→ modelling and simulation
→ control design
→ system troubleshooting
→ technology transfer and training
→ energy efficiency investigation
→ software tools

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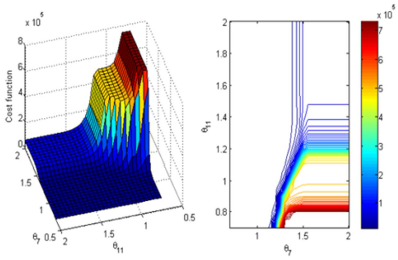

Thermal Management of Electric Vehicle Batteries

This document briefly reviews the state-of-the-art algorithms for thermal management of batteries in Electric Vehicles. Industrial Systems and Control (ISC) Ltd has expertise in advanced control systems for a range of industries including automotive. This includes applications for the energy management of hybrid/electric vehicles.

Battery Thermal Management

Electric vehicles (EVs) are one of the most promising technologies, owing to their remarkable energy saving capabilities and the potential to exploit renewable energy via a power grid. Traction battery packs are currently the most common electric energy carrier onboard and play an essential role in the performance, economy, and the acceptance of EVs. To make costly batteries safe, efficient, and durable in a complex vehicle environment, meticulous monitoring and control of internal battery states, e.g., battery thermal dynamics, is required.

In ideal conditions, a battery would operate around a prescribed temperature (that is different for each battery type due to electrochemistry) and maintain such a temperature within the prescribed limits identified by the manufacturer. This applies to both the average temperature of the battery pack and the temperature distribution over the pack. Temperature variations from module to module in a pack could lead to different charge/discharge behavior for each module. This, in turn, could lead to electrically unbalanced modules/packs, and reduced pack performance.

The aim of a BTMS is to deliver a battery pack at an optimum average temperature (dictated by life and performance trade-off) with a uniform temperature distribution (or only small variations between the modules and within the pack) as identified by the battery manufacturer. However, the pack thermal management system has to meet the requirements of the vehicle as specified by the vehicle manufacturers (it must be compact, lightweight, low-cost, easily packaged, and compatible with the location in the vehicle). In addition, it must be reliable, and easily accessible for maintenance. It must also use low parasitic power, allowing the pack to operate over a wide range of climatic conditions (very cold to very hot), and provide ventilation if the battery generates potentially hazardous gases.

Battery Thermal Management System Design

Different methods exist for developing a Battery Thermal Management System (BTMS). Each approach can be customized to a particular battery pack and related to the application, also considering other aspects such as the level of sophistication, the availability of information, or the budget.

In general, a BTMS is developed following a well-established workflow:

- **Define the BTMS design objective and constraints.** These are dictated by the battery type, acceptable temperature range, acceptable temperature variations, and the packaging requirements for the vehicle.
- **Obtain module/pack heat generation and heat capacity.** These will affect the size of the cooling/heating system and how fast the pack responds to temperature fluctuations.
- **Perform a first-order module and BTMS evaluation.** Preliminary analysis is performed to determine the transient and steady-state thermal response of the module and pack in order to select an initial strategy. Various options, choices of heat transfer medium (air or liquid), and different flow paths (direct or indirect, series or parallel) are evaluated.
- **Predict the battery module and pack thermal behavior.** Detailed analysis is done to evaluate the impact of various parameters under various conditions and driving duty cycles for both battery module and pack.
- **Design a preliminary BTMS.** Based on the packaging and expected performance, the system parameters are specified.
- **Build and test the BTMS.** A prototype BTMS is built and then tested on the bench and in the vehicle under various loads and conditions.
- **Improve the BTMS**. Based on the test data and analysis, the design is fine-tuned or modified for the next step.

Our Expertise

- **In-depth understanding of control technologies**
- **Extensive experience in diverse industrial applications**
- **High-fidelity modelling of system behaviour**
- **Expert analysis of complex problems**
- **Proven project management and research skills**

Our Core Competencies

- **Dynamic modelling & simulation**
- **Control strategy design and implementation**
- **Optimization**
- **Algorithm development**
- **Benefits analysis and technology review**
- **Research & Development**
- **Troubleshooting**
- **Training**

Our Philosophy

- **Approaching problems with an open mind**
- **Dedicated to identifying practical and innovative solutions without compromising performance.**
- **Imparting understanding and empowering clients to drive improvements themselves.**

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Control Policy for BTMS

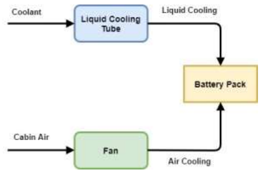

Figure 1. An Air and indirect liquid combined BTM system for HEVs

The BTM control problems can be posed in an optimization framework. Such an approach allows the battery temperature to be regulated in order to ensure to be maintained at the optimal operating points. This optimizes the battery performance and can satisfy other specifications (e.g. minimization of power consumed for cooling/heating) and system constraints (e.g. maximum/minimum battery temperature). The optimal control framework involves the definition of a cost-function to be minimized, which represents the control objective to be achieved. For example, consider the control scenario, as shown in

Figure 1, where a fan and a liquid tube control the battery temperature, where one of the cost-terms may be the power consumption used by the actuators. The control problem can be formulated as

$$\min_{P_{air},P_{liq}} \left((T_{batt}(t) - T_{ref}) + P_{air}(t) + P_{liq}(t)\right)$$

where $T_{batt}(t)$ is the battery temperature, T_{ref} is the optimal battery operating temperature and $P_{air}(t)$ and $P_{liq}(t)$ represent the power consumed by the fan and the liquid tube actuators, respectively. The problem can also include a set of constraints representing physical and design limits, for example:

$$T_{batt}^{MAX} \leq T_{batt}(t) \leq T_{batt}^{min}$$
$$P_{air}^{MAX}(t) \leq P_{air}(t) \leq P_{air}^{min}(t)$$
$$P_{liq}^{MAX}(t) \leq P_{liq}(t) \leq P_{liq}^{min}(t)$$

The BTM control problem may be formulated using different control methods (e.g. LQG or ad-hoc rule-based policies). Among them, Model-based Predictive Control is a possible candidate for optimally managing the battery temperature and satisfying different constraints. The predictive control framework would take account of the future dynamic behavior of the temperature, and time-varying environmental conditions affecting the temperature and battery usage (e.g. future driving cycle information and environmental changes such as external temperature). The choice of cost-function and system model description will greatly affect the robustness and reliability of the solution, and it is here that ISC has particular experience and expertise.

Industrial Systems and Control Ltd.

Industrial Systems and Control (ISC) Ltd., was set up almost 30 years ago to provide technology transfer between the University of Strathclyde' Industrial Control Centre and industry.

ISC Ltd., works across industrial sectors and has gained wide experience in a range of applications. It is this peripheral vision, which is valuable for automotive companies, which have a complete understanding of current advances in the automotive industry but might gain from design and technological advances in other sectors.

ISC Ltd. has particular expertise and experience on the following areas and methodologies:

- Physical system modelling and simulation, including training simulators.
- Developing tailored optimal or predictive control solutions for real-world applications.
- Production of bespoke estimation and filtering algorithms for nonlinear control.
- Use of stochastic or robust controls for different industries like wind energy and marine.
- Design of Machine Learning algorithms for industrial and embedded domains.
- Training courses mostly for the automotive industry based in the US.

How Does ISC Work?

The degree of cooperation with the companies we serve is probably much closer than with many consulting companies because of our University origin. ISC has long experience in the application of advanced controls across different industrial sectors and this is a strength we bring to the projects. However, the engineers in the companies we work with know more about the applications and this requires close contacts to be maintained and regular reporting. I often claim and I believe it to be true that by the end of our projects the engineers we work with know more about the advanced methods that we are applying than ourselves. This is because they are the ones at the sharp end of evaluating the techniques on the engines or other applications

Clients Include

- **Torotrak: variable transmission system.**
- **Visteon: applying LabVIEW to automotive power control.**
- **General Motors: SI engine control.**
- **General Motors: SCR system identification.**
- **General Motors: Control model calibration.**
- **Toyota: Diesel engine control.**
- **Cummins: Diesel engine design methods assessment.**
- **Ford: Autonomous vehicle control.**
- **FCA: Training Activity via Electronic throttle design study.**
- **NXP: Hybrid Electric powertrain control.**

Recent Automotive Training Courses

- **Ford at Dearborn annual courses between 2004-2019**
- **Cummins at Columbus, 2018**
- **Toyota at Ann Arbor 2014 & 2018**
- **Chrysler at Auburn Hills 2011-2016**
- **Freescale in Glasgow and Detroit 2008**
- **NXP in Glasgow 2018**
- **GM Detroit 2015**
- **Jaguar in Coventry and Gaydon 2006 & 2009**
- **Riccardo in Leamington and Shoreham 2006 & 2009**
- **Visteon in Detroit 2004**

"Approaching a problem with an open mind is an important aspect of the ISC philosophy, as is using the simplest, most cost-effective solution."

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