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Battery Peak Power Shaving Strategy to Prolong Battery Life for Electric Buses

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Abstract: This paper presents a battery peak power shaving strategy for battery electric buses. The developed strategy restricts the battery charge/discharge power when the propulsion power demand is high to avoid high deterioration of the battery capacity during operation. Without reducing the propulsion power, the developed strategy optimizes the power demand of the passenger cabin air conditioning system while guaranteeing the passenger temperature comfort. An equivalent consumption minimization strategy (ECMS) technique is extended to include the thermal comfort of the passenger in the energy management system of the bus. The developed strategy is analytical, real-time implementable and verified via hardware-in-the-loop test. Simulation results demonstrate the capability for satisfying the propulsion power demand and passenger temperature comfort while reducing the battery peak power (up to 20% during acceleration) to restrict the battery degradation significantly.

Keywords: Energy Management System, Integrated Energy Management, Equivalent Fuel Consumption Minimization, Battery Electric Bus, Passenger Thermal Comfort.

1. INTRODUCTION

For public transportation in urban areas, application of electric drive technology to buses could significantly reduce harmful emissions, noise and improve the vehicle energy efficiency as well as reducing CO_2, (Zivanovic and Nikolic (2012)). Compared to conventional buses, where the Internal Combustion Engine (ICE) is the only power source, electric buses utilize electric power sources to support the ICE and/or power the vehicle. Regarding the power sources, electric buses can be classified into four categories namely, hybrid electric buses, plug-in hybrid electric buses, battery electric and fuel cell electric buses. These categories have their own potential for improving the vehicle operation performance such as emissions and noise reduction. This paper focuses on battery electric buses which are refferred to EBuses in the remainder of this paper.

EBuses have been in commercial production for several years, e.g. Proterra's EcoRide BE35, BYD eBUS-12, SMG battery electric bus and Optare's battery-powered Versa, (Zivanovic and Nikolic (2012)). Although EBuses are promising technology to considerably limit the environment impact of road transport, their market share is still small compared to conventional bus driven by the ICE only. Primary investment cost and limited driving range are two of the major concerns for successful commercialization of EBuses. The cost concern reflects a hidden future investment needed for replacement of the high-voltage battery over the vehicle lifetime. It is neccessary to maximize the battery life in EBuses to improve the business case of the EBus.

During operation, battery capacity is degraded with a rate depending on several factors, e.g., charge/discharge rate, temperature and total energy throughput (Ecker et al. (2012)). In previous research (Wang et al. (2013); Pham (2015); Pham et al. (2015)), it is identified that to preserve the battery life, the battery should not be charged/discharged at too high power to avoid high deterioration of its capacity.

This paper introduces a battery peak power shaving strategy to reduce the battery charge/discharge power when the propulsion power demand is high, e.g. during acceleration period. This is done by controlling the auxiliary system power demand. When the propulsion power demand is high, the auxiliary system power demand is limited to reduce the battery charge/discharge power while guaranteeing the auxiliary system functional requirements, e.g., HVAC system should guarantee the thermal comfort of the driver/passenger.

In Andersson (2004), a rule-based peak shaving strategy is developed to control the auxiliary system loads for the conventional/hybrid buses. This strategy helps to improve the total vehicle fuel consumption without decreasing the energy consumption of the auxiliary system. In this paper, the battery peak power shaving strategy is developed using an optimal control framework and the Equivalent Consumption Mininization Strategy (ECMS) technique which

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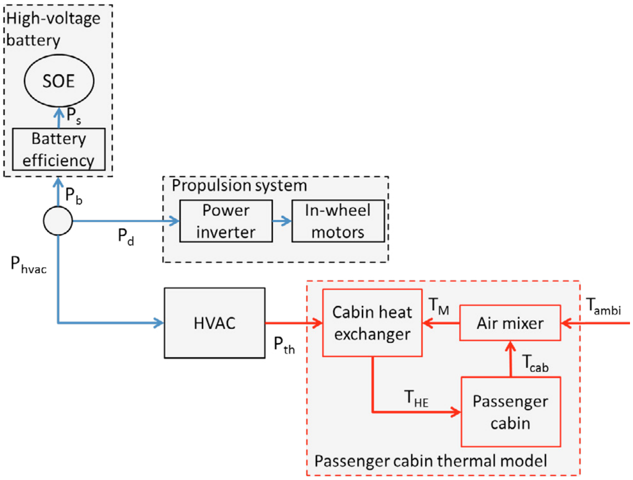

Fig. 1. Schematic overview and related signals for developing the model-based battery peak power shaving strategy in the EBus

is often used for research topics for energy management in hybrid electric vehicles (Delprat et al. (2004); Guzzella and Sciarretta (2007); Kessels et al. (2008); Ambuhl et al. (2010)).

Among various auxiliaries in the EBus, the HVAC system is the largest energy consumer (Andersson (2004); Kambly and Bradley (2014)). The HVAC system cannot be ignored in the EBus since the thermal comfort of the driver/passengers in the bus is legal requirement for driver and highly influential for passenger experience. This paper optimizes the HVAC power demand to reduce the battery peak power while guranteeing the thermal comfort of the passenger and satisfying the propulsion power demand. The developed strategy is real-time implementable and verified via Hardware-in-the-loop (HiL) test.

This paper is organized as follows; Section 2 presents the EBus powertrain model including the HVAC system and the thermal model of the passenger cabin. The battery peak power shaving optimal control problem is formulated in Section 3 and the solution is derived in Section 4. Preliminary results with HiL test of the developed strategy are discussed in Section 5. Conclusions and outlook for future work are given in Section 6.

2. SYSTEM DESCRIPTION

This paper develops a model-based control strategy to reduce the battery charge/discharge peak power to avoid high deterioration of battery capacity during its operation. The developed strategy integrates the HVAC system operation into the operation of the propulsion system to limit the battery charge/discharge power when the propulsion power demand is high while satisfying the thermal comfort requirement of the passenger. This section presents the control model which is used for the control strategy development. This control model includes the EBus powertrain with HVAC system model and the thermal model of the cabin air temperature. It is noted that the EBus simulation model, which will be used in the HiL test, is developed in the ADVANCE environment, a research tool developed by TNO (van den Tillaart et al. (2002)). The simulation model is forward facing and its powertrain model is validated with measured data from the bus manufacturer. Since this paper focuses on developing the control strategy, development of the simulation model is outside the paper's scope.

Regarding the control model, Fig. 1 denotes the topology of the EBus powertrain including the HVAC system and passenger cabin thermal model. Definition of the symbols in Fig. 1 is given in Table 1. The high-voltage battery supplies the power demands from the propulsion and HVAC system. The power realtion is depicted in equation (1)

$$P_b = -(P_d + P_{hvac}) \tag{1}$$

It is noted that P_b is positive/negative when the battery is charged/discharged. Relation between the battery power P_b at its terminals and the net internal battery power P_s is denoted in equation (2)

$$P_s = P_b - P_{b\_loss} \tag{2}$$

with P_{b_loss} [W] is the battery power loss emerging from charging and discharging. It is considered that all the electric losses in the battery emerge as thermal heat. By modeling the losses quadratic with the battery power (Koot et al. (2005)), the battery power loss is obtained as

$$P_{b\_loss} = \beta P_b^2 \tag{3}$$

where β [−] is the battery power loss coefficient. The battery State of Energy (SOE) is governed by

$$\dot{SOE} = \frac{P_s}{E_{s\_cap}} \tag{4}$$

with E_{s_cap} [J] is the fresh battery energy capacity. The HVAC system converts the electric power P_{hvac} into thermal power P_{th} (heating/cooling power) to heat up/cool down the air temperature inside the passenger cabin to satisfy the passenger thermal comfort constraint. It is noted that based on the ASHRAE Standard (ANSI (2013)), the passenger thermal comfort is characterized for both temperature and humidity. This paper focuses on the thermal comfort of the passenger which means that the cabin air temperature should be kept inside a predefined range. Extension of the model to capture the humidity as the other aspects of comfort perception (such as air flow, clothing, etc.) is considered as future work. The thermal power P_{th} is computed from the electric power P_{hvac} using the COP (Coefficient of Performance) value of the HVAC system

$$P_{th} = COP \times u_{mode} P_{hvac} \tag{5}$$

Table 1. Definition of the symbols which are denoted in Fig. 1

Symbol	Unit	Definition
SOE	J	Battery State of Energy
P_s	W	Net internal battery power
P_b	W	Battery (dis-)charge power at its terminal
P_d	W	Propulsion power demand
P_{hvac}	W	HVAC power demand
P_{th}	W	HVAC heating/cooling thermal power
T_{ambi}	K	Fresh air temperature
T_{HE}	K	Air temperature at cabin HE outlet
T_M	K	Air temperature at mixer outlet
T_{cab}	K	Air temperature inside passenger cabin