fig.3 shows the results of a simulation of the clamping plate's first four resonant frequencies in the order a) to d). The deformation during the oscillation is greatly exaggerated in order to visualize the results.

Table1: First-order resonant frequencies of the clamping plate

Fundamental	Frequency (Hz)
First	51.71
Second	51.79
Third	109.46
Fourth	127.26
Fifth	141.01
Sixth	164.4

Tab.1 lists all the first order resonant frequencies of the clamping plate below 333 Hz, which is the highest fundamental mechanical frequency any of the test bench's machines can excite. Since designing an inherently stiff clamping plate for frequencies below 333 Hz is impractical, the focus has to lie on keeping the number of resonant frequencies in the relevant band as low as possible.

2.2 Machines

Both the input and the wheel machines are able to provide a high torque over a wide range of speeds. Simulating an ICE with torque ripple is not needed on this test bench. However, the electric machines are able to easily emulate other electric machines with lower speed-torque characteristics, which in case of transmission testing leads to a very good approximation of the real-world use case of the DUT.

The input machine is a permanent-magnet synchronous motor (PMSM) capable of a maximum speed of 20,000 1/min and a maximum speed gradient of 62,000 1/min/s. It can produce 900 Nm of torque and deliver a power of 700 kW in S8 operation (as defined by IEC 60034-1 [4]) every 600 s for a 10 s period with a recovery load of 90 % nominal load. During S1 operation (continuous running duty as defined by IEC 60034-1 [4]), the machine is rated at 700 Nm of torque and 432.5 kW of power.

Since the centre of the input machines rotor is only 160 mm from the ground, a base is needed to be able to support the widest range of drivetrain geometries as possible. However, this base needs to be very rigid in order to not compromise the machine’s capabilities by lowering the systems fundamental and/or harmonic frequencies. Due to that, the input machine’s base is not able to be adjusted in vertical or horizontal direction.

To verify the input machine’s design capabilities, a reversing load of $\pm T_{\max}(n)$ was applied at a range of strategically selected speeds of rotation. Reversing loads are a way to generate high motoric and generative loads without using a DUT by bracing the machine against the rotational mass of its rotor.

To verify the measurements, the air gap torque needed to accelerate and decelerate the input machine’s rotor with the measured speed gradient is calculated. In accordance with the following formula, T_{AirGap} is the air gap torque, I_{rotor} is the moment of inertia of the input machine’s rotor (obtained from its data sheet) and ω is the measured angular velocity of the rotor:

$$T_{AirGap} = I_{rotor} * \frac{d\omega}{dt} \quad (1)$$

Multiplying (1) with ω yields the mechanical power P_{mech} input into the system:

$$P_{mech} = T_{AirGap} * \omega = I_{rotor} * \omega * \frac{d\omega}{dt} \quad (2)$$

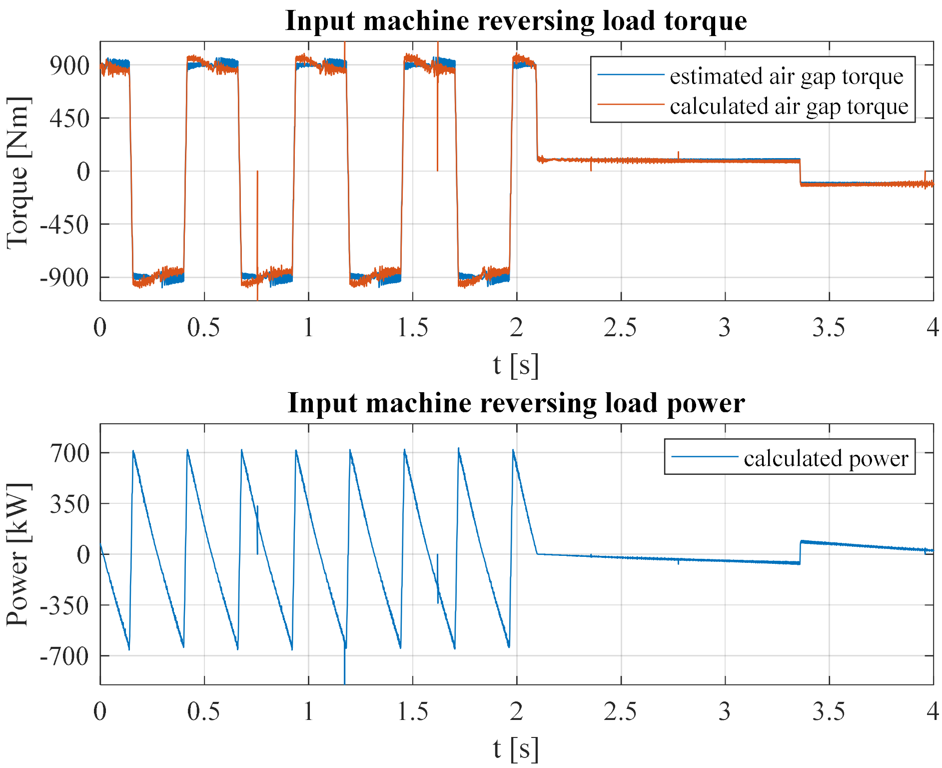

Figure4: Input machine reversing load

The estimated air gap torque T_{AirGap} from the inverter as well as the calculated air gap torque $T_{\mathrm{AirGap,calc}}$ can be seen in the top plot of Fig.4. In the lower plot, the calculated mechanical Power P_{mech} is shown.

The two wheel machines (also PMSM) are capable of a maximum speed of 3,000 1/min and a maximum speed gradient of 37,000 1/min/s. They can produce 6000 Nm of torque and deliver a power of 722 kW in S8 operation every 600 s for a 10 s period with a recovery load of 90 % nominal load. During duty type S1, the machine is rated at 3,500 Nm of torque and 421.5 kW of power.

Since the input machine's base is not adjustable due to the aforementioned reason, it is an essential compromise for the wheel machines to have vertically and horizontally adjustable bases. This way, the alignment of the machines and the DUTs flanges can be finely adjusted. However, applying a reversing load of T_{max} to the wheel machines on their bases causes their swing speeds to exceed the manufacturer's recommended maximum due to the lowered rigidity and leverage provided by the adjustable bases. Taking the machines from their bases and strapping them directly to the clamping plate eliminated this behaviour.

The procedure of verifying the two wheel machines' design capabilities was to brace them against each other using a driveshaft connecting both machines' torque sensor flanges via an adapter flange. This way, one machine's mode of operation is motoric, outputting positive torque, while the other machine operates in generative mode, producing negative torque.

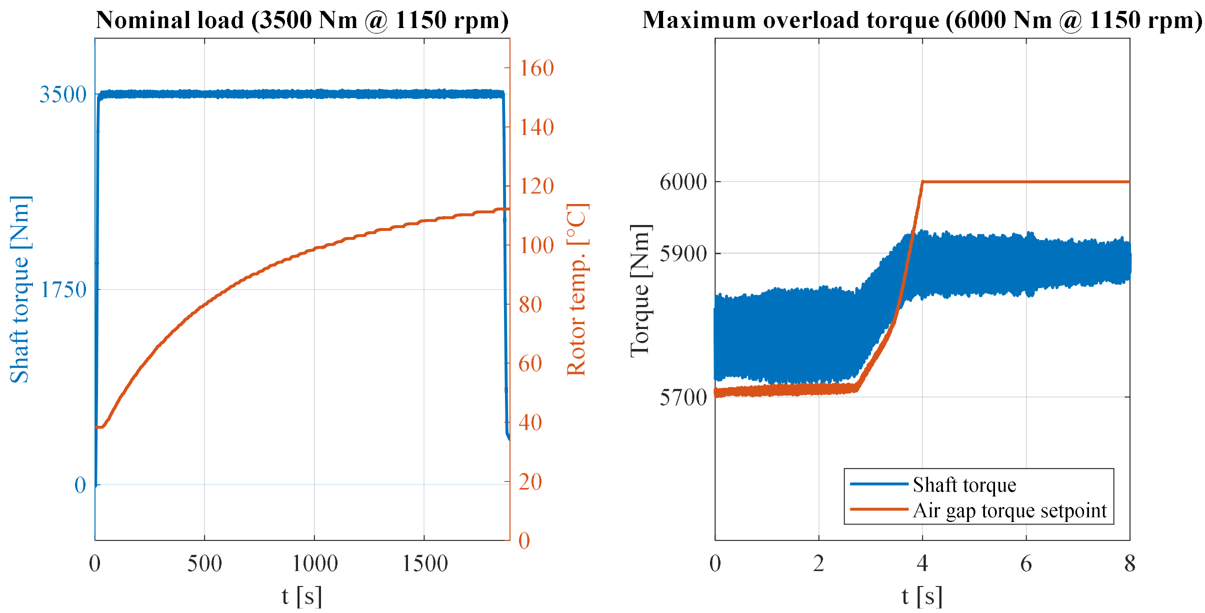

Figure5: Wheel machine nominal load and maximum overload torque

The left part of Fig.5 shows the shaft torque and rotor temperature during a 30 minute stress test at nominal load. The manufacturer's recommended maximum cut off temperature for the rotor temperature is 160 °C and while the rotor hasn't reached thermal equilibrium yet, it is unlikely that its temperature will exceed that value. In the right of Fig.5, the maximum overload torque of one of the wheel machines is shown. The air gap torque setpoint is raised to 6,000 Nm at 4 seconds. Due to core losses and losses in the air gap, the shaft torque reaches a maximum of around 5,900 Nm, which corresponds to 98.3 % of 6,000 Nm.

2.3 Inverter

The three-phase Inverter for each test bench machine consists of three half bridge circuits. IGBTs with a switching frequency of 12 kHz are used as switching elements. Field oriented control (FOC) is used in junction with sinusoidal pulse width modulation (SPWM) to drive the test bench machines. The maximum frequency of sine waves generated by SPWM is around 1/10th of the used switching frequency in state of the art applications, allowing for a theoretical maximum speed of 24,000 rpm, assuming a machine with three pole pairs. This underlines the importance of high switching frequencies in electric powertrain test benches. The inverters share an intermediate circuit operating at a voltage of 780 V and are controlled by a real-time control system via the EtherCAT protocol with a 4 kHz update frequency, fulfilling the requirements defined in 1.1.1.

2.4 Vehicle Energy System (VES)

The VES consists of four resonant converters and two step-down converters (called DCUs), which can be used separately or in parallel for a higher current delivery. DC voltages of up to 1 kV and currents of up to 1,600 A using both DCUs in parallel can be output for 30 s in S8 operation, allowing a maximum power delivery of 1.16 MW. There is no fixed cooldown period, a thermal model governs the use of the S8 duty type. S1 operation is limited to 500 kW for each DCU. The VES is capable of four quadrant operation and of running complex battery models as a HiL-System, which is a requirement for test runs including regenerative braking. To test the dynamic response, residual ripple, control quality and cooling system of the VES, an ohmic loadbank was used.

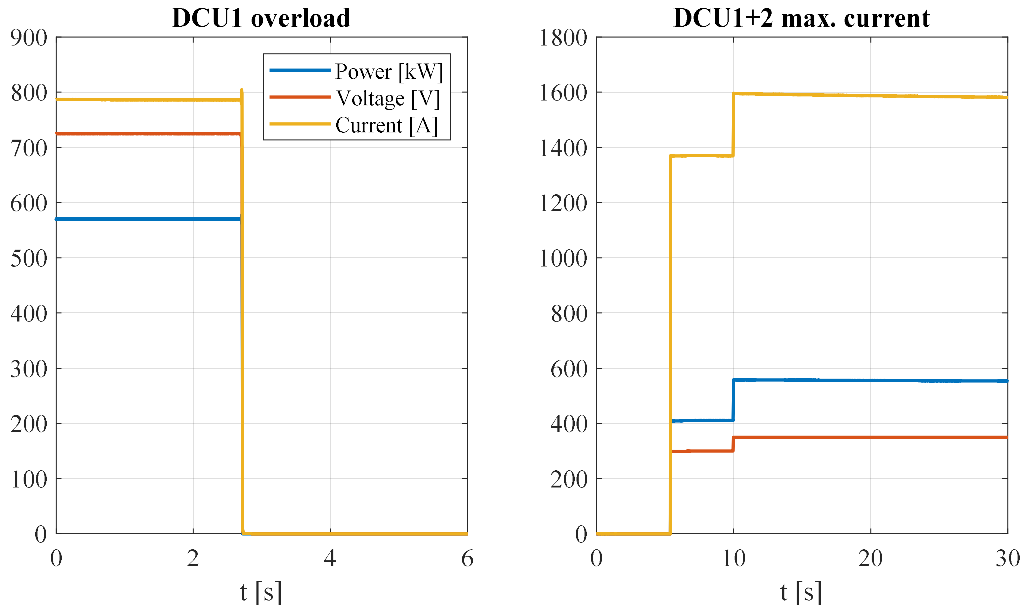

Figure6: Single DCU S8 operation and maximum current in parallel operation

Fig.6 (left) shows a measurement near the maximum possible power output of a single DCU in S8 operation. For this measurement, the loadbank's resistance was set 0.92 Ohm and the DCU was set to 725 V, resulting in a current of 786 A and a power output of 570 kW. Fig.6 (right) shows a measurement of the maximum current possible using DCU1 and DCU2 in parallel. For this measurement, the loadbank's resistance was set 0.22 Ohm and the DCU was set to 350 V, resulting in a current of 1,600 A and a power output of 560 kW. A drop in output current can be seen from 10 s onward. This is due to the rising temperature in the loadbank, resulting in an increased resistance and thus a lower current at the same, constant voltage.

2.5 Safety Control System

Using dedicated safety-related control hardware, the test bench reaches performance level d (PL d), which is the second highest obtainable safety standard regarding machinery control systems as defined is EN ISO 13849-1 [5].

2.6 Automation System

The Automation System consists of four real-time QNX-systems controlling the test bench equipment and taking measurements, and one Windows system, which is used to visualize measurement parameters and provide a GUI to operate the test bench.

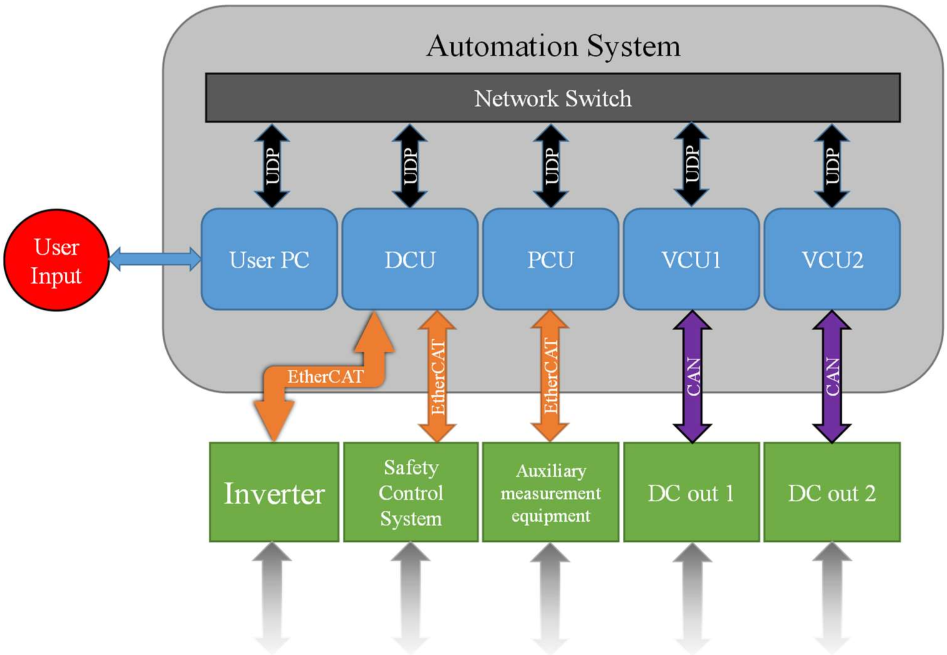

Figure7: The Automation System and its I/Os

Fig.7 shows a schematic of the Automation System including its I/Os. The dynamic control unit (DCU) operates at a 4 kHz system interrupt frequency and handles communication with the inverter and the safety control system via the EtherCAT protocol. The test bench machines' rotary encoder signals and data from the torque sensors are captured on the DCU as well. It is also used to run a Matlab Simulink vehicle model and road load simulation (RLS). The process control unit (PCU) operates at a 1 kHz system interrupt frequency and handles communication with the test benches auxiliary measurement equipment via the EtherCAT protocol as well as the calculation of the respective control variables in the available test bench control modes which will be explained in chapter 3.

The two VES control units (VCU1 and VCU2) also operate at a 1 kHz system interrupt frequency and handle the communication and control variables of the individual VES DC outputs.

3 Test case configurations [6]

The Test bench's test case configurations are handled in the Automation System. Depending on the test case, a different application with different available control modes is used.

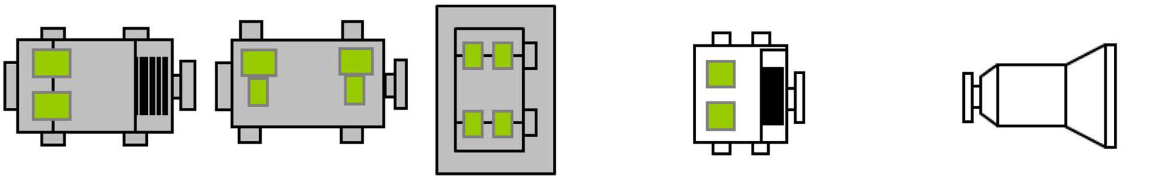

Figure2: Test bench components

Fig.2 shows the test bench components in order to visualize some of the many different possible test case configurations.

3.1 Electric machine testing

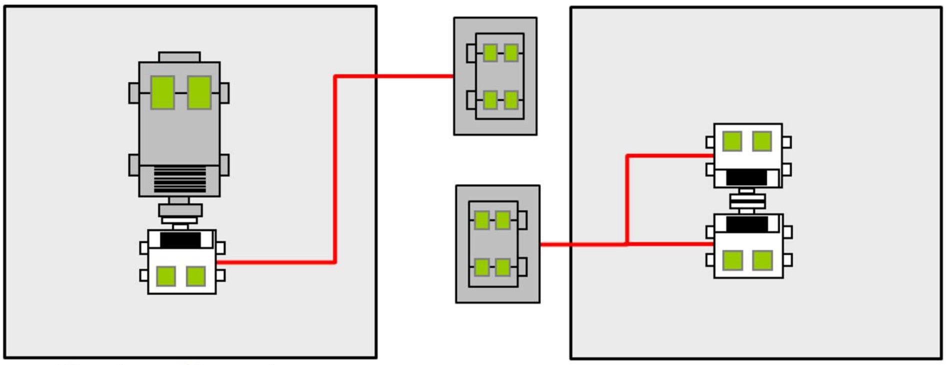

Figure3: Electric machine testing

Electric machines can be tested against the input machine as seen on the left side of Fig.3, or two identical DUTs can be tested in back-to-back configuration.

Table2: Available control modes for electric machine testing

Control mode	A-side	B-side
T/n	Torque	Speed
n/T	Speed	Torque
n/off	Speed	-
off/n	-	Speed

Table2 contains a list of the available control modes for electric machine testing. Step execution tables are available as a tool to automate test cases. Depending on the DUT and control mode, the automation system feeds values into a bus simulation supplied by the DUTs manufacturer on the B-Side. Measurement variables serving as inputs can also be taken either from the bus simulation or auxiliary measurement systems.

3.2 Drivetrain testing

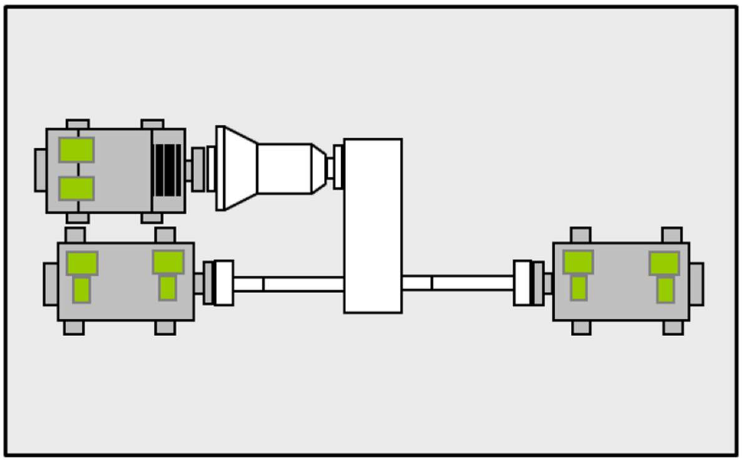

Figure4: Drivetrain testing

All of the HEPs three machines are used in drivetrain testing as shown in Fig.4.

Table3: Available control modes for drivetrain testing

Control mode	A-Side	B-side
T/n	Torque	Speed
nT/off	Speed + Torque	-
n/T	Speed	Torque
off/Tn	-	Torque + Speed
n/n	Speed	Speed
v/RLS	Velocity	RLS
alpha[1]/RLS	alpha	RLS
alpha/n	alpha	Speed
T/RLS	Torque	RLS
n/RLS	Speed	RLS

Table3 contains a list of the available control modes for drivetrain testing. The RLS control mode uses a proprietary 4 kHz simulation which allows simulating a curvature via a speed difference in the wheel machines or defining a slope among other things on the stationary test bench. Setting a value for alpha triggers the automation system to feed that value into a user-defined engine map where the torque for the respective operating point is retrieved from. Step execution tables are available as a tool to automate test cases.

[1] alpha: accelerator pedal angle

3.3 Powertrain Testing

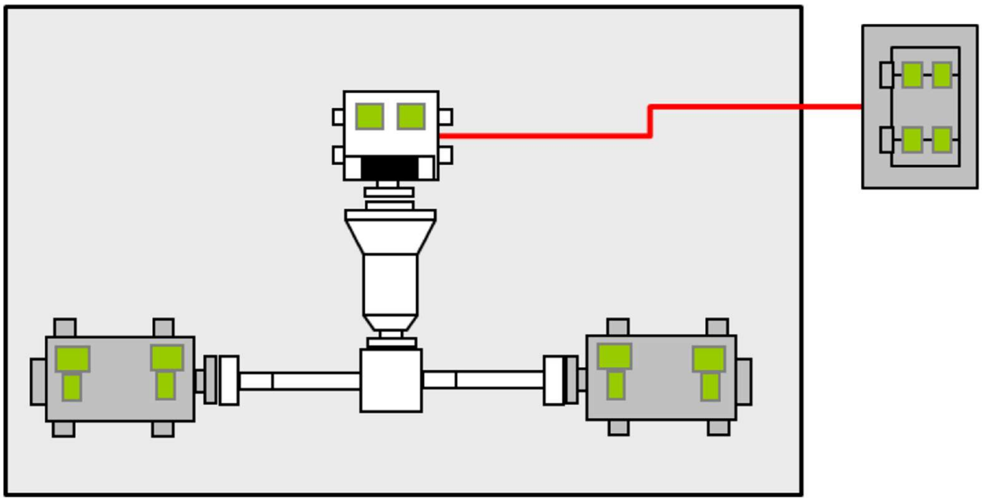

Figure5: Full powertrain testing

A possible setup of full powertrain testing is shown in Fig.5. In contrast to electric machine testing, the VES is used to power the DUT in an otherwise comparable setup with the same available control modes as in the test case of drivetrain testing. Setting a value for alpha triggers the automation system to feed that value into the bus simulation. I/O with the bus simulation is handled in the same way as in the test case configuration of electric machine testing.

4 Conclusion

As the commissioning of the HEP is reaching its final stages and the test bench is becoming ready to run the first commercial project, it becomes more and more clear that the newly imposed challenges of EV powertrain testing are to be taken seriously. The capabilities of each test bench component had to be verified individually to create reference points for future troubleshooting. This time consuming process required large amounts of fine tuning and creative thinking but rightfully so, as far reaching changes to the test bench software, hardware and configuration during productive operation are almost always impossible and irresponsible to the OEM the testing service is provided to.

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