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Powertrain sizing of electrically supercharged internal combustion engine vehicles

Nikolce Murgovski * **Sava Marinkov** ** **Daniël Hilgersom** **
Bram de Jager ** **Maarten Steinbuch** ** **Jonas Sjöberg** *

* *Department of Signals and Systems, Chalmers University of Technology, 41296 Gothenburg, Sweden (e-mail: nikolce.murgovski@chalmers.se).*
** *Department of Mechanical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands.*

Abstract: We assess the concept of electrically supercharged internal combustion engines, where the supercharger, consisting of a compressor and an electric motor, draws electric power from a buffer (a battery or a supercapacitor). In particular, we investigate the scenario of downsizing the engine, while delivering high power demands by supercharging. Simultaneously, we seek the optimum buffer size that provides sufficient electric power and energy to run the supercharger, such that the vehicle is able to deliver the performance required by a driving cycle representing the typical daily usage of the vehicle. We provide convex modeling steps that formulate the problem as a second order cone program that not only delivers the optimal engine and buffer size, but also provides the optimal control and state trajectories for a given gear selection strategy. Finally, we provide a case study of sizing the engine and the electric buffer for different compressor power ratings.

Keywords: electric supercharger, convex optimization, powertrain design, energy management, optimal control

1. INTRODUCTION

Recent years have shown high interest in the reduction of energy consumption and pollutant emissions of ground transportation. With the goal of improving energy efficiency and employing renewable energy sources, vehicle manufactures are currently introducing several types of electrified vehicles. Nevertheless, the internal combustion engines (ICE) are expected to remain the dominant force in the automotive market for decades to come [Shahed and Bauer, 2009].

To meet the ever-tightening expectations on fuel economy, the automotive industry has pursued the path of engine downsizing [Leduc et al., 2003]. The latter is often followed by a practice of ICE overpowering to improve the vehicle drivability. In general this also results in reduced carbon emissions and a better fuel economy compared to a larger engine, mainly due to the reductions in engine weight, friction and throttle valve losses [Fraser et al., 2009]. ICE overpowering is made possible by the use of boosting devices such as a turbocharger (driven by hot exhaust gases) or a supercharger (driven mechanically by the crank shaft via a chain or belt). In both cases, a compressor increases (boosts) the pressure or density of the air supplied to the engine, providing the engine with more oxygen (air). This allows more fuel to be injected and burned, thereby increasing the ICE maximum torque and power limits. However, turbo-charged ICEs exhibit a relatively low-torque capability at low engine speeds [Taylor and Howe, 2007] which compromises vehicle drivability and acceleration performance. Namely, at low speed the downsized ICEs suffer from the insufficient exhaust gas-flow to adequately propel the turbocharger at the moment the gas pedal is pressed, inducing the well-known turbo-lag [Leduc et al., 2003]. The belt-driven supercharger, on the other hand, does not experience the turbo-lag phenomenon, but is less fuel economic as it increases the engine parasitic losses. One way to efficiently provide the required low-end torque and at the same time eliminate the turbo-surge/lag is to electrify the mechanical superchargers, *i.e.,* replace/equip their mechanical power source (prime mover) with an electric motor [Villegas et al., 2011, Chayopitak et al., 2012, Kachapornkul et al., 2012, Wang et al., 2005]. The resulting device, an electric supercharger, *i.e.,* a motor-compressor unit (MCU), follows a popular automotive trend of vehicle electrification that has already proven capable of improving the efficiency and performance of numerous systems such as the steering, water pump and air conditioning. The success achieved by electrification so far is primarily due to the electric machine's ability to efficiently produce the requested, instantaneous torque in a remarkably wide speed range, from zero to several hundred thousands rotations per minute.

Historically, the lack of compact, high-power/energy-density electric sources and of light-weight, high-speed, high-power-density electric motors prohibited the prolif-

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eration of the MCU devices throughout the automotive sector. The widely used 12 V battery system is at the limit of providing sufficient power for the electrical boost [Taylor and Howe, 2007]. Besides, the high power surges from the MCU may incur high battery losses.

Today the situation regarding electric storage elements is somewhat different as a plethora of high-power batteries and high-energy capacitors appear on the market. However, the choice of electric buffer technology and the optimal buffer size in terms of power ratings and energy density is still an open question.

In this paper we seek the optimum buffer size that provides sufficient electric power and energy to run the supercharger, such that the vehicle is able to drive a representative driving cycle. Besides sizing the buffer, we also investigate the scenario of downsizing the ICE, while delivering high power demands by supercharging. The resulting optimization problem is a dynamic program, where the ICE and buffer are optimal sized only when the vehicle is also optimally controlled on the studied driving cycle. The problem is non-convex, nonlinear and mixed-integer dynamic program, where both plant design and control are optimization variables.

The plant design and control problem is typically handled by decoupling the plant and controller, and then optimizing them sequentially or iteratively [Assanis et al., 1999, Galdi et al., 2001, Wu et al., 2011, Fathy et al., 2004, Peters et al., 2013]. However, sequential and iterative strategies generally fail to achieve global optimality [Reyer and Papalambros, 2002]. An alternative is a nested optimization strategy, where an outer loop optimizes system's objective over the set of feasible plants, and an inner loop generates optimal controls for plants chosen by the outer loop [Fathy et al., 2004]. This approach delivers the globally optimal solution, but it may incur heavy computational burden (when, e.g., dynamic programming is used to optimize the energy management [Tara et al., 2010]), or may require substantial modeling approximations [Filipi et al., 2004, Kim and Peng, 2007, Sundström et al., 2010].

This paper addresses the problem by first decoupling the integer decisions, *i.e.,* the gear selection strategy, and then formulating the remaining problem as a convex second order cone program (SOCP) [Boyd and Vandenberghe, 2004]. The integer signals are decided outside the convex program, by using a simple heuristic strategy that has been observed to give near optimal results for the problem of sizing series and parallel hybrid electric vehicle powertrains [Murgovski et al., 2012c, Pourabdollah et al., 2013].

Finally, a case study is provided that depicts the optimal engine and electric buffer sizes for different compressor power ratings and two buffer technologies, a lithium-ion battery and a supercapacitor.

This paper is organized as follows. Section 2 provides background to the electrically supercharged ICE configuration and states a verbal problem formulation. The mathematical modeling is provided in Section 3 and the convex optimization problem is formulated in Section 4. Section 5 presents a use-case study. Discussion and conclusions are drawn in Section 6.

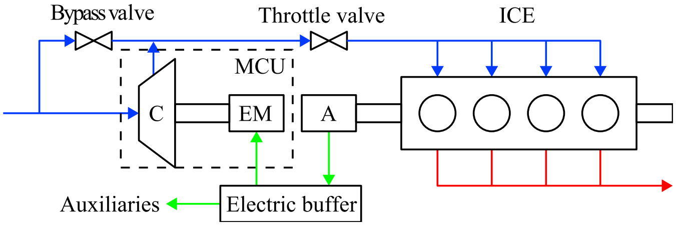

Fig. 1. ICE equipped with a stand-alone motor-compressor unit (MCU). The electric buffer is discharged by auxiliary loads and the electric motor (EM), which in turn drives the compressor (C). The buffer is charged by the conventional car-alternator (A), which is driven by the internal combustion engine (ICE).

Table 1. Optimization problem for powertrain components sizing and energy management.

Minimize:
Operational + component cost;
Subject to:
Driving cycle constraints,
Energy conversion and balance constraints,
Buffer dynamics,
Physical limits of components,
...
(For all time instances along the driving cycle).

2. THE POWERTRAIN SIZING PROBLEM

The block diagram of the ICE electrically supercharged with an MCU is illustrated in Fig. 1. The MCU, which is placed in the ICE air intake along with a bypass valve, enables more power to be delivered from the ICE, *e.g.,* while overtaking or when starting-off at traffic lights. When the excess power is needed, which we refer to as supercharging, the bypass valve is closed, while it is open during naturally-aspirated operation.

The bursts of mechanical MCU power have to be matched by the power ratings of the electric buffer that drives the MCU. However, deciding the optimal buffer energy requirement is not trivial, since this depends on the typical daily usage of the vehicle. A common form of representing the vehicle usage is by recording speed and acceleration profiles for a period of time, and then constructing a driving cycle that contains both the vehicle speed and road topography as functions of time. An example of such cycle is the Class 3 World Harmonized Light Vehicle Test Procedure[1] (WLTP3), which is used here as a proof of concept for realization of the method being proposed.

The vehicle is required to exactly follow the speed demanded by the driving cycle (in a backwards simulation approach), thus ensuring that a possible downsizing of the powertrain does not compromise the demanded performance. To have a fair comparison, the buffer is required to sustain its initial charge at the end of the driving cycle, meaning that any energy used for supercharging has to be put back in the buffer at some point, through the conventional car-alternator driven by the ICE. This may require high utilization of the electric buffer, making it beneficial to increase its size. However, a larger buffer increases the cost of the vehicle. Then, to keep the cost

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[1] http://www.dieselnet.com/standards/cycles, March 2015.