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Instrumentation of a battery thermal management system test bench for electric city busses

Instrumentierung eines Prüfstandes für Batteriekühlanlagen elektrischer Stadtbusse

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Abstract

Lithium-ion batteries are the most promising energy storage for electric city busses and thus key technology for a successful market launch. Temperature of Lithium-ion batteries has a high impact on performance, lifetime and safety of battery cells. Therefore, a battery thermal management system (BTMS) is necessary to control the battery temperature in a small range (15 – 35 °C). Well established conditioning applications are cooling plates to control the temperature by a coolant flow. Both, ambient temperature and battery waste heat transferred to the coolant have to be known to design an efficient BTMS and are simulated by the developed hardware-in-the-loop (HiL) test. The ambient temperature is controlled in a climate chamber and the battery waste heat is provided by an electrical heater integrated into a coolant circuit. Hence, the developed HiL test bench enables the investigation of BTMS for electric busses under real operating conditions.

Introduction

Two challenges of the 21st century are global warming due to carbon dioxide emissions and energy saving (Martin 2007). Cities also face increasing urbanization, noise emissions, congestion and decreasing air quality. Gao et al. identified that diesel busses play a significant role to air pollutions in urban areas. Hence, electric city busses have high potential to be a part of the solution and are addressed by many research and industrial projects (Kunith 2017, ZeEUS 2018). The market share of electric busses in Europe is still on a low level, e.g. in Germany about 1.3 % (Rohs 2018). Nevertheless various independent studies predict over 30 % of the world bus fleet will be electric in 2030 (Mahle 2018, Bloomberg 2018). Due to the limited energy capacity of electric busses compared to conventional busses the important challenge is the smaller driving range, especially at low ambient temperatures. Two different charging strategies are mainly discussed: opportunity and overnight charging (Kunith 2017). Overnight charging uses large batteries to achieve high driving ranges and recharges at the depot. Whereas opportunity charging strategy is based on smaller high power energy storages and recharges at bus stops for typically 15 to 120 seconds with high power up to

600 kW. However, energy management is essential for both the strategies. Hence energy management is an important research object for electric busses (Musardo et al. 2005). Air conditioning as a decisive part of energy management shows high potential to decrease the energy consumption of the electric bus system (Jeffries et al. 2015). Furthermore, thermal management of the powertrain including power electronics, electric engine and battery is important matter for electric busses (Liebers et al. 2016). Rechargeable lithium-ion batteries are well suited for operation in electric busses due to high energy and power density, high potential, no memory effect and long cycle lifetime (Affani et al. 2005). However, safety, life-time and performance of lithium-ion batteries are related to temperature of the cells. At low temperature and high charging rates lithium plating can occur at the negative electrode: the internal resistance of the cells dramatically increases and capacity decreases with the risk of a short circuit. Furthermore, the performance of battery cells decreases at low cell temperature due to slower chemical reactions. High temperature of battery cells increases the aging process and can lead to a thermal run away. i.e. an exothermic reaction with destruction of the cells (Feng et al. 2017). Chemistry of the cells has high influence on the thermal behavior. States of the art in electric busses are Lithium-Ferrit-Phosphate (LFP), Lithium Titanate Oxide (LTO) and Lithium Nickel Manganese Cobalt Oxide (NMC). Whereby temperature related safety of LFP and LTO are higher compered to NMC cells but also have lower energy density. Cell temperature depends on heat transfer with ambient and inner heat production due to ohmic losses and reversible heat during discharge. Thus, the load profile of the traction battery is significantly responsible for heat production inside the cells. Various researches on general battery thermal behavior have been made (Dincer et al. 2017, Xia et al. 2017, Richter et al. 2017). Tourani et al. analyzed thermal behavior of a Lithium Manganese Oxide (LMO) pouch cells in dependency with the driving profile of an electric car using a 1-d electro-chemical model coupled with a 2-d thermo-electro model. Lajunen et al. studied energy losses of an electric city bus depending on real and standardized driving cycles (i.e. Braunschweig, Manhattan). However, the results are calculated with the analytic tool Amesim from Siemens. To investigate a BTMS the thermal behavior of the battery has to be known. Therefore driving profile and energy demand of the electric bus system has to be calculated to derive the load profile of the battery in order to simulate battery thermal behavior. Because of the two-phase flow in the refrigerant circuit, simulations of BTMS are challenging and always need to be validated by measurements. This study aims to present a hardware-in-the-loop (HiL) test bench for BTMS to simulate real driving conditions using waste heat of the battery and ambient temperature as input. Design, control concept and method are developed based on calculations of driving cycles, charging strategy and requirements of BTMS of electric public transport busses.

Design basis

To design a HiL test bench for BTMS, real driving conditions have to be known. Results for battery waste heat, crucially ambient temperature and behavior of the BTMS are used as input and design basis for the HiL test bench.

Calculation of battery waste heat

An analytic simulation tool is used to calculate energy and power demand of electric busses. Calculation inputs are height profile, velocity and over 40 characteristics of an electric bus. Driving resistances, air conditioning and auxiliary energy demand are included in the assessment. Thereby, the load profile of the battery and also for separate battery modules of 12 cells can be calculated. In figure 1 the current profile of a 12 cell module for the Standard-

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ized-On-Road-Test-Cycle 1 (SORT1) is shown. This load profile can be used to calculate the waste heat of the battery according to the Bernardi et al. formula

$$\dot{Q} = I(V - U) + IT\frac{\partial U}{\partial T} + C_p\frac{dT}{dt}, \quad (1)$$

where $\dot{Q}$ $[W]$ is the generated heat, I $[A]$ is the current, V $[V]$ is the cell potential, U $[V]$ is the open-circuit voltage , T $[K]$ is the temperature und C_p $[J/K]$ is the heat capacity. The battery waste heat for overnight charging strategy is up to 6 kW and due to big batteries and thus high heat capacity the dynamic of the battery temperature change is significant lower compared to opportunity charging. During opportunity charging up to 50 kW can occur, for a short period of time, inside the cells.

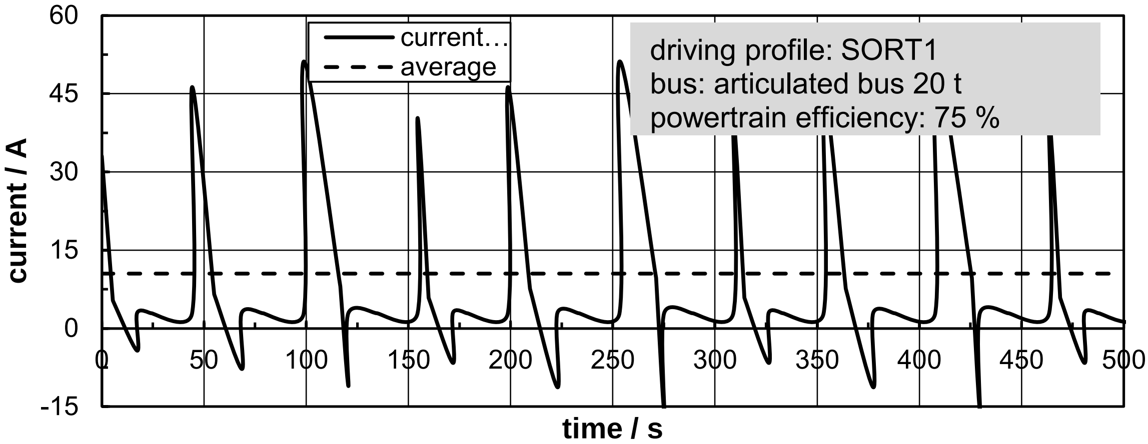

Figure 1: Current profile and current average value for one battery module; calculated for Standardized On-Road Test Cycle 1 (SORT1) with articulated bus of 20 t total mass

Battery thermal management system

To design a HiL test bench for a BTMS of electric city busses detailed knowledge about the test unit (BTMS) is necessary. There are various possibilities to design BTMS for electric city busses. Distinctions are made between air cooling and coolant cooling. At the air cooling method, cooled air flows through the battery cells to cool them down. Due to lower heat capacity and heat transfer of air compared to coolant, air cooling has lower efficiency and fast charging is not possible. Also only battery chemistry with high temperature resistance andlower energy density can be used like LFP. On the other hand air cooling can be cheaper than coolant cooling and is simpler to integrate in the air conditioning system of the bus. Coolant cooling has higher cooling rates and allows fast charging up to 3 C. A well-established method on cell level uses cooling plates to control the temperature by a coolant flow. Task of the BTMS is the conditioning of the coolant and a state of the art stand-alone BTMS is shown in figure 2. Starting from the battery, the coolant flows through the radiator or the chiller, depending on ambient temperature and heat load of the battery. At lower ambient temperature and waste heat of the battery, the coolant is cooled by the primary coolant circuit (i.e. radiator). At higher ambient temperature or waste heat of the battery, the coolant is cooled by a secondary refrigerant circuit (i.e. chiller). The chiller is integrated in a refrigerant circuit with electric compressor, expansion valve and condenser. An electric heater in the coolant circuit heats up the coolant in case of cold ambient temperature. The BTMS automatically adjusts the fan and compressor speed to reach the target temperature.

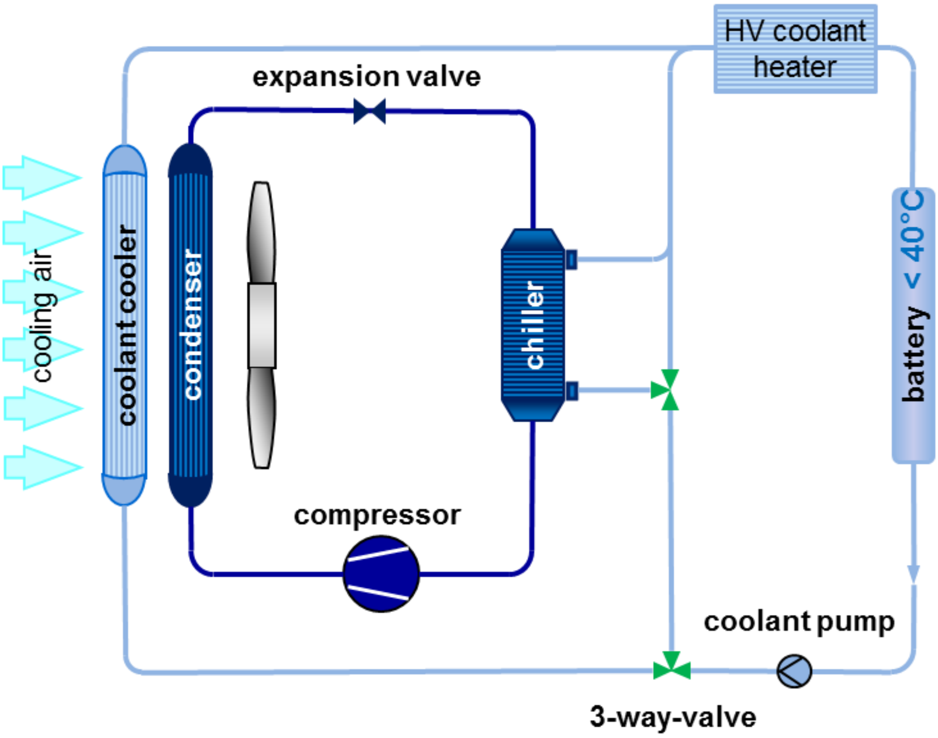

Figure 2: MAHLE battery thermal management system

Experimental Setup

A climate chamber (figure 3) is set up to simulate different ambient temperatures (T = 10 °C up to 55 °C). Thereby, typical operating conditions of a BTMS can be covered. The temperature of the air is controlled by an electric heater (50 kW) and a coolant cooler (50 kW). Power of the electric heater can be defined as a constant value or regulated by PID-controller. The controller regulates the air temperature of the inlet into the BTMS measured with a Pt100 sensor (class A, 4 wire-circuit). The temperature of the fluid within the coolant radiator is controlled and provided by a refrigerator to a constant value. An electric fan conveys the air flow through electric heater and coolant cooler into the chamber and can be adjusted by a potentiometer. The air inside the chamber is used by the battery thermal management system to cool down the inner coolant or refrigerant circuit of the system. The heated air from the BTMS will be blown out of the chamber. The fan of the test bench provides more air than needed by the BTMS, excess air is by-passed by an outlet of the climate chamber. By that, a constant ambient pressure is provided inside the chamber. Temperature of air side are measured by calibrated, k-typ thermocouples. To achieve higher accuracy 39 sensors are implemented and especially downstream condenser the temperature profile can be covered. Volume flow through the BTMS is measured at the outlet of the system. A flow straightener upstream of the hot-wire probe increase accuracy of the measurement results. A coolant circuit with a 50:50 mass% mixture of water glycol (G40) simulates the battery cooling circuit. The heat source (i.e. battery) is implemented by an electric water heater with a small reaction time and 22 kW heating power. Using a programmable logical controller the real operation profile of the battery is implemented. It is also possible to define an inlet temperature to the BTMS controlled by a PID-controller and a Pt100 sensor (class A, 4 wire-circuit) at the coolant inlet of the system. The flow rate of the battery coolant circuit is measured by a magnetic inductive flow meter (accuracy: 0,2 %) and controlled by an electric pump within 10 and 80 l/min. Temperature of the coolant at inlet and outlet of the BTMS is highly important for energy balances of the System. Therefore, three k-type, calibrated thermocouple and one calibrated, 4 wire-circuit Pt100 (class A) are implemented, respectively. Pressure of the coolant is also measured at inlet and outlet to calculate the pressure drop of the system. The heat input of the electric heater to the coolant is measured by the power support unit. To double-check, three calibrated, k-typ thermocouples are instrumented upstream the heater. The data acquisition system dewetron dewe2 is used. The test bench also supports the power supply and CAN communication with the BTMS. The presented HiL test bench provides all instrumentations to measure battery thermal management systems, including cooling capacity for various operating conditions, pressure drop over the system and significant data of the refrigerant circuit. Cooling capacity can be calculated according to

$$\dot{Q}_{BTMS} = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T, \quad (2)$$

where $\dot{V}$ is the measured volume flow, ρ is the density, c_p is the specific heat capacity and ΔT is the measured temperature difference between inlet and outlet of the BTMS. Investigations of the refrigerant circuit are possible for condenser, compressor and chiller with expansion valve. The mass flow of the refrigerant can be calculated by

$$\dot{m}_{refrigerant} = \frac{\dot{Q}_{BTMS}}{\Delta h_{chiller}(T,p)}, \quad (2)$$

where $\Delta h_{chiller}(T,p)$ is defined by measured temperature and pressure before the expansion valve, which is assumed to be isenthalp, and behind the chiller. Thereby absolute energy balances for separate parts of the refrigerant circuit are possible. Furthermore, 18 temperature sensors enable conclusions about the two-phase-flow inside of the condenser due to temperature distribution. The measured data of the HiL test bench can be used for investigations and characterization of BTMS and also to validate simulation models.

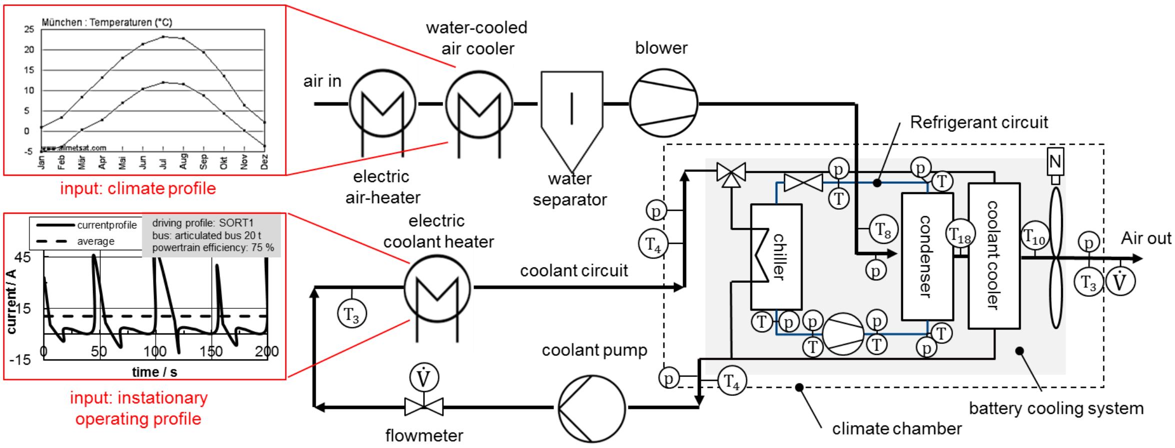

Figure 3: schematic test bench with integrated battery cooling system, T_X: X-temperature sensors, p: pressure transducer, $\dot{V}$: flowmeter, N: rpm sensor

Conclusion

A hardware-in-the-loop (HiL) test bench to investigate battery thermal management systems of electric transport busses has been presented. Furthermore the generation method of input data like battery thermal waste heat was described. The HiL test bench provides the possibility to measure BTMS in real operating conditions and enables investigations in terms of cooling performance, efficiency and instationary behavior.

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