2022-01-0674 Published 29 Mar 2022

Energy Management System for Input-Split Hybrid Electric Vehicle (Si-EVT) with Dynamic Coordinated Control and Mode-Transition Loss

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Citation: Biswas, A., Rane, O., Rathore, A., Anselma, P.G. et al., "Energy Management System for Input-Split Hybrid Electric Vehicle (Si-EVT) with Dynamic Coordinated Control and Mode-Transition Loss," SAE Technical Paper 2022-01-0674, 2022, doi:10.4271/2022-01-0674.

Received: 15 Mar 2022 Revised: 15 Mar 2022 Accepted: 11 Jan 2022

Abstract

Instantaneous optimization-based energy management systems (EMS) are getting popular since they can yield near-optimal performance in unknown driving situations with minimalistic tuning parameters. However, they often disregard the drivability score of the powertrain as a performance assessment criterion, and this leads to too frequent or even infeasible mode-transitions during the multi-mode operation of a hybrid electric powertrain. Aiming to bring down the mode-transition frequency below a feasible limit, this paper proffers an instantaneous optimization-based EMS, which also accounts for the energy lost during mode-transitions into the cost function along with the electrical and chemical energy losses. The energy lost during a single mode-transition event refers to the summation of change in rotational energy for all the prime-movers, i.e., internal combustion engine and electric machines. However, this approach will add another weighting factor for weighting the mode-transition loss term in the same equivalent scale used for weighting other loss terms too. A dynamic coordinated control prescribed in literature is also employed along with the EMS to enhance the drivability score of multi-mode hybrid electric powertrains. Simulation results corroborate the efficacy of the proffered EMS framework in ameliorating the drivability issues without sacrificing much in the fuel consumption and charge sustainability performances.

Introduction

Electrified powertrains have been revolutionizing the automotive market for the last 15 years with their astounding potential of eradicating the carbon footprint from the transportation sector [1, 2]. While bigger automotive original equipment manufacturer (OEM)s are targeting all passenger vehicles to be fully electric by 2035, hybrid electric vehicle (HEV) technology has a major role in mitigating the greenhouse gases (GHG) emissions. The HEV technology is no longer in nascent stage and it is playing a pivotal role in reducing GHG emissions. While many HEV architectures have been deployed so far, the power-split architecture has gained the most amount of attention in the industry due to its versatile characteristics.

Toyota hybrid system (THS) has pioneered the power-split architecture for HEV, and it has been evolving through a couple of generations (1st, 2nd, 3rd, and 4th) since its introduction in early 2000s. The THS is widely accredited as the most successful electrified powertrain (ePT) architecture so far in the industry [3]. Stellantis group (erstwhile Fiat Chrysler Automobiles) has also proposed and deployed an improved version of power-split architecture referred as single-input electrically variable transmission (Si-EVT) for different application vehicles in 2016 [4]. The *Two-mode hybrid system*

$\boldsymbol{\Omega_{batt}, C_{batt}, I_{batt}}$ - Internal resistance, charge capacity, and current of HVB

$\boldsymbol{H, x, u, t}$ - Generalized notation for Hamiltonian, state variable, control variable, time used in instantaneous optimization

$\boldsymbol{u^*, \lambda^*(t)}$ - Generalized notation for optimal control vector and optimal co-state vector

$\boldsymbol{u_{mode}^{opt}}$ - Optimal control for a time-instant for with optimal chosen mode

$\boldsymbol{T_f, \Delta t}$ - Final time-step of the drive cycle, Sample time-step of the simulation (0.1 seconds)

$\boldsymbol{T_f, \Delta t}$ - Final time-step of the drive cycle, Sample time-step of the simulation (0.1 seconds)

$\boldsymbol{\omega_{idle}}$ - Idle speed of ICE

$\boldsymbol{\omega_{gen_{min}}, \omega_{mot_{min}}}$ - Minimum possible angular speed of generator and traction motor

$\boldsymbol{\omega_{gen_{max}}, \omega_{mot_{max}}}$ - Maximum possible angular speed of generator and traction motor

$\boldsymbol{\tau_{gen_{min}}, \tau_{mot_{min}}}$ - Minimum possible torque of generator and traction motor

$\boldsymbol{\tau_{gen_{max}}, \tau_{mot_{max}}}$ - Maximum possible torque of generator and traction motor

$\boldsymbol{\omega_{sun_1}, \omega_{sun_2}, \omega_{ring_1}, \omega_{ring_2}}$ - Angular speed at sun gear and ring gear for 1st and 2nd PG-set

$\dot{\theta}_{fire}, \dot{\theta}_{fire}, \dot{\theta}_{ice\ plant}$ - Firing speed and shut-off speed of ICE, ICE Speed feedback from the plant model

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ISSN 0148-7191