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Optimisation of Electric Vehicles within a Dynamic Inductive Charging Infrastructure

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Executive Summary

The strong interaction between electric vehicles and the charging infrastructure presents new challenges towards system-level optimization. Moreover choices between the power level, duration, and frequency of charging events can have direct impact both on energy efficiency, as well as the overall lifetime of vehicles. This paper presents a preliminary study into the optimization scheme for such systems, with the focus on an electric bus application. The results illustrate an energy saving when comparing the EMS and baseline strategy of ~ 1.6 % improvement measured in kWh/km, alongside a potential cycle life prolongation factor improvement of the EMS compared to the baseline is 1.5 in average.

1 Introduction

Inductive-charging has been recognized as a promising solution to improve the Electric Vehicles (EVs) driving range and, to reduce the cost of the EV, given the need for a smaller battery [1]. This paper presents an energy management in the EVs and preliminary analysis on the relation among the inductive-charging power capability, driving range and battery cycle-life for an EV.

An energy management strategy (EMS) is firstly developed to optimize the energy efficiency in the EVs. The EMS minimizes the cumulative battery energy loss by exploiting a flexible heating/cooling power of an active Battery Thermal Management System (BTMS). It is noted that in EVs, the BTMS aims at keeping the battery temperature in an optimal operating range (20^{o}C-40^{o}C) to maximize the battery performance, efficiency and lifetime. [2]. The developed EMS is compared with a base line (BL) strategy to demonstrate the capability to extend the driving range of an EV. In BL strategy, the BTMS heating/cooling power is constant over the entire driving cycle.

Having the developed EMS for the EV, a sensitivity analysis is performed to show the dependence of the range extension (when using the developed EMS) on the inductive-charging power capability. Moreover, using an existing battery cycle-life model in literature [3] [4], trade-off between the inductive-charging power capability and the battery cycle-life is also presented.

This paper is organized as follows: Section 2 describes the overview of an EV powertrain in relation to an inductive-charging system. Section 3 formulates an Optimal Control Problem (OCP) for minimizing the cumulative battery energy loss in an EV. Solution of the formulated OCP is developed in Section 4. Section 5 presents the capability of the EMS to extend the driving range compared to the BL strategy and, the relation between the inductive-charging power capability at the charging station, the EV's range and the battery cycle-life. Conclusions and future work are given in Section 6.

2 System Description

Figure 1 denotes the powertrain topology of an EV in relation with an inductive-charging system. The inductive charging system consists of several charging stations visualized as Primary conductors in Figure 1. These inductive-charging stations are installed at predefined locations on the driving cycle and are powered from the electric grid.

The EV powertrain, shown inside the dash black rectangular, is equipped with a secondary conductor to allow charging the battery wirelessly when the EV stops at the charging-station. The battery is used to not only power the electric machine (EM) to propel the vehicle but also, satisfy the power requested by the auxiliaries and BTMS.

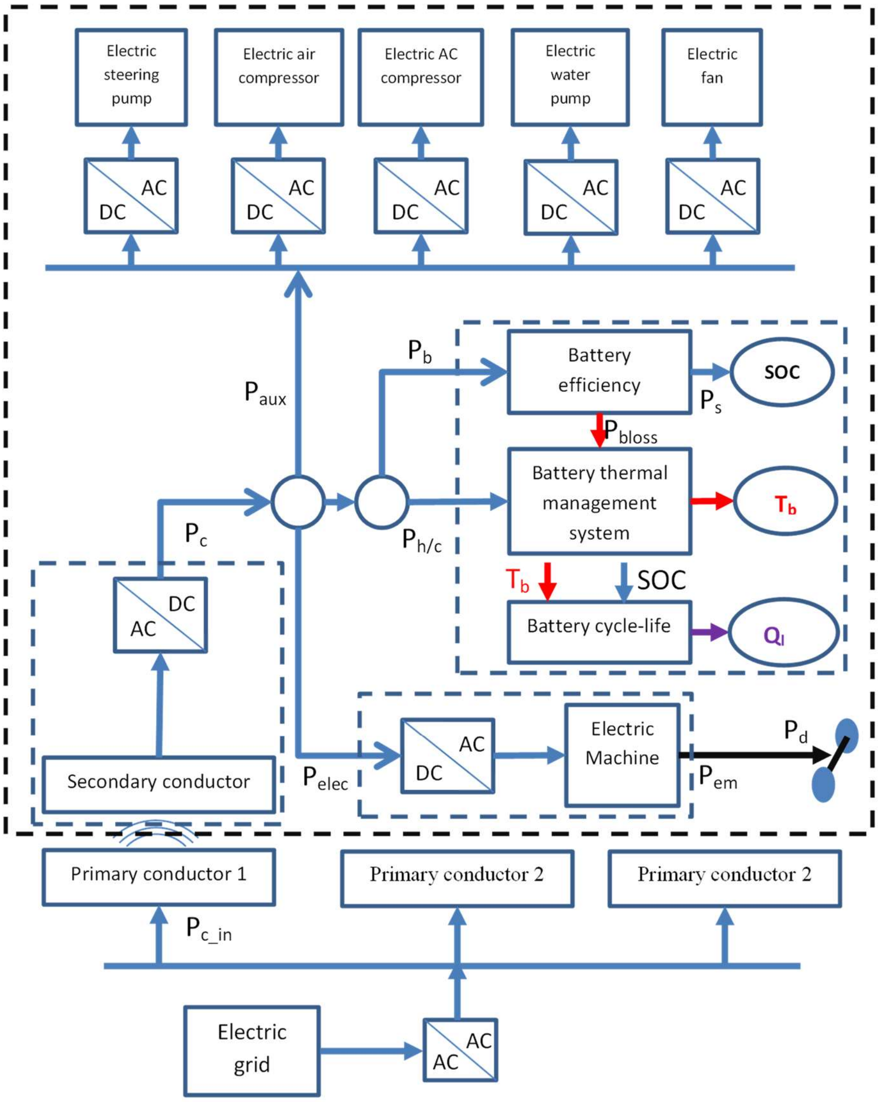

Figure 1. Overview of an electric vehicle powertrain topology in relation with an inductive-charging system.

Definition of the symbols in Figure 1 in given in Table 1. It is noted that Pb is positive when charging the battery. On the other hand, Pb become negative valued during discharging the battery. Pelec is positive/negative when the electric machine operates in Motor/Generator. Ph/c>0 for when cooling the battery whereas Ph/c<0 when heating the battery.

Table 1. Definition of the symbols denoted in Figure 1.

Symbol	Unit	Definition
P_{c_in}	[W]	Inductive-charging input power
P_c	[W]	Inductive-charging output power
P_{aux}	[W]	Auxiliaries power request
P_{elec}	[W]	Electric machine electric power
P_{em}	[W]	Electric machine mechanical power
P_d	[W]	Power demand from drivetrain
$P_{h/c}$	[W]	Heating/cooling power demand of the battery thermal management system
P_b	[W]	Battery charge/discharge power at its terminal
P_s	[W]	Net stored/retrieved battery power
P_{bloss}	[W]	Battery power loss
SOC	[%]	Battery State of Charge
T_{ambi}	[ºC]	Ambient temperature
T_b	[ºC]	Averaged battery temperature
Q_l	[%]	Cumulative battery capacity loss

Mathematical model of the system, shown in Figure 1, is briefly described as below

- Inductive charging model:

$$P_{c\_in} = \frac{P_c}{\eta_c\left(P_{c\_in}\right)} \tag{1}$$

where η_c is the inductive-charging efficiency including the efficiency of the AC/DC power inverter.

- Vehicle model:

$$P_c = P_{elec} + P_{aux} + P_b + P_{h/c} \tag{2}$$

$$P_{em} = P_d \tag{3}$$

- Electric machine model:

$$P_{em} = \min\left(\eta_e^- P_{elec}, \frac{P_{elec}}{\eta_e^+}\right) \tag{4}$$

where η_e^+ and η_e^- are the EM efficiency (including the DC/AC power inverter efficiency) for Generator and Motor mode, respectively.

- Battery pack model
    - Battery efficiency model:

$$P_s = P_b - P_{bloss} \tag{5}$$

$$P_{bloss} = \beta P_b^2 \tag{6}$$

$$\dot{SOC} = \frac{1}{E_{s\_cap}} P_s \tag{7}$$

Where β [-] is the battery power loss coefficient. E_{s_cap} [J] is the fresh battery energy capacity.

- Battery thermal model:

$$\dot{T}_b = \frac{1}{C_b}\left(P_{bloss} - \eta_{h/c} P_{h/c}\right) \tag{8}$$

Where C_b [J/K] is the thermal capacity of the battery pack. $\eta_{h/c}$ [-] is the heating/cooling efficiency. We also assume that the battery cooling circuit is an active fluid cooling system and the battery pack is quite isolated from the ambience.

- Battery cycle-life model:

$$\dot{Q}_l = h(P_s, T_b) Q_l^{\frac{z-1}{z}} \tag{9}$$

Where z is the power law factor. This model is developed and verified in [4]. It can be used to analyze qualitatively the influence of dynamic battery power, temperature profiles on the battery capacity loss (representing the battery cycle-life). It is assumed that the auxiliaries power and driver power demand are provided. Modelling of auxiliaries and drivetrain are omitted.

3 Problem Formulation for Energy Management in EVs

- Objective: Minimizing the cumulative battery energy loss

$$J = \int_{t_0}^{t_f} P_{bloss}(t) dt \tag{10}$$

- Control variables: $P_{h/c}$
- Constraints:
  - Heating/cooling power limitation

$$\underline{P_{h/c}} \le P_{h/c} \le \overline{P_{h/c}} \tag{11}$$

  - Battery SOC:

$$\underline{SOC} \le SOC \le \overline{SOC} \tag{12}$$

  - Battery temperature:

$$\underline{T_b} \le T_b \le \overline{T_b} \tag{13}$$

4 Energy Management Solution

The objective of the formulated optimal control problem (OCP) is to minimize the cumulative battery energy loss while taking into account the constraints on battery SOC and temperature. Using Pontryagin's Minimum Principle [5], the Hamiltonian function is constructed from the objective function (10) and the battery SOC (7), temperature (8) dynamics.

$$H = \beta P_b^2 + \lambda_1 E_{s\_cap} \dot{SOC} + \lambda_2 C_b \dot{T}_b \tag{14}$$

$$H = \beta P_b^2 + \lambda_1 \left(P_b - \beta P_b^2\right) + \lambda_2 \left(\beta P_b^2 - \eta_{h/c} P_{h/c}\right) \tag{15}$$

Substituting $P_b = P_c - P_{h/c} - P_{elec} - P_{aux}$ from (**2**) to the above equation, we obtain

$$H = H\left(P_{h/c}, \lambda_1, \lambda_2, P_{elec}, P_{aux}\right) \tag{16}$$

The necessary conditions for the optimal solution are derived as

$$P_{h/c} = \arg \min_{\underline{P_{h/c}} \le P_{h/c} \le \overline{P_{h/c}}} H\left(P_{h/c}, \lambda_1, \lambda_2, P_{elec}, P_{aux}\right) \tag{17}$$

$$\dot{\lambda}_1 = -\frac{\partial H}{\partial SOC} = 0 \tag{18}$$

$$\dot{\lambda}_2 = -\frac{\partial H}{\partial T_b} = 0 \tag{19}$$

From (17-19), the optimal solutions are obtained as

$$\lambda_1^o = \lambda_1(t_0), \forall t \in \left[t_0, t_f\right] \tag{20}$$

$$\lambda_2^o = \lambda_2(t_f), \forall t \in \left[t_0, t_f\right] \tag{21}$$

$$P_{h/c}^o = \max\left(\min\left(\frac{\lambda_1^o + \eta_{h/c}\lambda_2^o}{2\beta\left(1 - \lambda_1^o + \lambda_2^o\right)} + P_c - P_{elec} - P_{aux}, \overline{P_{h/c}} \right), \underline{P_{h/c}} \right) \tag{22}$$

5 Simulation Results

Simulation Environment

The focus of this paper is to study an application of an Electric Bus (EBus) where the daily route is specified. The inductive-charging station is installed at three pre-selected bus stops. When the EBus stops at the charging station, the inductive-charging station can provides a charging power at its output up to 200kW. When the EBus is charged at the inductive-charging station, the charging power is constant. The authors are aware that the charging pattern also affects the battery cycle-life [6]. Optimizing the battery charging pattern is a relevant topic for future research.

The total electric power requested from the drivetrain and the auxiliaries (P_{elec}+P_{aux}) is shown in the upper plot of Figure 2. The lower plot of Figure 2 shows the availability of the inductive-charging stations on the driving cycle. It is assumed in this study that there are three inductive-charging stations installed on the bus route.

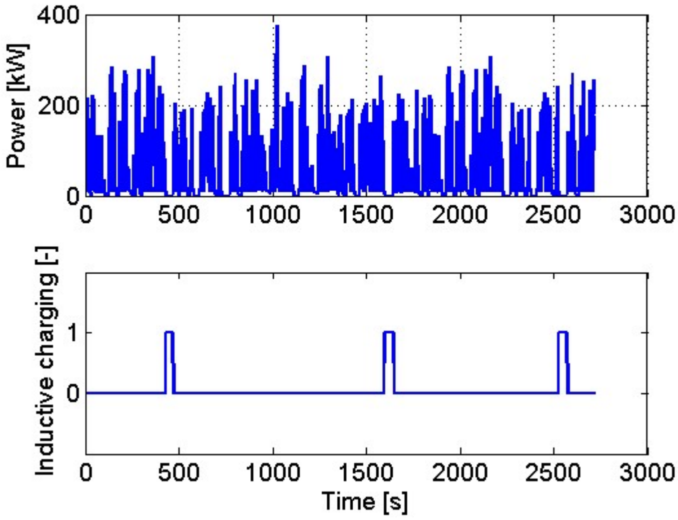

Figure 2. Upper plot: Electric power requested from the drivetrain and the auxiliaries. Lower plot: Availability of the inductive-charging where '0' is not and '1' is yes

Other simulation parameters are shown in Table 2.

Table 2. Simulation parameters

Parameter	Unit	Value
$\overline{SOC}$	[%]	100
$\underline{SOC}$	[%]	0
$SOC(t_0)$	[%]	50
$\underline{T_b}$	[ºC]	20
$\overline{T_b}$	[ºC]	40
$T_b(t_0)$	ºC	25ºC

Comparison Between BL Strategy and the Developed EMS

In this section, the developed EMS is compared with the BL strategy to show its capability in extending the vehicle driving range. The comparison also demonstrates how the developed EMS extends the vehicle driving range. It is noted in the BL strategy, the battery heating/cooling power is constant over the entire driving cycle. The constant heating/cooling power value is chosen such that the battery temperature is kept in its predefined operating range (20ºC-40ºC) and the battery temperature at the end of the driving cycle is equal to 40ºC.

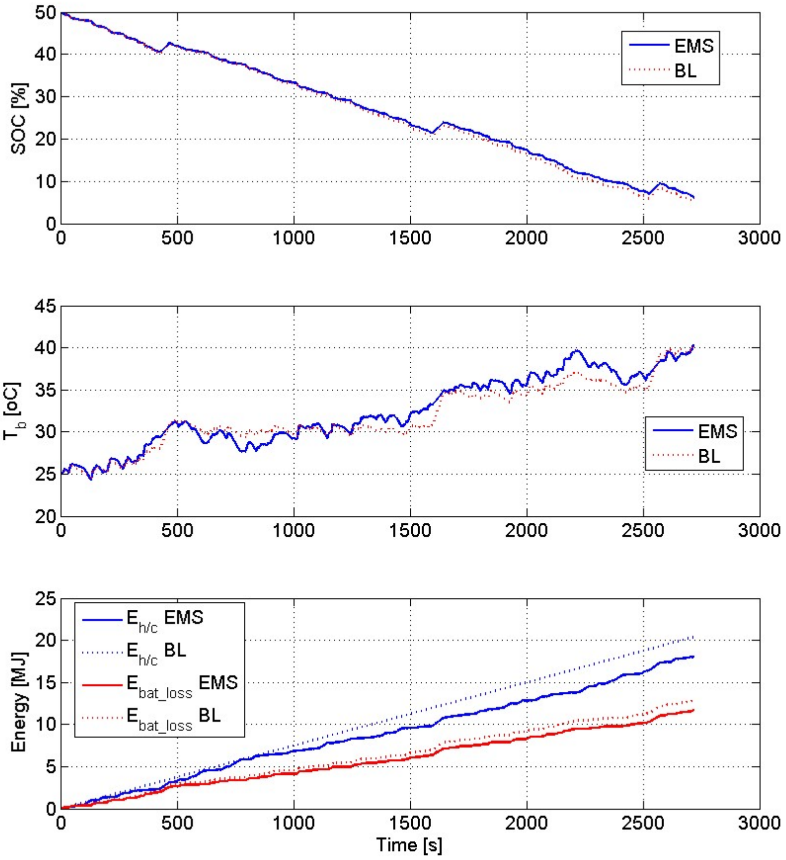

Figure 3. Comparison between BL strategy and the developed EMS regarding the battery SOC, temperature, cumulative heating/cooling energy and cumulative battery energy loss

Figure 3 shows the comparisons of system responses when using the BL strategy and the developed EMS. Both strategies keep the battery SOC and temperature within their predefined boundaries. The upper plot of Figure 3 shows that at the end of the driving cycle, the battery SOC ends up at higher level when using the developed EMS compared to using the BL strategy. It suggests that the developed EMS is able to extend the vehicle range.

The bottom plot of Figure 3 demonstrates the cumulative energy of the battery heating/cooling action ($E_{h/c}$) and the cumulative battery energy loss E_{bat_loss}. One can see from the plot that the developed EMS uses less heating/cooling energy but can still keep the battery temperature in its predefined range, see the middle plot of Figure 3. Moreover, by using the developed EMS, the battery is operated more efficiently regarding the smaller battery energy loss compared to using the BL strategy. It also helps to extend the vehicle range. The following text explains how the developed EMS can reduce the battery energy loss compared the BL strategy.

Figure 4 zooms in the driving cycle in a period from 1350 [s] to 1650 [s].

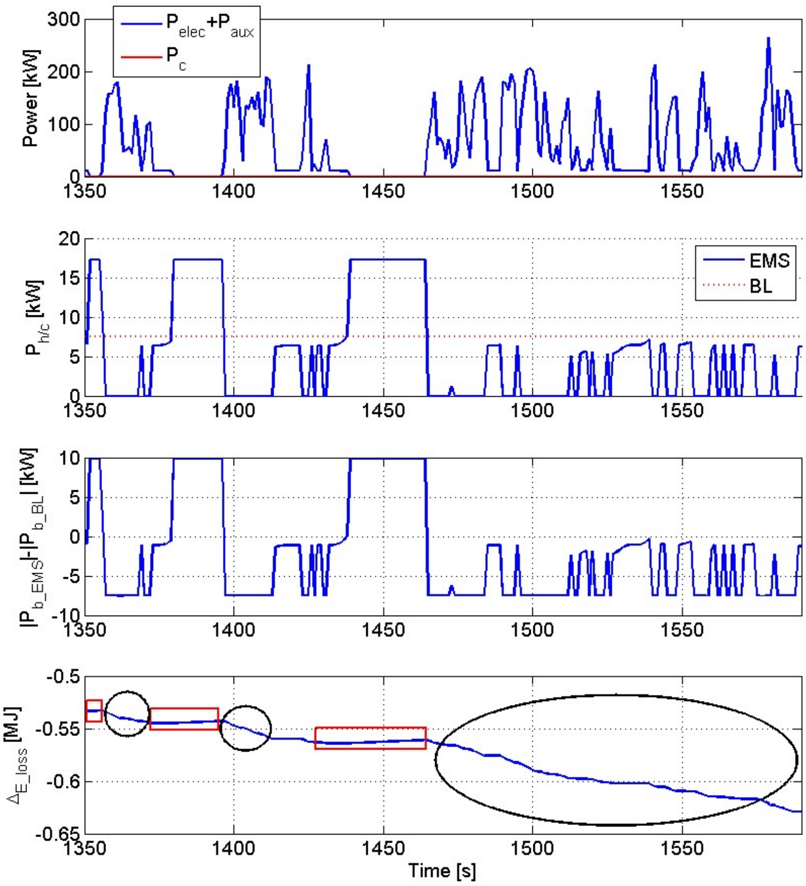

Figure 4. System responses comparison between the developed EMS
and the BL strategy to explain how the EMS can reduce the battery energy loss effectively.

It is observed from the first and second plots of Figure 4 that higher requested electric power (from the drivetrain and auxiliaries) leads to smaller battery heating/cooling power $P_{h/c}$ when using the developed EMS. When the requested electric power is high, the developed EMS tries to limit the battery heating/cooling power $P_{h/c}$ to avoid the surplus increase of the battery (peak) discharge power. As a result, the battery power loss can be reduced effectively since the battery power loss is proportional to the square of the battery charge/discharge power $P_{bloss} = \beta P_b^2$.

The third plot of Figure 4 shows the difference between the absolute values of the battery power when using the developed EMS and the BL strategy. For high requested electric power (from the drivetrain and auxiliaries), the battery is discharged with smaller power when using the developed EMS compared to using the BL strategy.

The bottom plot of Figure 4 shows the difference between the cumulative battery energy loss when using the developed EMS and the BL strategy, $\Delta_{E\_loss} = \int_{t_0}^{t_f} P_{bloss\_EMS}(t) - P_{bloss\_BL}(t)dt$.

The smaller Δ_{E_loss}, the more effective the developed EMS can reduce the battery energy loss compared to the BL strategy. It is also observed that, the slope regarding the decrease of Δ_{E_loss} (e.g., highlighted as black circles) is steeper than the slope regarding the increase of Δ_{E_loss} (e.g., highlighted as red rectangular). Ultimately, it results in a smaller battery energy loss when using the developed EMS.

Relation between inductive-charging power, range extension and battery cycle-life

Having the energy efficient EMS developed in previous section, the sensitivity analysis is performed and shown in Figure 5 to study the relation among the inductive-charging power capability, range extension and battery cycle-life.

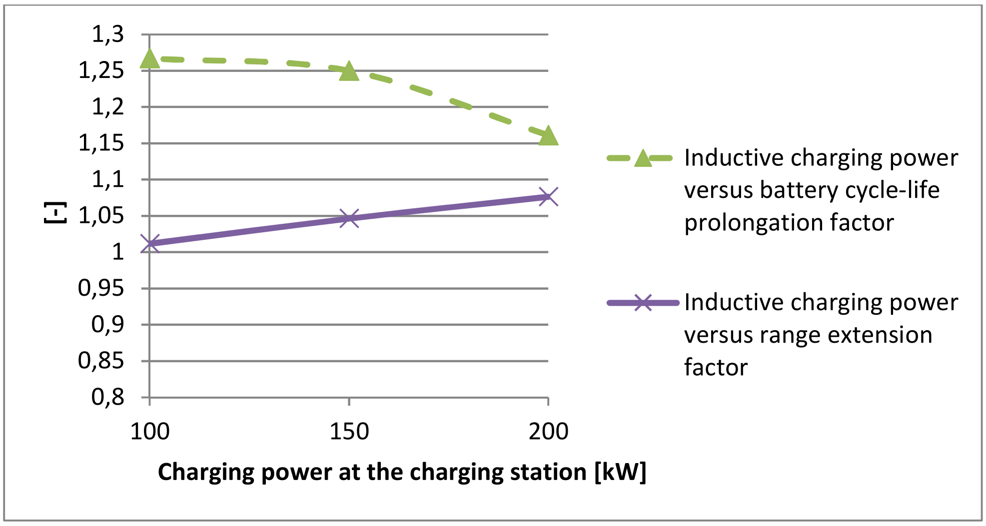

Figure 5. Relationship between the inductive-charging power capability, range extension and battery cycle-life

The battery cycle-life prolongation factor is computed as the ratio between the estimated battery cycle-life when using the developed EMS and the estimated battery cycle-life when using the BL strategy. It is noteworthy that the battery cycle-life is estimated using the model (9) with the assumption that the EBus runs on the same route for its entire vehicle life.

The range extension factor is computed as the ratio between the (maximum) driving range of the EV when using the developed EMS and the driving range when using the BL strategy.

As observed from Figure 5, higher inductive charging power at the charging station leads to higher range extension factor but smaller battery cycle-life prolongation factor. Moreover, the range extension factor is linear proportional to the inductive-charging power capability. On the other hand, the battery cycle-life prolongation factor reduces exponentially for higher inductive-charging power capability. It suggests that there is a compromise between the battery cycle-life of the EV and the inductive-charging system power capability. This compromise should be carefully considered to achieve the most economical solution for building the EV within the inductive-charging system.

6 Conclusions and Future Work

Conclusions

The simulation results indicate an energy saving when comparing the EMS and baseline strategy is ~ 1.6 % improvement measured in kWh/km. In addition to this, the utilized models show a potential cycle life prolongation factor improvement of the EMS compared to the BL is 1.5 in average. The following conclusions are made regarding the energy management strategy and the sensitivity analysis for the inductive-charging EV.

- The EV can be operated more efficiently to reduce the energy consumption by optimizing the battery heating/cooling power. Specifically, when the requested electric power from the drivetrain is high, the battery heating/cooling power should be small to avoid adding surplus increase to the battery discharge power if no temperature constrains are violated.
- Driving range extension is linearly proportional to the inductive-charging power whereas the battery cycle-life reduces exponentially for higher inductive-charging power.
- There exists a compromise between the battery cycle-life of the EV and driving range extension when using inductive-charging system. This compromise should be carefully considered to achieve the most economical solution for building the EV within the inductive-charging system.

Future work

The following research questions are relevant for future research

For energy management in the EV:

- Besides the thermal buffer of the battery temperature, what are the other buffers beneficial for further energy saving in the EV (thermal CAB, passenger comfort)? What are their added values and how to realize their benefit with more smart/optimal energy management?
- What are the impacts of different driving scenarios (driving cycles, ambient conditions, driving style) on the developed EMS regarding for example, energy saving, robustness?
- How to manage the battery life degradation in an EV while driving?

For inductive-charging system

- What are the optimal number, location of the inductive-charging system for a specific bus route to achieve the smallest investment cost (infrastructure cost + battery cost)?
- What is optimal stopping time for charging the battery in relation to range extension, battery lifetime?
- What is the optimal battery charging power pattern regarding the charging time, battery cycle-life when charging the battery at the inductive-charging station?

7 Acknowledgments

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8 References

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9 Authors

Dr. Thinh Pham obtained his PhD in 2015 in the Control System group of the Electrical Engineering Department at Eindhoven University of Technology. His research deals with integrated energy management for hybrid electric vehicles, being part of a Dutch multidisciplinary research project entitled: “Hybrid Innovation for Truck (HIT)”. He is currently a powertrain control research scientist within TNO, the Dutch Organization of Applied Research. His activities include battery management system modelling and control, predictive integrated powertrain control (IPC) algorithm development and real-time implementation among others. He is currently involved in the European projects 3CCar and ORCA, focusing on predictive powertrain control technologies.

Dr. Steven Wilkins works as a scientific research engineer with a background in hybrid and electric vehicle systems and powertrain modelling and simulation, originally based at Imperial College London where he completed his PhD and post-doctoral studies, is now an part-time Assistant Professor within the University of Eindhoven, with focus on battery management systems. He has been involved in a wide range of research projects funded by EPSRC, Industrial and Governmental, and the E.U. within Frameworks 5, 6, and 7. He is now based in the Netherlands as a senior research scientist within TNO, the Dutch Organization of Applied Research. He is a member of the Powertrains department within TNO, is an active member of EARPA and EGVIA, and is involved in the FABRIC, TRANSFORMERS, CONVENIENT, EMC2, ABattReLife, AMBER-ULV, ORCA and 3CCar European project amongst others.