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Full MCS – Road to 3000 A Charging in Battery Electric Trucks

Steffen Büttner[1], Fabian Schweizer[2], Maximilian Schuckert[3],
Prof. Malte Jaensch[3]

[1]*Technical University of Munich, 80992 München, steffen.buettner@tum.de*

[2]*MAN Truck&Bus SE, 80995 München*

[3]*Technical University of Munich, 80992 München*

Executive Summary

As part of the NEFTON Research Project funded by the German BMWK, the technical feasibility of MCS charging at up to 3000 A for long-haul heavy-duty Battery Electric Trucks (BETs) is being investigated. Experimental results from testing the prototype 3000 A capable on-board HV system developed by MAN Truck & Bus SE are presented and compared to already published data. Finally, possible use cases and estimations of charging system efficiency for different current levels are discussed with the help of a vehicle simulation model.

Keywords: Electric Vehicles, Heavy Duty electric Vehicles & Buses, Packaging, Cooling & Heat Transfer, Modelling & Simulation, Thermal Management

1 Introduction & Motivation

In Germany, more than 70% of goods are transported by road, while the total transport volume is projected to increase further in the coming years. At 148 million tons $CO2_{eq}$, the German transport sector is responsible for approximately 20% of total greenhouse gas emissions in the country. Heavy-duty commercial vehicles above 12 metric tons emit 28% of transport-related emissions [1]. To achieve the European Union's transport emission reduction goals, it is imperative that CO2-neutral heavy-duty vehicles such as Battery Electric Trucks (BET) are rolled out urgently.

1.1 Battery Electric long-haul trucks

With current Li-Ion battery technology, rapid recharging during the driver's mandatory 45-minute rest period offers the best option for achieving operational parity in terms of daily range and payload capacity with Diesel trucks [1]. The milestone of charging a BET at 1 MW has already been demonstrated in a first public demo at the NEFTON Event on July 19, 2024 [2], but even higher charging power could enable greater operational flexibility. Therefore, one goal of the NEFTON consortium is designing and testing a BET HV distribution / charging system capable of 3000 A charging on the test bench. To date, a 3000 A BET HV distribution system has been designed by MAN Truck & Bus SE and the first testing phase at the Institute of Sustainable Mobile Powertrains at TU Munich, investigating the prototype's thermal performance at low voltages but representative current levels, has been completed. This work gives an overview of the results and compares them to previously published MCS testing results, most notably from the NREL laboratory [3].

1.2 Use Cases for above 1 MW Charging

To put the experimental results in a broader context, a simplified vehicle driving and charging simulation model has been built in MATLAB/Simscape. The vehicle is a long-haul BET, with parameters shown in Table 1. The

Table 1: BET Driving and Charging Simulation Model Parameters.

Parameter	Value	Unit
Vehicle Class	Tractor (EU) HDV Group 5	-
Tractor Curb Mass	9853	kg
Trailer empty Mass	7400 [4]	kg
Payload	13840 [5]	kg
Drag Area ($A \times C_d$)	5.68 [6]	m^2
Drivetrain Type	4x2 Central Drive	-
Gearbox	2-speed AMT	-
Electric Motor Rated Power	400	kW
Battery Configuration	203S 6P 6M	-
Cell Type	Tesla 4680 (cylindrical)	-
Pack Energy Content	605	kWh

modelled vehicle is a tractor trailer combination which falls under the European Heavy Duty Vehicle Group 5. The battery pack, the central component of the drivetrain, has been modelled as a lumped thermal mass without spacial heat transfer processes. The electrical model uses a lookup table-based Simscape Battery block, only taking into account the cell resistances themselves and omitting connectors and busbars. An automotive 4680 cylindrical cell from a Tesla Model Y with NMC 811 cathode with parameters published in [7] is used to model a truck battery back with a nominal voltage of 750 V in line with current *800 V* systems. Parameters for drag area C_d, trailer mass and average long-haul payload are taken from publications by the ICCT [4], [6] and the European Commission [5]. An estimation of the mass of a battery electric tractor without its battery of 5850 kg [4] has been combined with an estimated battery pack mass calculated from the 4680 cell's specific gravimetric energy of 232.5 Wh/kg and a gravimetric cell-to-pack ratio of 0.65 [4]. The 2-speed automated manual transmission is taken from the generic E2 architecture BET supplied with the VECTO Tool, the single 400 kW electric motor has been scaled up from an included 125 kW PSM machine, with torque, loss maps and inertia scaled up from the included 125 kW example by a factor of 3.2 [8]. Fig. 1 shows the VECTO long-haul drive cycle speed profile as well as the required electrical power at the DC terminals of the battery for the modelled BET. This includes a rather pessimistic traction inverter efficiency of $\eta_{inv} = 0.95$ [9]. The effect of regenerative braking using the electric drive is notable, resulting in peaks of several hundred kilowatts of battery charging power during braking.

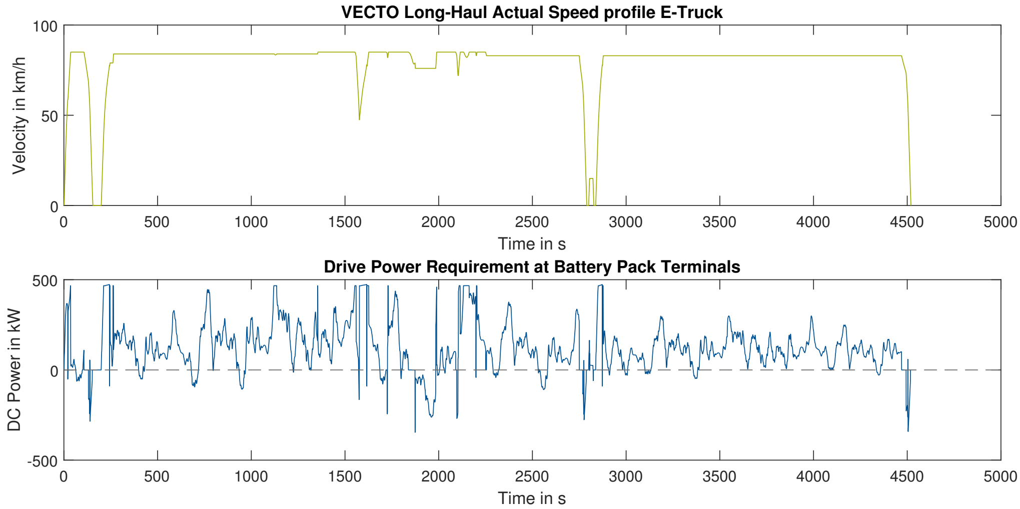

Figure 1: Speed Profile and DC Bus Power Requirement of the modelled BET on the VECTO Long-Haul Cycle.

From a single VECTO long-haul cycle taking approximately 4500 seconds and covering just over 100 km, a typical 9 hour daily drive was assembled, with a single charging stop during the mandated driver rest period of 45 minutes. The state of charge (SOC) during the day is shown in Fig. 2, along with the battery pack voltage and current during the charging stop. A peak charging current of 1100 A is needed in this scenario, resulting in a peak charging power of 930 kW. If the BET can be recharged during the night, time parity with a Diesel-powered truck is achieved in this scenario, similar to the driving scenarios shown in [10].

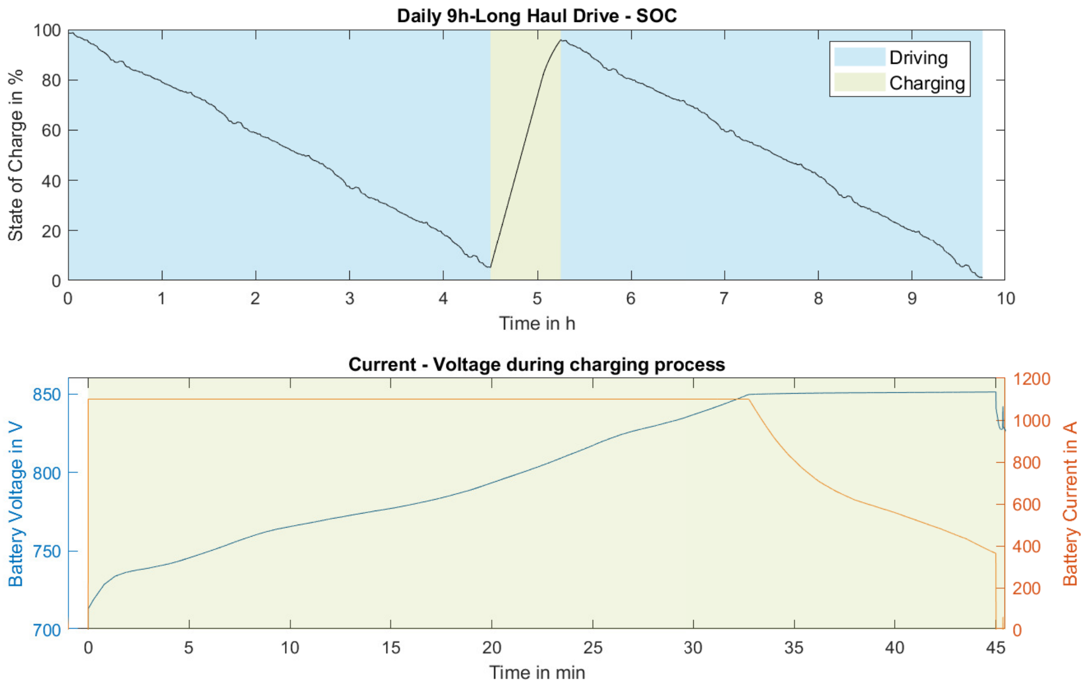

Figure 2: Standard 9h daily long-haul BET operation with synchronized charging and rest period.

BET operation could benefit from charging powers greater than 1 MW when charging is not possible during the entire 45 minute rest period. According to EU regulation, the rest period may be split into a 15 min and a 30 min segment. This flexibility can also make it easier to match rest periods to loading and unloading operations. Fig. 3 illustrates a scenario, where no charging is available during the first 15 min break. 1100 A charging is then compared to a charging process with peak current of 3000 A, which can charge the vehicle's battery to the required SOC within 27 minutes rather than 45 minutes. With 3000 A charging, the difference can now be used as additional driving time, assuming an average 9-hour driver work day. It is notable that 3000 A charging only results in an 18 minute time saving. The reason for this is the sharp de-rating of charging current as the upper limit of the cell voltage is reached. The SOC window where 3000 A charging is possible with this particular 4680 cell configuration is very limited, therefore the benefit of the significantly higher charging current is only marginal. This is further analyzed in Section 3.3.

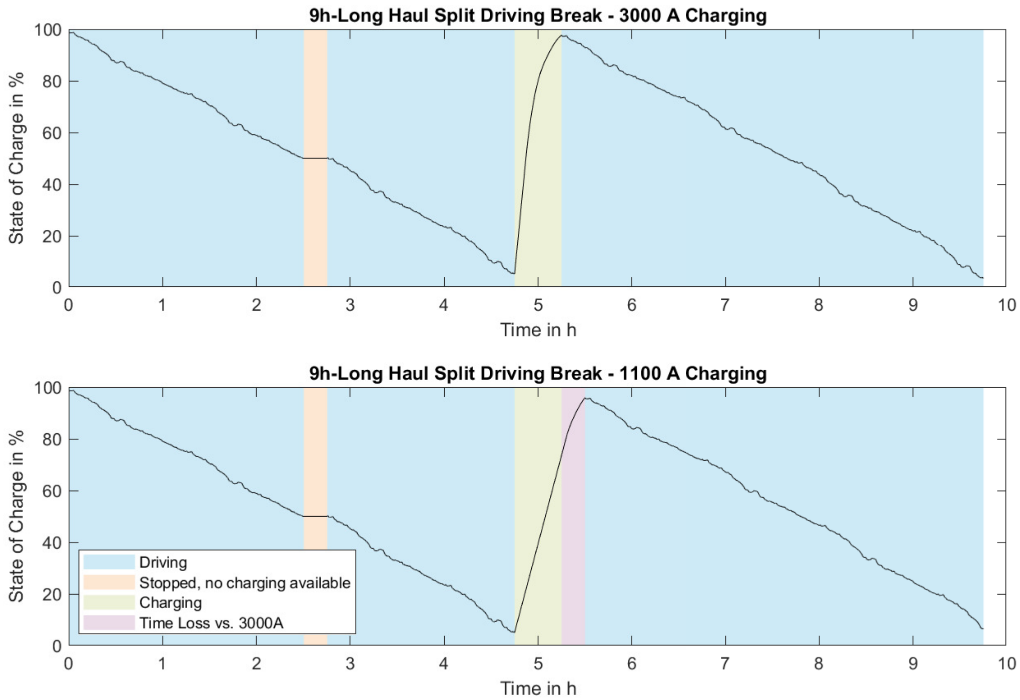

Figure 3: Time advantage of 3000 A charging during split driving break scenario.

Another example scenario, where higher power charging can reduce time loss vs. Diesel truck operation is shown in Fig. 4. Here, overnight charging is not available, thus the first charging break is taken immediately at the beginning of the shift.

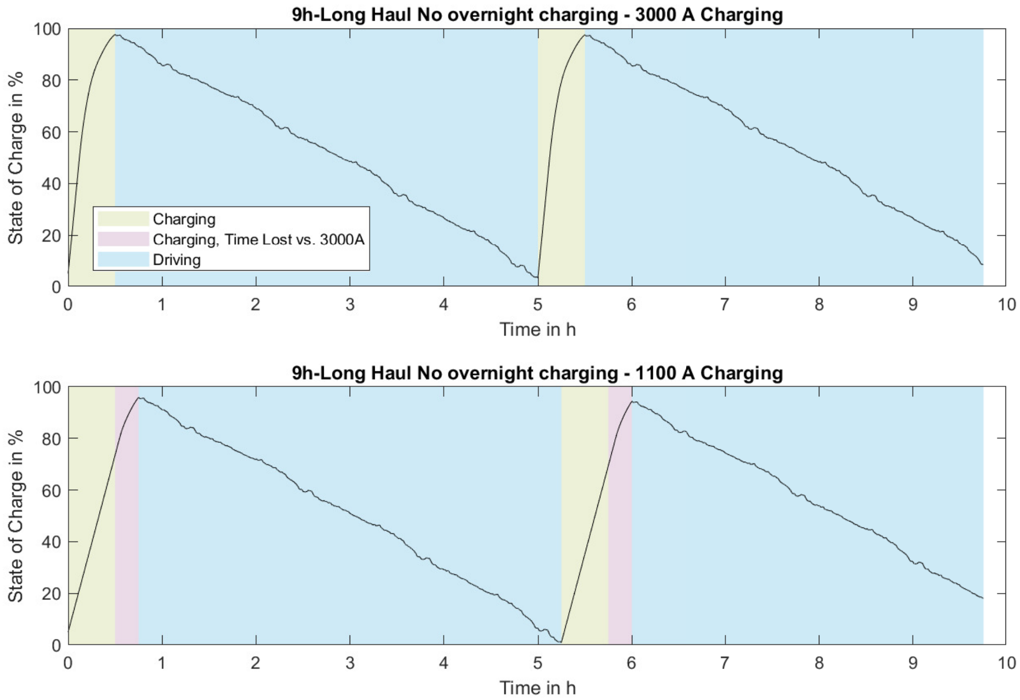

Figure 4: Time advantage of 3000 A charging during split if no overnight charging available.

In addition, 3000 A MCS truck charging may become interesting other markets with more lenient driving time regulation or when operating with two drivers. Another application for the full MCS current are vehicles with larger battery capacities, ranging from coach buses to off-road or marine equipment [11].

2 Methodology

After the motivation for increasing charging power in BETs has been explored using the simulation model, the methodology of the experimental investigation of 3000 A BET charging is introduced. Due to the low technical readiness in some areas, e.g. Li-Ion battery cells and pack architectures capable of repeated charging C-Rates > 3C, high energy density, and enough endurance to complete the BET life cycle of > 1 million kilometers, as well as safety-relevant aspects during testing and the early development stage of such a high power system, the partners chose to conduct tests on test rigs without battery cells. In Subsection 2.1, the prototype onboard HV distribution/charging system is introduced.

2.1 NEFTON 3000 A Charging System Prototype

The architecture of the prototype charging system is visualized in Fig. 5. Much like the current MAN eTGX [12] the NEFTON 3000 A Concept HV system features multiple battery packs, which are connected in parallel, when the vehicle is switched on. Each battery pack is equipped with a battery junction box (BJB), containing a cutoff device, main battery contactors and additional sensors for battery monitoring.

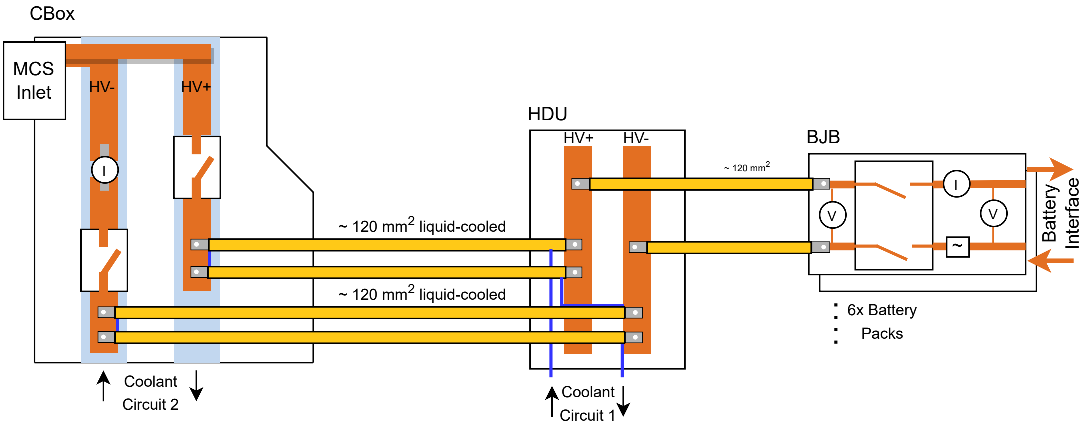

Figure 5: NEFTON 3000 A Concept BET HV distribution system.

The high-voltage distribution unit (HDU) is an entirely passive component to which the battery packs and all HV consumers are connected. The charging box (CBox) contains the sensors and switchgear required for MCS charging. Both the cables between CBox and HDU, as well as the CBox itself, are liquid cooled. The cooling plate in the CBox housing is designed to draw heat away especially from the MCS inlet busbars, in order to manage MCS contact temperatures. This prototype system has been designed by MAN Truck&Bus SE according to their physical and electrical requirements, including ISO 5474-3 electrical safety compliance and cooling system requirements. All liquid-cooled components are designed to be cooled using standard automotive coolant such as a 50-50 mix of water and monoethylene glycol. Furthermore, it was a design goal to cool the shown onboard components without the use of a refrigeration system by using the same high temperature coolant circuit that the drive inverter and E-machine are cooled by. This circuit is directly cooled by an air-to-liquid heat exchanger / radiator at the front of the vehicle and can reach temperatures of up to 60 $°C$.

2.2 NEFTON 3000 A LV Test Rig

The low-voltage, high-current test rig at TU Munich is used to evaluate general functionality and performance of the active cooling system. The custom test rig can deliver up to 5000 A current at voltages up to 60 V using 5x Elektro Automatik E/A PSB 10060-1000 bidirectional power supplies. Short circuit bridges or cables are used in different combinations such that the desired current flow through HDU and BJBs is achieved. Alternatively, the power supplies can be connected at different points in the system and act as an electronic load. Multiple cooling systems emulate both vehicle-side (automotive-grade water-monoethylene glycol coolant) and EVSE-side (nonconductive water-monopropylene glycol coolant) cooling conditions. The waste heat from all coolant loops is rejected via a single 40 kW_{therm} water chiller. All coolant circuits feature variable-speed pumps, a bypass valve for temperature control, and temperature as well as pressure measurement at the inlet and outlet and a plate heat exchanger to allow for heat transfer to the secondary chiller loop. Loops 1 and 2 are filled with automotive coolant and simulate different operating points of the vehicle high temperature cooling system. Loop 3 contains an additional ion filter and is filled with a deionized water-monopropylene glycol mixture. Fig. 6 shows the integration of the Device-under-Test (DUT) connected to the test rig. A 3000 A MCS cable is used to interface with the CBox MCS inlet. At least 3x power supplies in Master-Slave configuration are connected to the MCS cable via its breakout box. Coolant circuit 3 is used to cool the charging cable at 20-25 $°C$ inlet temperature into the cable. Both the control of the test rig and DUT, as well as measurement data acquisition are handled by a

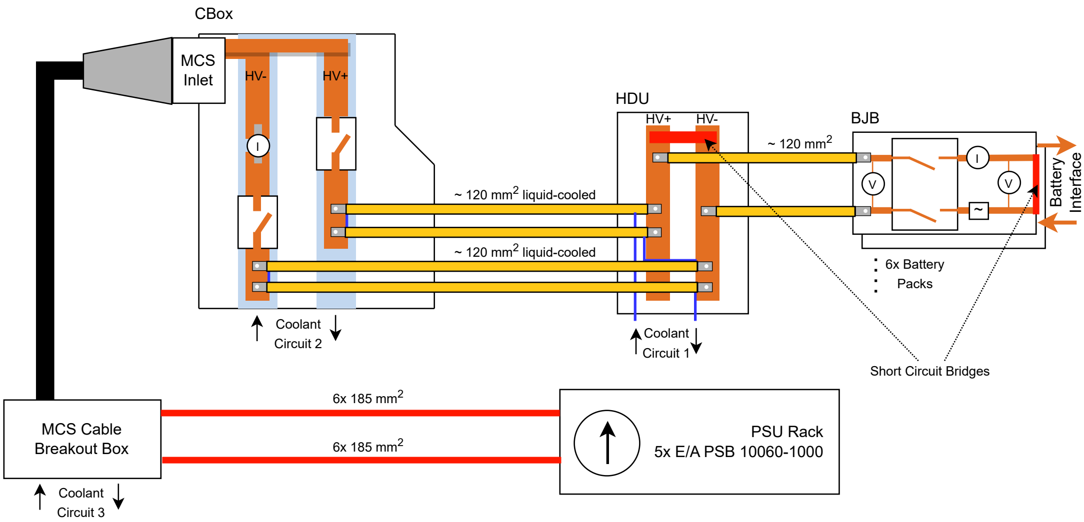

Figure 6: Concept BET HV distribution system on the LV test rig.

National Instruments CompactRIO real-time device. Temperatures on active conductors are taken via insulated thermocouples.

3 Results & Discussion

The main focus of this results section lies on the thermal measurements at the MCS connection as well as at different locations inside of the CBox. The presented MCS temperature measurements are compared with the measurements taken at NREL [3]. With the help of the previously presented vehicle simulation model, the losses during different charging rates, both in the HV distribution and the battery pack are presented and charging efficiencies are calculated.

3.1 MCS Connection Temperatures

Two different MCS inlets were tested. For each combination, measurements were taken for vehicle coolant temperatures of 30 $^{\circ}C$ and 60 $^{\circ}C$. Table 2 lists the maximum temperatures for each configuration. The two 3000 A combinations tested at NREL are also listed for reference. In their report, the temperatures are given as temperature increase above ambient. The targeted standard maximum temperature at the MCS pins is 100 $^{\circ}C$ [13].

Table 2: MCS Connection Contact Temperatures at 3000 A.

Connector Combination	Vehicle-Side Coolant Temperature in $^{\circ}C$	Inlet Contact Temperature in $^{\circ}C$ (max.)	Connector Contact Temperature in $^{\circ}C$ (max.)
Cable A - Inlet A	30	73	57
	60	90	63
Cable A - Inlet B	30	83	67
	60	100	71
NREL (JJ - LL) [3]	10	47.5 + 25	-
NREL (KK - LL) [3]	10	58.6 + 25	-

The main differences between the NREL measurements and our measurements are the coolant temperature levels and the level of integration into a vehicle component. Since the ambient temperature during testing at TU Munich was approximately 25 $^{\circ}C$, this ambient temperature is added to the NREL values. NREL used coolant temperatures of 10 - 12 $^{\circ}C$ in their tests. Keeping this in mind, not only are both tested combinations compliant with the MCS pin temperature limit, they even achieve this at 60 $^{\circ}C$ coolant temperature. Interestingly, the NREL temperatures are approximately comparable to the presented measurements at 30 $^{\circ}C$. These results in comparison with the NREL measurements seem almost unphysically positive. One possible explanation for this difference is the different sensor setup. The NREL testing used several additional thermocouple sensors fitted to the connector and inlet DUTs in addition to the manufacturer installed PT1000 elements, while the testing at TUM relied on the manufacturers' PT1000 elements to avoid compromising the insulation characteristics for later HV testing. The NREL report does not state at which sensors the maximum temperatures were reached and likewise, the exact location of the manufacturer installed PT1000 sensors in the components tested at TUM is unknown. Fig. 7 shows the temperatures measured at the PT1000 sensors at steady state for each of the tested MCS combinations at 60 $^\circ C$ coolant temperature. In both setups, the MCS inlet pins are significantly warmer than the cable/plug pins, which can be easily explained by the low EVSE-side coolant temperature. The superimposed periodic changes especially noticeable in the plug pin temperatures are caused by the cycling of the water chiller. It is notable that in the Connector A - Inlet B measurements, the DC+ connections seems to have a higher contact resistance, and thus higher temperatures of approximately 10 K.

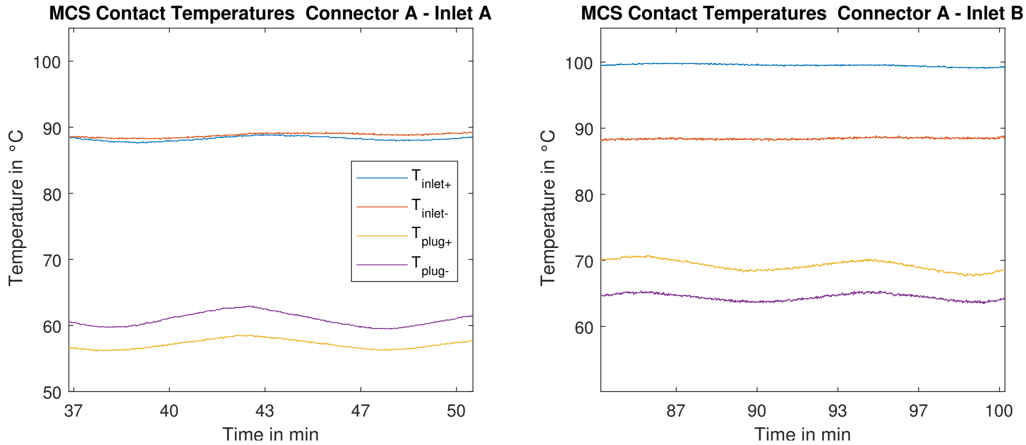

Figure 7: Comparison of integrated PT1000 temperature measurements of tested MCS combinations.

3.2 CBox Component Temperatures

The CBox initially carries the full charging current before it is distributed across several parallel conductors. This means that the contact and conduction resistances of CBox components such as the previously-discussed MCS inlet, but also the shunt-based current sensor as well as the charging contactors, are especially critical. An abnormal increase in either electrical resistance or thermal resistance to the CBox cooling plate easily leads to overheating in these components. Fig. 8 shows the most relevant temperature measurement locations.

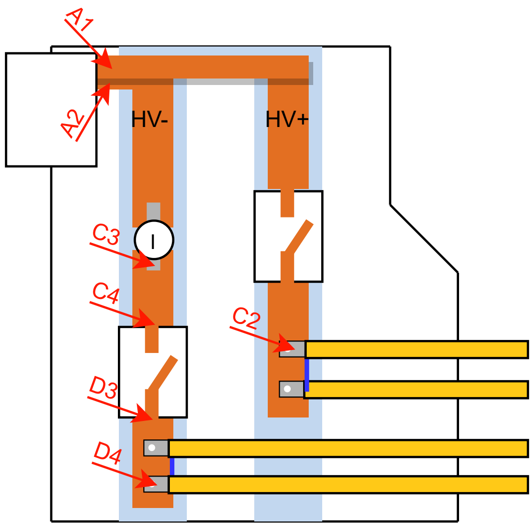

Figure 8: HV thermocouple locations inside CBox.

In total, 16 HV insulated thermocouples have been installed in the CBox. The following Table 3 list the most interesting ones, as they are located at the connection points between the CBox busbars and internal components. The temperatures shown were taken while operating the system at 3000 A with vehicle-side coolant at a temperature of 60 $^\circ C$. Two temperatures, measurement points C3 and C4 were identified as abnormal.
Especially the 165.6 $^\circ C$ at the current sensor terminal is a major issue, as the current sensor is only rated for 105 $^\circ C$. The likely cause of these hot spots is the very thick (3-4 mm) layer of thermally conductive pad. The nominal

Table 3: CBox HV thermocouple measured temperatures.

ID	Temperature in $^{\circ}C$
A1	89.7
A2	91.8
C3	165.6
C2	81.4
D4	103.8
D3	98.9
C4	120.3

thickness in other locations in the CBox is 1 mm. At the identified hot spot, the manufacturing tolerances of the prototype necessitate this thick thermal pad. This issue will be addressed in future prototype generations.

3.3 Charging Losses

In this section, the charging losses and overall charging efficiencies for the two simulated charging speeds are discussed. Losses in both battery cells as well as the HV distribution are taken into account. Fig. 9 compares the two charging processes, which both charge the battery pack from 5 - 96 % SOC. The 1100 A cycle reaches a peak charging power of 930 kW. The 3000 A charge cycle reaches a peak power of 2537 kW. This corresponds to peak C-rates of 1.54 and 4.19 respectively. The 3000 A charge cycle is deemed as not practical for the truck battery with this cell, even without taking into account factors such as cell ageing. As stated before, the charging current is de-rated after less than 7 minutes due to the cells' upper voltage limit. During the 1100 A charge cycle, a battery chiller power of 25 kW_{therm} was employed in the simulation model, resulting in the temperature curve on the bottom left of Fig. 9. For the 3000 A, an unreasonable chiller power of 100 kW_{therm} was required to keep the cells from reaching critical temperatures of above 60 °C.

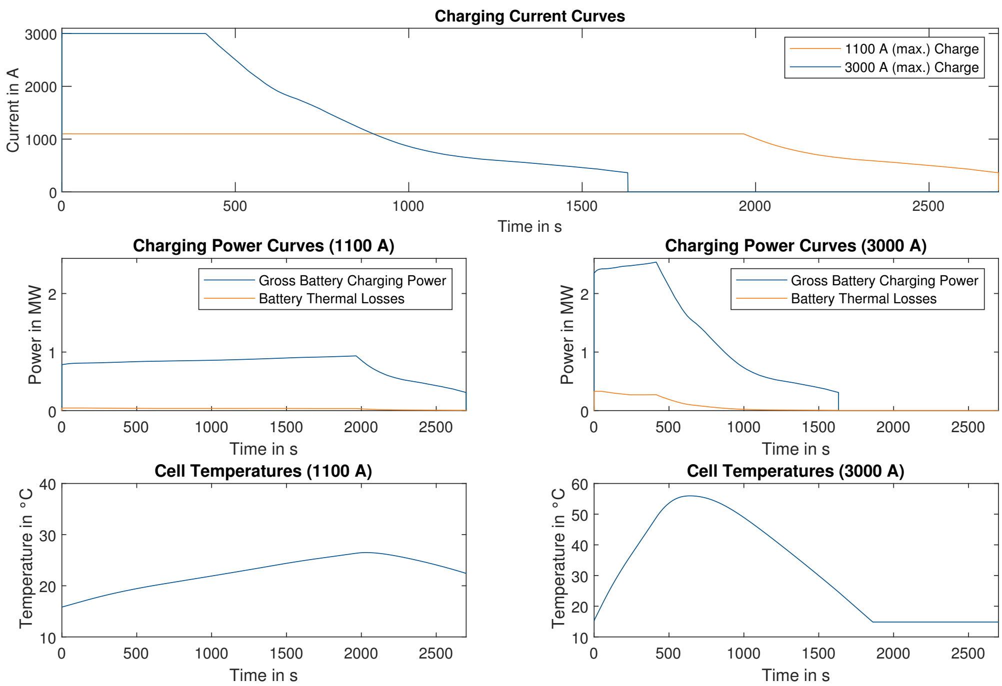

Figure 9: Comparison of 1100 A and 3000 A charge cycles.

Table 4 lists the cumulative charging efficiencies integrated over the entire charging process for both charge cycles shown in and compares the losses in the onboard HV distribution vs. the cells themselves. The contribution of the charging current path towards the losses is only around 1% in both examples. The peak charging losses in the cells during the 3000 A charge are extremely high at over 300 kW, which further underlines the statement that the Li-Ion cell featured here is not suitable for these high charging rates.

Table 4: Comparison of charging losses for 1100 A and 3000 A charging.

	Cell losses (peak) in kW	On-board Distribution losses (peak) in kW	Cumulative charging efficiency in $\%$
1100 A Charge	44.2	0.6	96
3000 A Charge	328.6	4.5	91

4 Conclusion

The presented experimental results are a valuable addition to the 3000 A MCS connector testing conducted by NREL and published in May 2024 [3], demonstrating the feasibility of MCS 3000 A charging in a BET application in terms of the onboard HV distribution system. This is especially relevant, as heavy electric road vehicles are set to become the first widespread application of MCS. This specific implementation of 3000 A MCS in a BET charging system shows the feasibility of charging at full MCS currents even with much higher coolant temperatures than used in the NREL reference testing. Some challenges remain with the current prototype's subcomponent temperatures. Two realistic use cases for charging power far beyond 1 MW have been demonstrated in simulation. Furthermore, the simulative study has shown that current automotive Li-Ion NMC battery technology with a focus on energy density is not yet suitable for ultrafast charging.

5 Outlook

In order to improve upon the cooling challenges of some CBox components, a new generation of 3000 A CBox prototype is currently being manufactured by MAN T&B SE and will be tested at TU Munich. In order to address the need for fast and selective current interruption devices as larger capacity and higher power batteries are installed in vehicles, new breaker concepts such as solid-state-relays (SSR) and Smart Contactors may become even more relevant. Short circuit testing of different automotive DC breaking devices at project partner Fraunhofer ISE in the second half of 2025 will give new insights into the performance and behavior of these next-gen circuit breakers. Finally, the 3000 A charging system prototype will be tested at full power up to 3 MW at Fraunhofer ISE.

Acknowledgments

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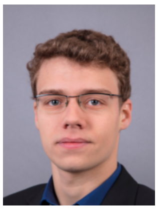
Presenter Biography



Steffen Büttner is a Ph.D. candidate and Research Associate at the Institute of Sustainable Mobile Powertrains at the Technical University of Munich. He graduated from TU Munich in 2022 with an M.Sc. in Electrical Engineering with a focus on Energy Systems. His current research fields include High Power EV Charging, bidirectional Charging and Microgrids.