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Fast Engine Torque Variation Compensation for HEVs Using Permanent Magnet Synchronous Motor and Explicit MPC

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Abstract

This research proposes to leverage the fast response time of Permanent Magnet Synchronous Motors (PMSMs) to compensate for crank angle resolved engine torque variations caused by cycle-by-cycle combustion variations. This method reduces powertrain vibration and enables engine calibrations with high combustion variation that produces low fuel consumption. This research integrates a Field Oriented Control (FOC) strategy with an Explicit Model Predictive Control (EMPC) to trace previewed current references. The previewed current references are computed from the engine torque difference between predicted nominal operation and the measured torque output. This research reveals that the MPC can track a *d-q* current reference without overshoot, rendering current magnitude constraints unnecessary in the MPC formulation. A control rate penalty is used to tune the aggressiveness of transient voltage demand and meet with the DC voltage limit. The proposed MPC formulation significantly improves computational efficiency and allows for an increased preview horizon length. Simulation results show that the proposed EMPC based PMSM control reduces electric motor torque response time from 45 ms, for a baseline FOC strategy, to less than 5 ms. A case study is performed, showing the proposed PMSM control strategy can completely compensate 4.8% Coefficients of Variation of IMEP (COV of IMEP) from the engine while the baseline FOC control strategy failed to respond. The investigated engine operating condition also demonstrates a 12.7% fuel economy improvement compared to a baseline that is stoichiometric without Exhaust Gas Recirculation (EGR) dilution. The electrical system energy losses caused by the EMPC strategy resulted in a 2.3% loss of equivalent engine efficiency, but a net fuel economy gain of 10.4% is still achieved from this case study.

Introduction

The powertrain of Hybrid Electric Vehicles (HEVs) consists of energy conversion systems of two or more energy sources. Most existing HEVs combine Internal Combustion Engines (ICEs) and Electric Motors (EMs). The addition of an EM enables fast power compensation during traction as well as regenerative capabilities which captures the vehicle's excessive kinetic energy during transients [1]. This research proposes using the EM to mitigate engine torque variations, enabling engine calibrations with high combustion variation that produces low fuel consumption. The tradeoff between the gained engine efficiency and energy loss due to the EM's regeneration efficiency, as well as its drive system, is investigated using high-fidelity simulation models. The engine torque trace and fuel consumption used in the simulation are recorded from a dynamometer test.

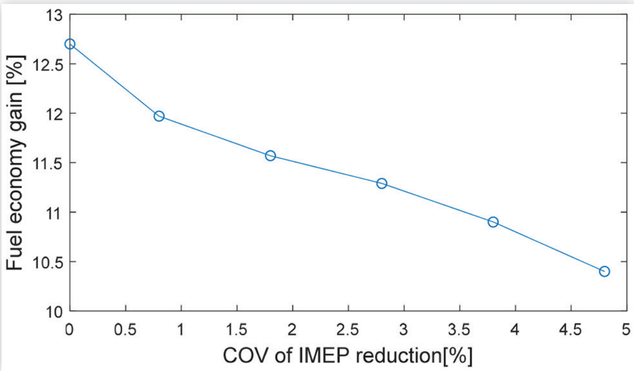
Some powertrain control systems of HEV exploit the fast torque response of EMs to compensate torque loss during transient operations, including gear change, turbo lag, and vehicle launching (e.g., [2, 3] and [4]). This compensation improves vehicle performance and smooths power demand for the ICE, enabling fuel-saving engine designs with a slow response time like downsizing and turbocharging. ICE technologies, including EGR and lean combustion, reduce fuel consumption with a cost of increased combustion variation [5, 6] and [7]. This variation induces vehicle vibration across a wide frequency range, making it challenging to suppress and perceivable by the passengers. The deterioration of the vehicle's drivability limits combustion dilution and hence prevents further improvement of fuel economy. The motor response required to compensate combustion variation is, however, much faster than that for airpath and vehicle dynamics. The existing feedback-based motor torque control strategy is challenged to deliver the required torque response.

The investigated powertrain has a P2 parallel configuration, in which a PMSM is connected to the ICE through a clutch pack. PMSMs have advantages of energy conversion efficiency and power density, making them preferred for EV and HEV powertrain applications. Torque control of PMSMs often employs the FOC strategy and Direct Torque Control (DTC) strategy. A comparison between these two control strategies was discussed intensively by Le-Huy in [8]. Depending on the motor size and control tuning, the existing PMSM control strategies used in HEV powertrains have

TABLE 2 Computational time analysis of the EMPC PMSM control

Computational time (μs)	With offline calculated gain matrices	Without offline calculation
max	1.1	63
mean	0.8	38
min	0.6	24

FIGURE 14 Fuel economy gain vs. the reduction of COV of IMEP



equivalence ratio of 1.4 and 20% of EGR. The torque variation at this engine calibration is not acceptable for passenger vehicles due to 4.8% COV of IMEP. The previewed motor torque reference is generated by subtracting the measured engine torque trace with the regenerated engine torque trace using the mean cylinder pressure measurement. The PMSM controlled by the proposed EMPC strategy tracks the torque reference with negligible error, completely compensating for the 4.8% COV of IMEP generated by the engine. The FOC strategy does not react to the torque reference change due to the feedback control nature and slow response time.

The investigated engine operating condition has a 12.7% fuel economy improvement compared to a baseline engine operation, which has stoich air-to-fuel ratio and no EGR dilution. With the proposed PMSM control mitigating the torque variation, this engine calibration is now acceptable for passenger vehicles from the vibration perspective. The energy losses caused by the electrical system's efficiency leads to a 2.3% loss of equivalent engine efficiency, resulting in a 10.4% net fuel economy gain from the baseline operation. Figure 14 shows the tradeoff between the net fuel economy gain from the baseline engine operation and the reduction of COV of IMEP.

Conclusion

This research proposes to utilize the electric motor integrated in an HEV to cancel the impact of engine torque variation caused by fuel economy-oriented calibration. A novel PMSM control strategy was developed to improve the transient torque response of the motor. The strategy integrates an EMPC to the inner d-q current control of the existing FOC strategy. The proposed EMPC formulation leverages the linear-like motor dynamics in the d-q reference frame and soft constraints method to reduce computational burden and memory requirements. The proposed system was validated via a high-fidelity power electronics simulation with Matlab Simscape Electrical toolbox and pre-recorded engine torque trace. Results show that the EMPC reduces motor torque response time by one order of magnitude compared against the default PID based FOC strategy. The improved response makes the PMSM capable of tracking the fast engine torque variations while the default PID based FOC failed to react. For the investigated engine operating condition, the proposed PMSM control is able to cancel the 4.8% COV of IMEP completely, with a 2.3% loss of equivalent engine efficiency. The tradeoff between COV reduction and net fuel economy gain was provided. Finally, computational time analysis reveals the potential for future hardware implementation and real-time testing.

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Definitions/Abbreviations

COV - Coefficient of Variation
DTC - Direct Torque Control
EGR - Exhaust Gas Recirculation
EM - Electric Motor
EMPC - Explicit Model Predictive Control
FOC - Field Oriented Control
HEV - Hybrid Electric Vehicle
ICE - Internal Combustion Engine
IGBT - Insulated Gate Bipolar Transistors
IMEP - Indicated Mean Effective Pressure
PMSM - Permanent Magnet Synchronous Motor
PWM - Pulse Width Modulation
QP - Quadratic Programming
ZDAC - Zero D-Axis Control

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