A Smart Control Strategy for a Battery Thermal Management System: Design, Validation and Implementation

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Abstract— **A Battery Thermal Management System (BTMS) controller with smart features is designed, validated through simulations, and implemented at lab level. The bedrock of the developed controller consists of four Proportional-Integral-Derivative (PID) controllers that manage independently the four actuators of the evaluated thermal system. The additional smart features respond to four different control goals: driving profile adaptation, energy consumption minimization, aging minimization, and fast-charge efficiency maximization. The designed controller's stability and applicability is validated through simulations thanks to the provided battery pack model, heat exchanger model and thermal actuators models. Finally, the controller has been implemented on the battery pack of the AUDI e-tron at lab level. The results confirm that the designed controller is suitable to be used on a real vehicle.**

Keywords-control; battery thermal management system; electric vehicle; experimental.

I. INTRODUCTION

Decarbonization and emission reduction of road transport are the main drivers for the electrification of vehicles. The envisaged European CO2 fleet emission targets for 2025 [1] and 2030 already require a massive market introduction of partially electrified vehicles or full electric vehicles. Furthermore, local or regional air quality regulations, such as potential zero emission zones, will drive demand for these vehicles. However, there are still some obstacles for user acceptance of those electric vehicles [2]: high cost, slow charging, limited range, unperceived added value and concerns of limited mobility. In order to remove these obstacles, it is necessary to increase the efficiency of the components of the battery pack system.

One of the most critical components in an electric vehicle is the Battery pack Thermal Management System (BTMS). A BTMS is the component that adjusts and balances the battery temperature to an appropriate range [3]. There are different BTMS-related technologies, but basically all the technologies can be categorized into two topics: BTMS design and BTMS control strategies.

The BTMS control strategy topic is addressed in this paper. The BTMS control strategies are the algorithms that manage the thermal actuators of the BTMS. They aim at controlling the temperature range and distribution inside the battery pack [3]. These control strategies have a direct effect on the performance rate of the thermal system [4]. There are many techniques available, but the most common and robust ones are the Proportional-Integral-Derivative (PID) and the state diagram control strategy.

The PID control is a control loop mechanism employing feedback that applies a correction based on proportional, integral, and derivative term of the difference between the desired set point and the measured one. The PID is widely used in industrial applications, and it is a suitable algorithm to control the BTMS [5]. It provides a continuous control based on the observed changes in the controlled variable and can bring the system to a stable state. However, this kind of control is far from being an optimal control method for the BTMS since it cannot be adjusted to different scenarios and/or objectives [6].

The state diagram control strategy is an expert control that defines the decision-making responses based on the system's state diagram [7]. These states, which have been defined based on the observations of the real system, define the way the actuators are managed. This type of controller is also called macro-control or rule-based control. It is easily implementable and provides high rate of adaptability to a variety of scenarios and can respond to different objectives. Nonetheless, it does not pay attention to the dynamics of the controller variable, and it is uncommon to bring the system to a stable state [8].

Consequently, this paper proposes a controller that brings the controlled variable to a stable state while being adaptable to different scenarios and objectives. The main element of the controller is the PID, that can reach a stable state. Above it, smart features have been added based on state diagram concepts. These smart features have the goal of improving the efficiency of the heating and cooling system of the battery pack.

The aim of the paper is to design, validate and implement at lab level this smart control that (0) has a continuous control that can bring the system to a stable state; (1) lengthens the life of the vehicle by minimizing the aging and adjusting the control strategy based on the driving profile; and (2) lengthens the use range by minimizing the total energy consumption and maximizing the charge events. This paper is structured as follows: the use case is introduced in Section II. The design is described in detail in Section III. The simulations used to validate the designed controller are explained in Section IV. The test at lab level is shown in Section V. The discussion is done in Section VI. The conclusions are drawn in Section VII.

II. USE CASE

The developed control strategy is designed for a commercial electric vehicle. The evaluated battery pack is the one inside the 2019 AUDI e-tron, see Figure 1.a. However, the thermal system used on the use case is not the commercial one, instead, it is the one developed in i-HeCoBatt European project, grant agreement No. 824300 [9].


(a) (b)

Figure 1. Evaluated use case: (a) battery pack [10]; (b) FLEXcooler [11].

The heat exchanger has been built using MIBA's FLEXcooler® technology, see Figure 1.b. Additionally, the heating process is done by resistances that are in direct contact with the batteries instead of heating the liquid of the heat exchanger.

III. DESIGN

The designed TMS strategy is a mix of PID controllers and state diagram controller's concepts. The result is a smart control strategy that brings the system to a stable state while adapting smartly to different scenarios and objectives, see Figure 3.

Firstly, three main states are defined following the state diagram controller design: cool zone, optimal operation zone and hot zone. These zones represent the actuation temperature ranges of the designed controller. At the cool zone, heating processes will be taken. At the hot zone, cooling processes will be taken. Finally, at the optimal operation zone, there will not be any active control. These control zones are divided by two temperature thresholds. The hot zone's temperature threshold is set up to 35ºC. The cool zone's temperature threshold is set up to 10ºC.

The base of the designed controller that provides the active control is the PID controller. Specifically, there are 4 PIDs. Three of the PIDs are used to control independently the three independent heating resistance areas that are in direct contact with the batteries. The fourth PID controls the chiller used to cool down the liquid that goes through the heat exchanger. The PIDs are saturated to avoid an unnecessary overlapping of processes. An anti-windup function is added to the integral component of all the PID controllers to avoid undesired responses of the controller.

The different PIDs have been parametrized using Ziegler-Nichols method [12]. The method consists of getting the transfer function of the system under a step perturbation, see Figure 2.

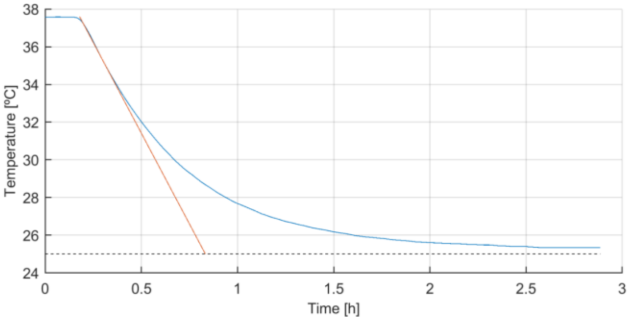


Figure 2. Applied Ziegler-Nichols method (red line) for the heat exchanger PID to the system response under a step perturbation (blue line).

The parameters of that transfer function are used to calculate the parameters of the PID controller, see Table I.

TABLE I. PID TUNING VALUES.

Parameter	Equation	Heat Exchanger A-sample
P (Kp)	1,2 x T / (L x yf)	10.5945
I (ki)	Kp / (2 x L)	0.0227
D (kd)	Kp x 0,5 x L	1238.3
N (td)	>100	105

Once we build up the basis of the controller (the main state diagram with the parametrized four PID controllers), additional states are defined. These states provide the smart features of the controller and fulfil the objectives of the controller.

Firstly, the states used to lengthen the life of the vehicle by minimizing the aging and adjusting the control strategy based on the driving profile are implemented. The obtained features on those states are the following:

- Optional sport mode. The aggressivity of the controller is modified at the driver's will. This is done by increasing the P value of the PID controller. For this work, the P value is increased 10 times if an aggressive driving is requested. The adjustment of the controller to the driver characteristics decreases the aging.
- Preconditioning when parked. The heating when parked is set to the state of having the contact switched on. The controller is informed via a Boolean signal. The signal can come from different sources, such as mobile phones or PCs. It reduces the aging that comes from cold or hot starts (depending on the room temperature).

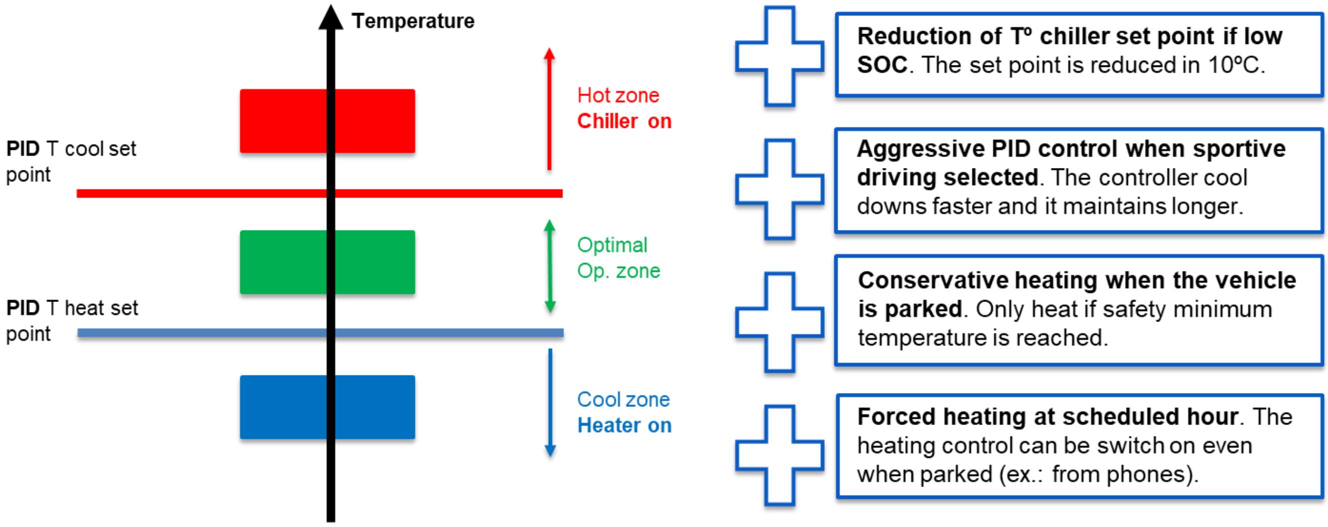


Figure 3. Design of the adaptive and smart control strategy.

Secondly, the features used to lengthen the use range minimizing the total energy consumption and maximizing the charge events are added. These features are the following ones:

- Conservative cooling-heating when parked (the contact of the vehicle is switched off). The temperature thresholds of the controller are modified to increase the optimal operation zone. The thresholds are modified to 45ºC and to -20ºC. Unnecessary energy consumption is avoided when parked.
- Reduction of temperature set point if conditions are met. The detection of an imminent charge event leads to act accordingly. The controller is informed via a Boolean signal. The detection can come from different sources, such as GPS signals or machine learning predictive algorithms. The upper temperature threshold is reduced to 15ºC. The efficiency of charge events is maximized thanks to reducing the limitations imposed by the temperature.

IV. VALIDATION

The validation process of the designed controller is undergone through simulations using a modeling library containing the battery pack model, heat exchanger model and the model of the thermal actuators provided in i-HeCoBatt project “unpublished” [13], see Figure 6.

The simulation environment is built up to have a current profile, the room temperature, the contact state, the driving profile selection, the preconditioning signal, and the sudden fast-charge event signal as inputs and have the thermal response of the battery pack, the thermal response of the liquid of the heat exchanger, the response of the controller and the energy consumption as outputs.

This simulation environment is used to validate the different features of the controller through 4 simulations:

- The first simulation is used to validate the overall stability of the controller, see Figure 6.a. For that, the whole battery pack model (heat exchanger and actuators included) is simulated at a standard driving mode with a mild vehicle driving cycle that has a fast-charge event at the end of the cycle, see current profile in Figure 3. The contact is assumed to be all the time on. The room temperature is set to be constant at 35ºC. The additional signals are set off.

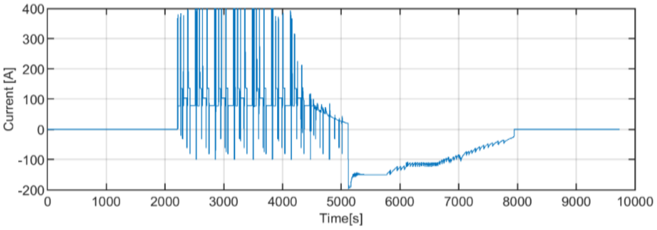


Figure 4. Realistic drive cycle current profile.

- The second simulation is used to validate the overall stability of the Sport mode used for aggressive drivers, see Figure 6.b. The inputs of the simulation are the same as in the first simulation except for the sport mode that is switched on.
- The third simulation is used to validate the efficacy of the added feature that maximizes the charge event, see Figure 6.c. The inputs are the same as in the second simulation except for the sudden fast-charge signal, see Figure 5.

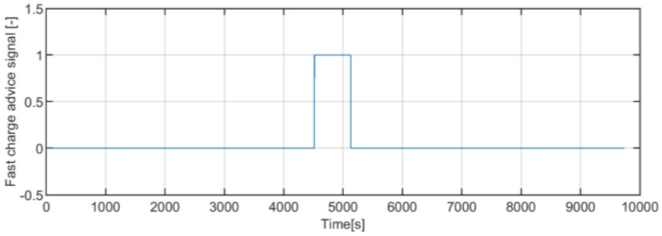
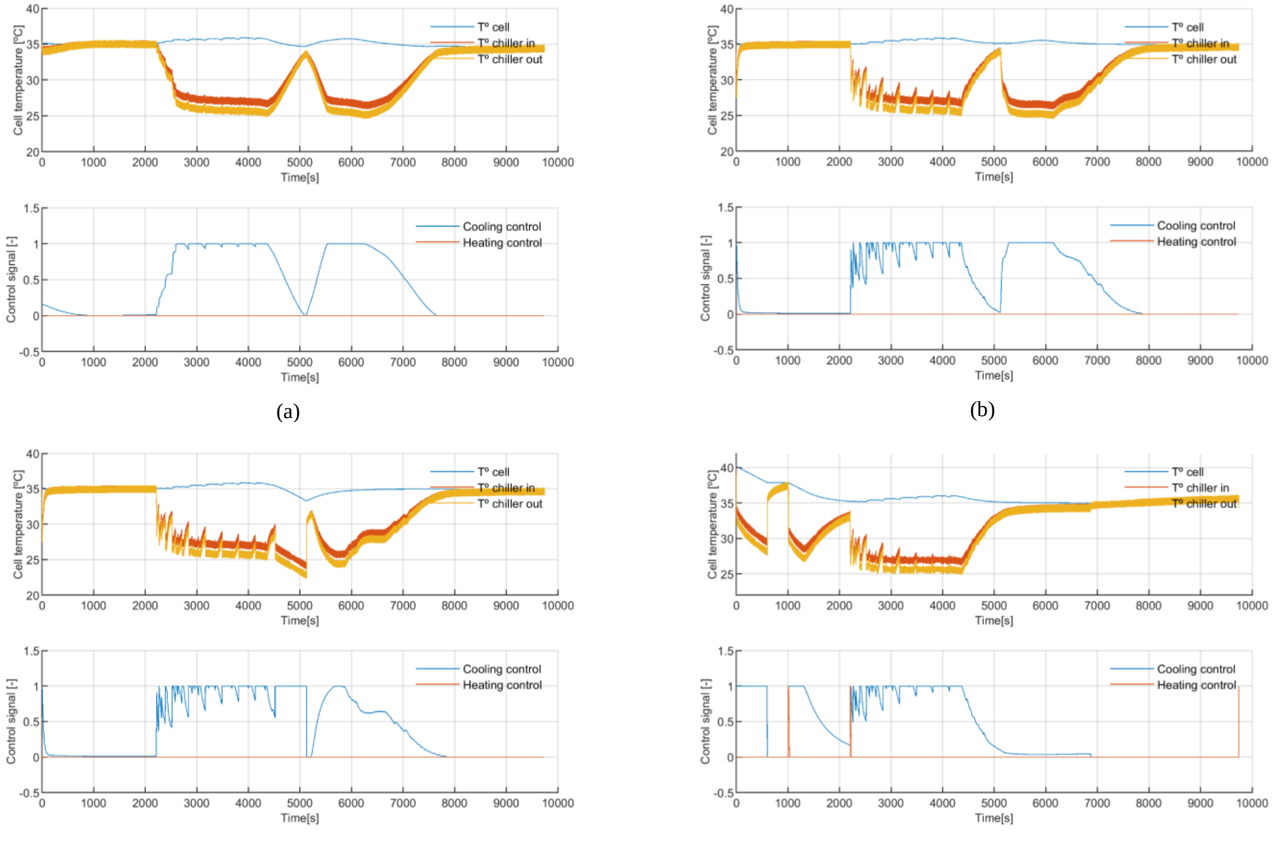


Figure 5. Sudden fast-charge event signal used in the third simulation.



(a)

(b)

(c)

(d)

Figure 6. Results from (a) the first simulation, (b) the second simulation, (c) the third simulation and (d) the fourth simulation.There are two figures for each simulation: the upper figure is the thermal response of the battery and the coolant temperature; the lower figure is the response of the controller.

- The fourth simulation validates the preconditioning features, see Figure 6.d. The inputs used in the second simulation are used in the fourth simulation, but with some modifications. The fast charge is eliminated from the current profile, the room temperature is increased to 40ºC, the contact signal is switched off in some ranges and the preconditioning signal is switched on 1h before the start of the driving cycle. The modified preconditioning and the contact signals are shown in Figure 7.

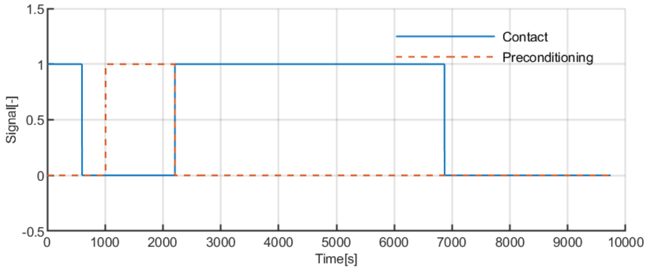


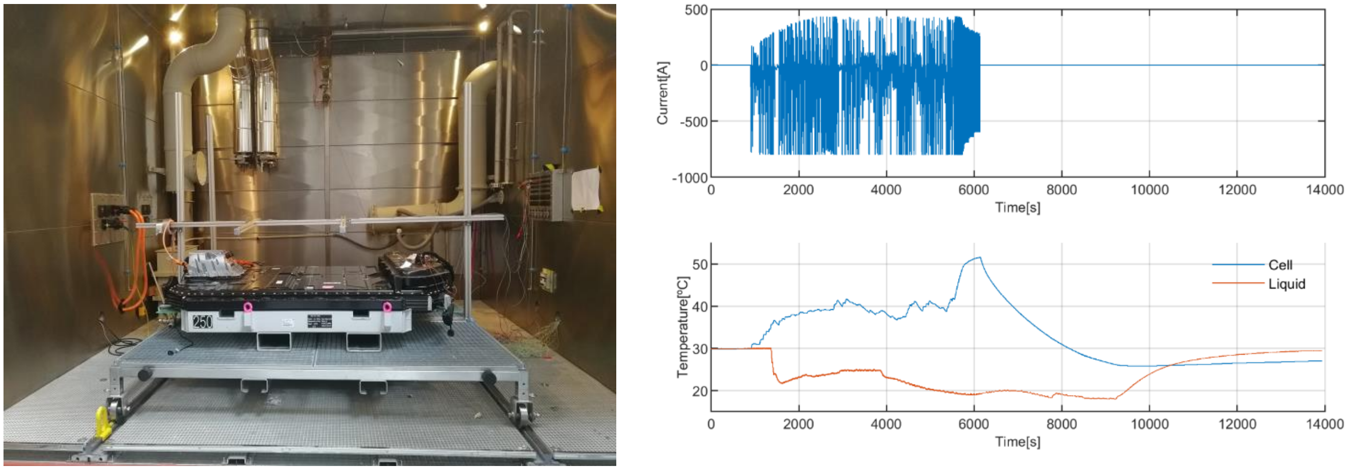
Figure 7. Contact and preconditioning signals in the fourth simulation.

V. IMPLEMENTATION

A test at lab level has been run to confirm the applicability of the designed and validated controller.

The set-up has been done in CEA’s laboratory, see Figure 8.a. The battery pack is positioned inside a climatic chamber where the heat exchanger is connected to an external thermal regulator to ensure the cooling and heating strategy during the test. The BP wiring box is connected to the electric regulation devices of the test bench (Current range: +/- 0-800 A and Voltage range: 60-1000V). In order to avoid convection heat transfer on the lower face of the BP, a plasterboard is added between the battery pack and the metallic frame that supports the battery pack.

Pressure and temperature sensors are positioned on the inlet and the outlet pipes of the heat exchanger. We have added 24 external temperature sensors on the battery pack surfaces. A small extra pressure drop is created by the non-rigid 0.5m pipe to ensure connection between the external chiller pipes and the heat exchanger. The pressure sensors are from Danfoss (Type MBS 1700) with precision of 0.5% of full scale (0-8 bars). The temperature sensors are PT100 that ware calibrated from 0 to 100°C.



(a) (b)

Figure 8. Tests at lab level of the developed controller. (a) the test bench with the tested battery pack; (b) results of the test at lab level: upper graph the applied current profile, the lower graph the thermal response of the battery and the coolant.

The inputs on the test at lab level are the following ones:

- The current profile of an exigent driving cycle, see upper graph of Figure 8.b.
- The room temperature is set up to a constant 30ºC through a climatic chamber.
- The driving adjustment is done to a standard-conservative driving profile (sport mode off).
- The contact is assumed to be active all the test (contact switched on).
- The preconditioning is not applied (preconditioning signal switched off).

There is no fast-charge event and therefore, the signal that announces the imminence of this event is not applied (fast-charge event signal switched off).

VI. DISCUSSION

The results of the simulation have successfully validated the designed control strategy. The first simulation shows how the cooling process is activated once the battery surpasses a certain temperature and how the controller is able to adjust the actuator in a continuous and smooth way, providing at the end a stable state.

The second simulation shows how the sport mode has a faster reaction to the temperature changes of the system, providing a faster response of the controller. The controller is able to adjust its response to a more aggressive driving pattern, hence minimizing the effect this aggressive driving pattern has in the aging of the battery.

The third simulation shows how the reduction of the upper temperature threshold through the fast-charge event notifying signal reduces considerably the temperature of the battery before that event (the battery temperature is reduced 3ºC), reaching lower temperatures at the peak of the fast-charge event (1ºC lower).

The fourth simulation shows that the preconditioning and energy saving features work properly.

In conclusion, the performance of the controller itself as well as the added smart features have been validated through simulations.

Lastly, the validated controller has been applied in a real battery pack with a demanding current profile. The results show how the controller starts working once the optimal operation zone is left. We can see how the controller is able to provide an appropriate smooth control even though the temperatures the battery reach are much higher than the ones observed in the simulations. This means that the controller is suitable to be used in real applications.

VII. CONCLUSIONS

This paper proposes a design of a smart BTMS control strategy that has a continuous and smooth control over the actuators while (1) lengthening the life of the vehicle by minimizing the aging and adjusting the control strategy based on the driving profile and (2) lengthening the use range by minimizing the total energy consumption and maximizing the charge events.

All the smart features of the controller have been validated through simulations and the stability and the applicability of the proposal have been observed through simulations and through a real test of AUDI's battery pack at lab level.

To sum up, the design is simple and implementable; the validation has shown its viability; and the tests done at lab level have shown its implementability.

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