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Real-Time Optimal Energy Management of Electrified Engines

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Abstract: The electrification of engine components offers significant opportunities for fuel economy improvements, including the use of an electrified turbocharger for engine downsizing and exhaust gas energy recovery. By installing an electrical device on the turbocharger, the excess energy in the air system can be captured, stored, and re-used. This new configuration requires a new control structure to manage the air path dynamics. The selection of optimal setpoints for each operating point is crucial for achieving the full fuel economy benefits. In this paper, a control-oriented model for an electrified turbocharged diesel engine is analysed. Based on this model, a structured approach for selecting control variables is proposed. A model-based multi-input multi-output decoupling controller is designed as the low level controller to track the desired values and to manage internal coupling. An equivalent consumption minimization strategy is employed as the supervisory level controller for real-time energy management. The supervisory level controller and low level controller work together in a cascade which addresses both fuel economy optimization and battery state-of-charge maintenance. The proposed control strategy has been successfully validated on a detailed physical simulation model.

Keywords: electrified engines, fuel economy optimization, real-time energy management, decoupling control, dynamics analysis

1. INTRODUCTION

Motivated by the increasing fuel costs and environmental pressures, countries around the world are passing increasingly stricter legislations on the fuel efficiency of internal combustion engines. Heavy duty vehicles (HDVs) contribute almost a quarter of the fuel consumption in transportation, and most are equipped with diesel engines due to their higher thermal efficiency and good durability. With state-of-the-art technologies, an estimated improvement in fuel economy of 35% - 50% of HDVs is considered realistic, with most of the potential concentrated on engine efficiency improvement and engine hybridization Boyd and Vandenberghe (2010). The electrified turbocharger is a critical technology in engine hybridization. It combines a variable geometry turbocharger (VGT) and an electric machine (EM) within a single housing. The EM is capable in bi-directional power transfer, so excess power can be recuperated by the EM to supply electrical accessories or to be stored in a battery for later usage. On the other hand, the EM accelerates the turbocharger to improve engine response, especially for transient torque demands. Due to its location in the air system, reasonably small electric systems can have a large effect on transient behavior and engine efficiency. In this sense the technology is superior to conventional hybrid systems that act on the engine crankshaft.

The electrified turbocharger has attracted considerable development interest. The mainstream diesel engine and turbocharger manufacturers have developed their own prototype electrified turbochargers, see Bailey (2000), Arnold et al. (2005), and Ibaraki et al. (2006). Investigations into the efficiency characterization of an electrified turbocharger through experiments with a heavy duty diesel engine have been made by Terdich and Martinez-Botas (2013) and Terdich et al. (2014). There is a broad agreement that the development of a systematic strategy in both real-time energy management and multi-input multi-output (MIMO) control is essential for exploring the maximum benefits of the electrified turbocharger.

A suitable control and energy management structure for the electrified turbocharged diesel engine (ETDE) is still to be established. In Ibaraki et al. (2006), the EM is controlled in an open loop manner. In Glenn et al. (2010), the EM, VGT, and exhaust gas recirculation (EGR) valve are controlled independently without considering the internal couplings in the engine or the generation setpoints. In 2014, a consortium led by Caterpillar Inc. developed a cutting-edge electrified turbocharger called electric turbo assist (ETA). Based on the ETA, several control methods and testing systems were developed in Loughborough University in simulations Zhao et al. (2015); Zhao and Stobart (2015); Zhao et al. (2016) and experiments Zhao et al. (2014, 2013); Winward et al. (2016); Yang et al. (2016).

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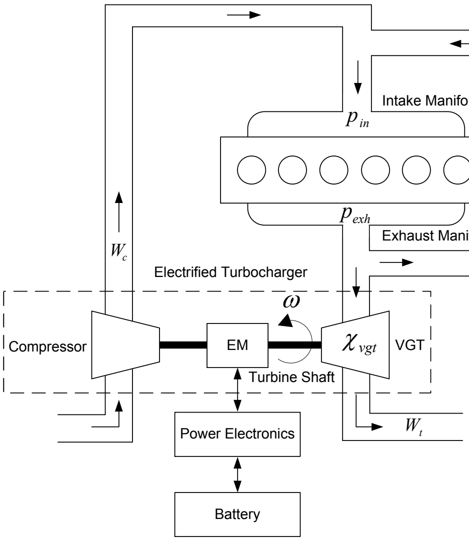

Fig. 1. Electrified turbocharged diesel engine

This paper presents an attempt to address this gap. The main contributions are:

1. An explicit principle for the selection of control variables of an ETDE is proposed based on the dynamics analysis. From this, clear guideline for the generation of setpoints follow.
2. A two-level structure of energy flow management and air path regulation is presented. On the supervisory level, the optimal setpoints of control variables are computed to distribute energy flows in the optimal way. On the low level, a MIMO controller is designed to implement the optimal energy flow distribution.
3. An equivalent consumption minimization strategy (ECMS) algorithm is designed as the supervisory level controller to guarantee the real-time optimization of fuel economy while keeping the sustainable battery usage.
4. A model-based non-smooth robust controller is designed as the low level controller to regulate the air path dynamics and to address the internal couplings among actuators.
5. The proposed control strategy is successfully applied on a physical engine model for validation.

The paper is organized as follows. Following the introduction in section 1, the electrified turbocharger model is described in section 2. The control problem is formulated in section 3, and the control-oriented dynamic system is analyzed in section 4. The supervisory level controller design is presented in section 5, and the low level controller in section 6. Validation results of the strategy are demonstrated in section 7, followed by conclusions in section 8.

2. ELECTRIFIED TURBOCHARGER MODEL

Table 1. Nomenclature

Variable	Description	Unit
N	Engine speed	rpm
T_L	Engine load	Nm
W_f	Engine fuelling rate	kg/s
W_c	Compressor air mass flow rate	kg/s
W_{egr}	EGR mass flow rate	kg/s
W_t	Turbine gas mass flow rate	kg/s
F_1	Burnt gas fraction, defined as $\frac{W_{egr}}{W_c+W_{egr}}$	–
λ	In-cylinder air-fuel ratio, defined as $\frac{W_c}{W_f}$	–
P_c	Compressor power	kW
P_t	Turbine power	kW
P_{em}	EM power	kW
p_{in}	Intake manifold pressure	kPa
p_{exh}	Exhaust manifold pressure	kPa
p_{am}	Ambient pressure	kPa
T_a	Ambient temperature	K
ω	Turbine speed	rpm
τ	Turbocharger time constant	s
η_c	Compressor isentropic efficiency	–
η_t	Turbine isentropic efficiency	–
η_m	Turbocharger mechanical efficiency	–
η_v	Volumetric efficiency	–
χ_{egr}	EGR valve position	–
χ_{vgt}	VGT vane position	–
c_p	Specific heat at constant pressure, 1.01	kJ/(kgK)
c_v	Specific heat at constant volume, 0.718	kJ/(kgK)
R_g	Specific gas constant, $c_p - c_v$	kJ/(kgK)
γ	Specific heat ratio, c_p/c_v	–
μ	$(\gamma-1)/\gamma$	–

The structure of an ETDE is illustrated in Fig. 1, while its variables and related parameters are defined in Table 1. A switched reluctance motor (SRM) is selected as the EM. It is an excellent option in extra-high speed applications thanks to its simple structure, see Bilgin et al. (2015). The EM can work in both assisting (motoring) mode and harvesting (generating) mode. In assisting mode, the EM extracts energy from the battery to improve the engine transient response, or provide steady state boost pressure to enhance low speed torque. In harvesting mode, the additional turbine torque resulting from excess exhaust energy causes a power flow to the generator.

The dynamics of the turbocharger can be modeled as a first-order lag power transfer function with time constant τ:

$$\dot{P}_c = \frac{1}{\tau}\left(P_t + P_{em} - P_{bl} - P_{wl} - P_c\right), \tag{1}$$

where P_{bl} and P_{wl} are the power to overcome bearing losses and windage losses, respectively. The mechanical efficiency η_m is introduced to quantify the energy losses. Therefore, (1) can be represented as

$$\dot{P}_c = \frac{1}{\tau}\left(\eta_m\left(P_t + P_{em}\right) - P_c\right). \tag{2}$$

W_c is related to P_c by

$$W_c = \frac{\eta_c}{c_p T_a}\frac{P_c}{\left(\frac{p_{in}}{p_{am}}\right)^{\mu} - 1}, \tag{3}$$

and P_t can be expressed by W_t:

$$P_t = \eta_t c_p T_{exh}\left(1 - \left(\frac{p_{am}}{p_{exh}}\right)^{\mu}\right)W_t. \tag{4}$$

3. PROBLEM FORMULATION

The development of the real-time energy management strategy is separated into an off-line stage and an on-line stage. In the off-line stage, the control variables are to be selected, which use the additional degree of freedom introduced by the EM actuator for best effect. In addition, the boundaries of selected control variables are to be chosen so as to guarantee that all the setpoints