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Characterisation, control, and energy management of electrified turbocharged diesel engines

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ABSTRACT

The electrification of engine components offers significant opportunities for fuel efficiency improvements. The electrified turbocharger is one of the most attractive options since it recovers part of the engine exhaust gas mechanical energy to assist boosting. Therefore, the engine can be downsized through improved transient responsiveness. In the electrified turbocharger, an electric machine is mounted on the turbine shaft and changes the air system dynamics, so characterisation of the new layout is essential. A systematic control solution is required to manage energy flows in the hybrid system. In this paper, a framework for characterisation, control, and energy management for an electrified turbocharged diesel engine is proposed. The impacts of the electric machine on fuel economy and air system variables are analysed. Based on the characterisation, a two-level control structure is proposed. A real-time energy management strategy is employed as the supervisory level controller to generate the optimal values of critical variables, while a model-based multi-variable controller is designed as the low level controller to track the values. The two controllers work together in a cascade to address both fuel economy optimisation and battery state-of-charge maintenance. The proposed control strategy is validated on a high fidelity physical engine model. The tracking performance shows the proposed framework is a promising solution in regulating the behavior of electrified engines.

1. Introduction

Fuel saving in the transportation is a global critical issue. The transportation sector is the second largest source of greenhouse gas generation and consumes a half of crude oil. In most developed countries, a clear target in improving fuel efficiency of the vehicles has been made by legislation and policies [1]. Engine downsizing offers promising fuel economy improvements by the reduction of friction, thermal losses, and mass [2]. It allows the engine to run in a more fuel-efficient region [3]. The reduced displacement of the downsized engine can be compensated by injecting more fresh air into the cylinder for better combustion [4]. Better air delivery is feasible now by turbocharging, where the state-of-the-art technology is the electrified turbocharger [5]. In the electrified turbocharger, an extra-high speed electric machine (EM) is mounted on the turbine shaft. In periods of speed acceleration or load acceptance, the EM can run as a motor to augment the turbine power to the compressor and, therefore, increase the flow fresh air from the compressor to improve engine performance. This is achieved through either increased availability of combustion air or a reduction in pre-turbine back pressure. In specific engine operating regions, the fuel economy benefit of using an electrified turbocharger is up to 10% [6]. Compared with feeding energy to the crankshaft, the electrified turbocharger is more efficient in improving fuel efficiency for the mechanical losses are reduced [7]. The EM can also run as a generator when exhaust gas power excess the requirement on the compressor side. Several other waste energy recovery technologies are also being developed, where the typical solutions are Organic Rankine Cycle (ORC) and thermal electric generator (TEG). As for the ORC, the major obstacles in installing it on ground vehicles are its high cost and systems complexity [8]. As for the TEG, breakthroughs on the bottlenecks of expensive materials and low energy conversion efficiency are still

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Abbreviations: EM, electric machine; ETDE, electrified turbocharged diesel engine; HDV, heavy duty vehicle; VGT, variable geometry turbine; EGR, exhaust gas recirculation; MIMO, multi-input multi-output; SOC, state-of-charge; ETA, electric turbo assist; SRM, switched reluctance motor; ECU, engine control unit; NRMSD, normalized root-mean-square deviation; NO_x, nitrogen oxides; PM, particulate matters; ORC, Organic Rankine Cycle; TEG, thermal electric generator.

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being expected [9]. The electrified turbochargers gains their popularity since it is easy to assemble and more cost effective [10].

Diesel engines are predominantly used in heavy-duty vehicles and therefore their downsizing would be essential for reducing total fuel consumption [11]. The electrified turbocharger offers a promising solution for the effective air charging of diesel engines. Several prototypes are being developed by leading diesel engine and turbocharger suppliers. In 2003, Caterpillar demonstrated the fuel economy benefit of using the electric turbocompounding on heavy-duty engines [12]. In 2005, Honeywell reported the improvements of fuel economy and transient response using the electric boosting system [13]. In 2006, Mitsubishi developed a hybrid turbo that achieves better combustion, purer exhaust gas, and improved torque response [14]. In academic pioneer works, theoretical analysis and experimental evaluations on the potential of using an electrified turbocharger in fuel economy benefit, exhaust emissions reduction, and torque enhancement are all investigated. The theoretical analysis is given in [15], where an optimisation problem is formulated and solved numerically. The experimental evaluations are given in [16], where the turbo-lag reduction in several typical driving cycles are analysed. The comparison of the transient response improvement using an electrified turbocharger and using an electric turbocompounding is given in [17]. The electrified turbocharger with a different configuration, such as a two-stage electrified turbocharger, is investigated in [18]. In 2014, a consortium led by Caterpillar developed an entirely new electrified turbocharger for heavy-duty diesel engines, called the electric turbo assist (ETA). The characterisation of the ETA has been fulfilled through both simulations and experiments. In [19], the potential of the ETA to reduce fuel consumption by both engine downspeeding and exhaust energy recovery is elaborated in steady states via simulations. In [20], the simulation studies are generalized to transient conditions. In experiments, the mathematical modeling is investigated in [21]. Furthermore, an efficiency mapping work is given in [22]. The improvements in engine energy efficiency and transient response in experiments are covered in [23]. The key issue in the success of an electrified turbocharged diesel engine (ETDE) is online management of energy flows. First of all, the timing control of the EM to work in the generating mode or the motoring mode is necessary. Furthermore, how much power should be applied or extracted needs to be known precisely. Finally at the system level, how the EM works in co-operation with other actuators is fundamental. The control of an electrified turbocharger is challenging because of couplings among different control loops. In modern turbocharged diesel engines, the VGT reduces fuel consumption and, together with exhaust gas recirculation (EGR), enables a reduction in exhaust emissions, particularly nitrogen oxides (NO_x). VGT and EGR work together to meet the desired burnt gas fraction and air-fuel ratio. The VGT loop and EGR loop are strongly coupled because the actuators are both in the exhaust gas flow. In an ETDE, the coupling also indicates that the EM affects the exhaust manifold behavior.

In an ETDE, the selection of control variables is the primary task, for a proper set of control variables can reveal critical engine dynamics [24]. In conventional turbocharged diesel engines, the boost pressure and fresh air flow are normally employed for air system control, with the inputs of VGT opening and EGR opening [25]. Many control methods have been demonstrated on turbocharged diesel engines, which can be mainly categorized into decentralized control and 2-input 2-output (2I2O) centralized control. One of the most influential control methods in decentralized control is linear parameter-varying control [26]. Another typical solution is sliding mode control [27]. On the other side, the most important centralized control method is model predictive control [28]. Recently, fuzzy control has also attracted wide interests [29]. In the ETDE, the EM power is an extra degree of freedom in air system regulation, and therefore, an extra control variable is required to be introduced to reveal the energy balance between fuel and electricity. A 3-input 3-output (3I3O) control structure would be established based on the three actuators and three selected control variables. Some pioneer works on the control of an ETDE have been contributed by the authors. In [30], a 3I3O explicit model predictive control solution is presented. In [31], a 3I3O decoupling control method is demonstrated. In [32], a loop-shaping-based 3I3O robust control method is introduced. However, the general method for selecting control variables is still untouched. This crucial work is regarded as the characterisation of the new layout engine.

After the engine characterisation, the fuel economy optimisation is transformed into the generation and tracking of the optimal values for selected control variables. The choice of these values delivers the optimal performance of the ETDE. The core problem to be highlighted is to identify the best values of all three control variables [33]. This is of practical importance and is common in diesel engines, regardless of the controller type. For the sustainable usage of on-board battery, the maintenance of the battery state-of-charge (SOC) is a critical constraint to be considered. A suitable control and optimisation structure for the ETDE is still to be found. In [34], the actuators are controlled in a rule-based way. However neither the principle of selecting control variables nor the handling of battery SOC constraint has been addressed. This paper presents an attempt to address this gap. The main contributions are:

1. A control-oriented characterisation on the air system of the ETDE is proposed. From this, a clear guideline for the selection of control variables for the ETDE follows.
2. A hierarchical structure for energy management and control is presented. On the supervisory level, the optimal values of control variables are computed to distribute energy flows in the optimal way. On the low level, a multi-input multi-output (MIMO) controller is designed to implement the optimal energy flow distribution.
3. A real-time energy flow management strategy is designed as the supervisory level controller to guarantee the optimisation 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 system dynamics and to address the internal couplings among loops.

To verify the effectiveness of the proposed framework, cross-platform simulations have been carried out on a high fidelity physical plant model built in `Dynasty`, a proprietary multi physics simulation software package developed by Caterpillar. The engine manifolds are modeled as one-dimensional modules, such that the pulsations caused by the engine actuators operation can be captured precisely. To accurately simulate the transient performance, the energy transferred from each cylinder to the turbocharger was modeled separately.

The paper is organized as follows. Following the introduction in Section 1, the control problem is formulated in Section 2. The ETDE system description is given in Section 3, and the control-oriented system characterisation is given in Section 4. The low level controller design is presented in Section 5, and the supervisory level controller in Section 6. Physical simulation results are demonstrated in Section 7, followed by conclusions in Section 8.

2. Problem formulation

The framework of characterisation, control, and optimisation is to be built as Fig. 1, while the task of each level is introduced in the following.