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IFAC-PapersOnLine 49-11 (2016) 406–411

# Model Predictive Heating Control for Electric Vehicles Using Load Prediction and Switched Actuators

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**Abstract:** Thermal management of electric vehicles in low-temperature environments poses an interesting control problem. While thermal control of the cabin is vital for passenger comfort, energy consumption and battery aging always remain an essential concern. Since more reliable information about the short-term future electrical power flow is becoming available by more sophisticated cruise control systems and map information, on-line model predictive thermal management systems can utilize this knowledge to improve battery life maintaining passenger comfort. In this contribution, such a model predictive heating control is proposed based on an on-board capable fast gradient method to solve the nonlinear optimization problem. Direct control of simple electronic switches by the proposed method reduces the need for dedicated PWM controllers embedded within the heating actuators and allows for a cost-efficient and easy realization.



*Keywords:* Energy Management, Electrochemical Systems, Battery Model and Battery Control

## 1. INTRODUCTION

Inclusion of knowledge regarding the future power requirement enables new possibilities for energy-efficient control strategies for electric vehicles. Since the electric battery remains the most limiting part for the long-term operation of electric vehicles, battery wear needs to be taken into account. The damage accumulated in a battery over its lifetime is, among others, mostly governed by the battery current in combination with the temperature. Research performed in this field generally employs large sets of measurement data (see e.g. Serrao et al. (2011) and Cordoba-Arenas et al. (2015a)) to generate control-oriented representations (e.g. Cordoba-Arenas et al. (2015b) and Tang et al. (2015)) or very detailed electro-chemical spatially distributed models of the aging process (Tippmann et al., 2014) which can then be reduced to control-oriented representations (Remmlinger et al., 2014). On the other hand, more general information can be gathered from the specifications of the cells' manufacturer. Those specifications usually state an allowed temperature window for the cells and current limits for charge and discharge, respectively, in addition to peak current values. It is also known that for temperatures outside the recommended range, current limits should be tightened in order to avoid damaging plating effects in the case of charging. These more general rules have been employed in e.g. Miro Padovani et al. (2013) and are exploited in this contribution as well. To facilitate the operation of the battery within its specified range, a dedicated heating actuator for the battery is considered in addition to a heater actuator for the cabin.

For the task of finding the best possible solution regarding the heating of battery and cabin taking battery aging into account utilizing knowledge of the future power requirements, model predictive control algorithms provide the necessary capabilities. Real-time capable solvers for nonlinear optimal control problems have become available in recent years, see for instance Käpernick and Graichen (2014). Since this solver has proven its performance and, especially, flexibility in many challenging applications (see e.g. Bächle et al. (2013)), it is employed for this contribution as well.

The task of optimal temperature control for electric vehicles taking into account the battery current has been considered in several publications, see e.g. Masjosthusmann et al. (2012) and Sakhdari and Azad (2015). However, the overall operation strategy of electrified vehicles can be improved significantly if the coupled control problem is considered in more detail.

Most commercially available cabin heaters for electric vehicles are composed of semi-conductor based, ceramic elements exhibiting a positive temperature coefficient (PTC) in their electrical resistance. This technology offers safety-oriented advantages due to their inherent thermal stability even in case of faulty (for instance, permanently welded close) contactors, where increased temperature of the heating element leads to higher resistance and therefore stabilization of power (Ting, 1972). However, operating heaters with this technology straightforward within an electric vehicle leads to significant inrush currents since the resistance at ambient air temperature is much lower than at the rated operating point. These high inrush cur-

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10.1016/j.ifacol.2016.08.060

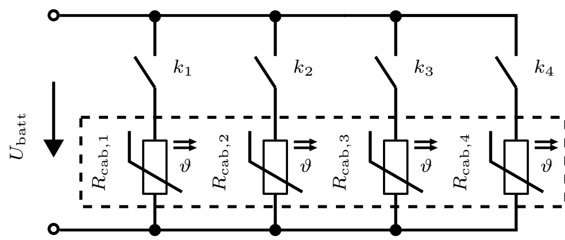

Fig. 1. Switched PTC air heater bank

rents generally need to be avoided since, depending on the current traction power, they might overstep boundaries set by the battery management system (BMS). For this reason, usually a control unit embedded within the heater system controls several heater legs in accordance to an external desired value using, for instance, pulse-width-modulation (PWM). On the other hand, the power flow can be commanded directly by the overall vehicle thermal management which takes into account and actively utilizes higher inrush currents during recuperation events, provided that the technology present in the heaters allows for these conditions without detrimental effects to the device itself. The thereby gained degree of freedom can be exploited for optimal heating of the cabin improving battery life by appropriately scheduling the usage of the heating power.

This contribution is structured as follows: Section 2 describes the physical considerations and modeling of the system to be controlled. Section 3 presents the nonlinear optimization problem as well as the employed real-time solver, Section 4 discusses simulation results while Section 5 provides a brief conclusion.

## 2. SYSTEM OVERVIEW AND MODELING

Because the physical complexity of an actual heating system in an electric car is considerable due to the varying battery voltage and the coupling between the actual power output of several heating channels, an accurate yet real-time capable model covering the most important aspects is required. Fig. 1 shows a schematic overview of the considered cabin air heater unit. Each heater leg $R_{\mathrm{cab},1}, \ldots, R_{\mathrm{cab},4}$ is controlled by a dedicated electronic switch $k_1, \ldots, k_4$ leading to the total heating power

$$P_{\mathrm{h,cab}} = \sum_{i=1}^{4} \frac{(U_{\mathrm{batt}} k_i)^2}{R_{\mathrm{cab},i}}, \quad k_i \in \{0, 1\} \ . \tag{1}$$

In the interest of gaining a control-oriented model for the heating actuator, a power-invariant input transformation is performed. For that, the relation between the resistors is chosen as $R_{\mathrm{cab},2} = R_{\mathrm{cab},3} = R_{\mathrm{cab},1}/2$ and $R_{\mathrm{cab},4} = R_{\mathrm{cab},1}/3$ at their rated operating points to reflect different power stages, as illustrated in Fig. 2. The dependency of those resistors on their temperature $\vartheta_{\mathrm{h,cab}}$ can be expressed by

$$R_{\mathrm{cab},1}(\vartheta_{\mathrm{h,cab}}) \approx p_{\mathrm{R},1} \mathrm{e}^{\vartheta_{\mathrm{h,cab}} p_{\mathrm{R},2}} + p_{\mathrm{R},3} \mathrm{e}^{\vartheta_{\mathrm{h,cab}} p_{\mathrm{R},4}} + p_{\mathrm{R},5} \ , \tag{2}$$

which has proven a good fit to values from literature. Since the resistors are mounted in proximity to each other, they are assumed to possess the same temperature $\vartheta_{\mathrm{h,cab}}$. The heating power can then be rewritten as

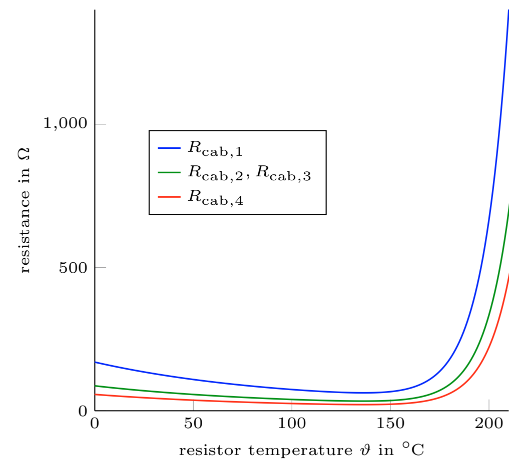

Fig. 2. PTC resistances over temperature

$$P_{\mathrm{h,cab}} = \frac{U_{\mathrm{batt}}^2}{R_{\mathrm{cab},1}} \left(k_1^2 + 2\left(k_2^2 + k_3^2\right) + 3k_4^2\right) = \frac{U_{\mathrm{batt}}^2}{R_{\mathrm{cab},1}} u_{\mathrm{cab}}^2 \tag{3}$$

depending on the virtual control $u_{\mathrm{cab}}$. An examination of the 16 possible switch positions yields a total of nine unique power stages

$$u_{\mathrm{cab}} \in \left[0, 1, \sqrt{2}, \sqrt{3}, \ldots, \sqrt{8}\right]$$

this new control can achieve due to $R_{\mathrm{cab},2} = R_{\mathrm{cab},3}$. In order to realize $u_{\mathrm{cab}}$ using the actual switches, a corresponding map of distinct combinations of $k_i$ is utilized.

Within the considered vehicle, a second heating actuator is present for direct thermal management of the battery with the resistances $R_{\mathrm{batt},1}, \ldots, R_{\mathrm{batt},4}$ and the control $u_{\mathrm{batt}}$. It follows the same basic functionality and topology as the cabin air heater, however features heater legs with constant, i.e. temperature-independent resistances and a significantly lower heating power.

Due to the battery's impedance, both heating currents influence the battery output voltage which in turn constitutes a main contributor in the actual heating power. The actual battery voltage is mainly governed by an open-circuit voltage

$$U_{\mathrm{OCV}}(\mathrm{SOC}) \approx p_{\mathrm{SOC},1} \mathrm{e}^{\mathrm{SOC}\, p_{\mathrm{SOC},2}} + p_{\mathrm{SOC},3} \mathrm{e}^{\mathrm{SOC}\, p_{\mathrm{SOC},4}} \tag{4}$$

given, among other influences like temperature and hysteresis effects, mainly by the state-of-charge (SOC). This model has proven a reasonable fit to data usually provided by cell manufacturers. Furthermore, the SOC is given by

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathrm{SOC} = \frac{-I_{\mathrm{batt}}}{3600 \cdot C_{\mathrm{batt,el}}} \ . \tag{5}$$

The actual terminal battery voltage is then a function of $U_{\mathrm{OCV}}$ and the battery current acting on the battery's impedance. While this impedance generally comprises static and dynamic elements, only the static dependency modeled by a series resistor $R_0$ is considered for this contribution, yielding

$$U_{\mathrm{batt}} = U_{\mathrm{OCV}}(\mathrm{SOC}) - R_0 I_{\mathrm{batt}} \tag{6}$$

with the battery current $I_{\mathrm{batt}}$ mainly governed by the power request $P_{\mathrm{trac}}$ from the drive train. Including the heating currents and eliminating

$$I_{\mathrm{batt}} = \frac{U_{\mathrm{batt}} u_{\mathrm{batt}}^2}{R_{\mathrm{batt},1}} + \frac{U_{\mathrm{batt}} u_{\mathrm{cab}}^2}{R_{\mathrm{cab},1}} + \frac{P_{\mathrm{trac}}}{U_{\mathrm{batt}}} \tag{7}$$