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On-Line Controller for Fuel Consumption on Spilt-Type Hybrid Electric Vehicle [⋆]

Hiroki Koguchi [*] **Koichi Hidaka** [**]

[*] *NIDEC ELESYS Corporation, Kawasaki, Kanagawa, Japan.*
[**] *Tokyo Denki University, Adachi, Tokyo, Japan, (e-mail: hidaka@cck.dendai.ac.jp)*

Abstract: This paper proposes a controller used by an extremum seeking (ES) algorithm with semi-optimal controller gains for a hybrid electric vehicle (HEV) system. The semi-optimization gains connect at each output of sample controllers that are given by benchmark problem in advance. These gains are decided according to the approximate convex on fuel economy function via each gains. The target engine speed of EM1 controller, ω^*, is perturbed with the ES algorithm based on fuel economy and State of Charge (SOC). Furthermore, the proposed algorithm switches controller depending on SOC for restraining of the decline of SOC. The sample controllers have four units, and each unit controller controls the driving of HEV. The sample controllers can drive the HEV. For showing the validity of our proposed controller, fuel economies of the proposed controller and sample controller are compared by simulator for this benchmark. While the fuel economy achieved by the sample controller is 41.44 mpg, the final fuel economy on the proposed method is almost 59.29 mpg, and the final SOC is 64.45 %. The performance of fuel economy can be improved by almost 43 % compared to the sample controller.

Keywords: Hybrid electric Vehicle control, Control system, Model-free Controller Design, Extremum seeking algorithm, Split hybrid electric powertrain

1. INTRODUCTION

The Hybrid electric vehicles (HEVs) are gaining market popularity and accelerating propelled by a mix of environmental concerns, rising fuel prices, and business opportunities. The typical HEV has multiple degrees of freedom for delivering wheel torque, unlike conventional vehicles. The conventional HEVs have three powertrain configurations, known as series, parallel, and split (series - parallel), respectively. In the parallel type, the internal combustion engine (ICE) and the electric machine (EM) are mechanically coupled to the drive shaft of the vehicle, and the wheel power is the sum of the individual power. The parallel topology can reduce drivetrain losses, and lead to a lower average ICE operating efficiency. The parallel structure limits ICE operating, however. The series powertrain is characterized by directly uncoupled between the ICE and EM. This powertrain can operate the ICE speed and torque regardless of the vehicle speed. Thus, the topology can operate the ICE at optimal conditions that minimize emissions and the combined loss of the ICE and generator. (See Egardt (2014)). However, the large size battery is needed. The split topology is a mixture topology and the features of both topologies have. The ICE, EM, and generator (GEN) are coupled with the planetary gear. The both EM and generator drive the vehicle. There needs a strategy for a control system to adjust between the two power sources, the ICE and EM in the parallel configuration, and the engine-generator unit and the electric storage system in the series configuration. The control task is referred to as energy management. The energy management problem has been investigated. (e.g., Lin (2003), Dextreit (2014), Larsson (2014)). On the other hand, the split configuration in the commuter vehicles, e.g., Toyota's Prius, is used. The split configuration has the both features between the parallel configuration and serial configuration, and the structures are complex. Thus, the control system of the energy management is important. (See Overington (2015)). The control systems for HEV drive system have been proposed. (e.g., Musardo (2005), Kim (2015), Mura (2015)), However, these systems are for series HEV. Therefore, JSAE (Society of Automotive Engineers of Japan) and SICE (The Society of Instrument and Control Engineers) provided three benchmark problems in 2011, and the one of the benchmark problems is given as "Fuel economy optimization of the commuter vehicle using hybrid powertrain". (See Yasui (2012)). The hybrid powertrain is using the split configuration. The control designs for the benchmark problem have been proposed, which are known as model free types and model based types. (e.g., Yu (2013), Ahmad (2014)). Model-based control is useful for the energy management for HEV. The present proposed model-based controllers have not be able to obtain more than 25 km/L of the fuel economy yet. (e.g., Iyama (2015)). On the other hand, the model-free control approaches are effective and useful for the energy management control of the commuter vehicle. The model free controls have the weakness on the changes of driving conditions. The EV controller based ES algorithm, which is a model-free and on-line controller, has been described by Yasui (2012). However, Yasui (2012) does

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not investigate the fuel economy of the driving for a total time, but only was tested to the fuel economy for 1500 sec. Furthermore Yasui (2012) does not investigate the performance via the cost function of F_c and SOC. In this paper, the controller using ES with semi-optimization gains is proposed. Our proposed method joins the six gains in sample controllers that are given by benchmark problem in advance. The target engine speed of EM1 controller, ω^*, is perturbed with the ES algorithm based on fuel economy. Furthermore, the proposed algorithm switches controller depending on SOC since restraining of the decline of SOC. We simulate the two ES algorithms and two kinds of controller gain vector, test each on the fuel economy and SOC. By comparing these results and the sample controller, the proposed algorithm can improve the fuel economy of HEV by almost 43% to the sample controller. This paper is organized as follows. Section 2 addresses the outline of the benchmark problem and the subject HEV structure. The same optimal controller gains decision process and the proposed hybrid electric powertrain controller using ES with the semi-optimal gains are described in Section 3. The simulation setup and results are presented and discussed in Section 4. In Section 5, we introduce the key idea of our proposed controller and discuss the effectiveness on this algorithm. Conclusions are drawn in Section 6.

2. OUTLINE OF BENCHMARK PROBLEM AND HEV SYSTEM

The controller-plant, HEV, is equipped with split type hybrid powertrain. A driving motor, a generator, and an internal combustion engine are linked by planetary gear set. After this, the driving motor, the generator, and the internal combustion engine are expressed as EM1, EM2, and ICE, respectively. Both EM2 and ICE can drive the vehicle and EM1, and EM2 can generate the electric power and charge the battery. The DCM is the driving cycle manager and HEV and driver model is the target plant. Figure 2 outlines the power flows via ICE, EM1, and EM2 for the HEV drivetrain system, and the figure 1 illustrates the structure of split hybrid electric powertrain. This powertrain has the following 6 modes, which are as (i) an electric vehicle mode driving by EM2, (ii) ICE and EM2 driving mode, (iii) ICE assists mode by EM2, (iV) regenerative braking mode, (v) charge mode by ICE, and (vi) stop mode. The speed of EM1, ω_1, the speed of EM2, ω_2, and the speed of ICE, ω_e, in the modes, (ii) and (iii), are given by

$$\omega_e = \frac{\varepsilon}{1+\varepsilon}\omega_1 + \frac{1}{1+\varepsilon}\omega_2 \tag{1}$$

where ε is a planetary gear ratio, and given as 0.3846. The target HEV is a medium class car with the engine displacement as $1,339$ cc, and the vehicle weight is $1,460$ kg. The maximum powers of ICE, EM1, and EM2 can generate 51 kW, 15 kW, and 25 kW, respectively. The detail conditions and setting of benchmark problem are described in Yasui (2012). The evaluation of energy management in HEV is usually investigated over the New European Driving Cycle (NEDC) in EU, the FTP-75 in the US, and the JC08 in Japan. (See Overington (2015)). However, the driving cycles in this benchmark problem are the actual driving patterns for 3 weeks shown in figure 3a, and the fuel economy is evaluated over the driving cycle. The driving conditions are changed according to “driving time“, “day of the week“, and “whether“. The driving cycles on Monday to Friday are measured data on commuting driving, and the data on the weekend are measured on driving for leisure. Therefore, the driving cycles on the weekend include the high-speed data. The object of the benchmark problem is the design of the controller for HEV in order to minimum the fuel economy, F_c, under keeping a driver's satisfaction function, $S_d(T_{end})$, more than 90%, where T_{end} is the total driving cycle time, and $S_d(T_{end})$ is given as

$$S_d(T_{end}) = 100 - \int_0^{T_{end}} \Delta S_d(t)dt \tag{2}$$

$$\Delta S_d(t) = \begin{cases} 0\ , & (e(t) \le 7.5) \\ 0.1\ , & (7.5 < e(t) \le 15) \\ 1\ , & (15 < e(t)) \end{cases} \tag{3}$$

$$e(t) = |v_d(t) - v_c(t)| \tag{4}$$

where $v_d(t)$ km/h and $v_c(t)$ km/h are the driver's demanded vehicle speed and the vehicle speed, respectively. F_c at T is defined as

$$F_c(T) = \frac{D_d(T)}{S_f(T)} \tag{5}$$

$$D_d(T) = \int_0^T |v_d(t)|dt\ ,\ S_f(T) = \int_0^T |s_f(t)|dt \tag{6}$$

$D_d(T)$: Driving distance at T

$s_f(t)$: Fuel economy rate per second L/s

The fuel economy via designed controller is investigated by driving cycle time for 3 weeks, which is given as $T = T_{end} = 80,430$ s. Figure 4a illustrates the simulation system model of the benchmark problem that is described by GT-SUITE of Gamma Technologies, Inc. and by using MATLAB/Simulink. The HEV system of benchmark problem has sample controller units in advance. The sample controller has four controller units, and each controller controls the ICE, EM1, EM2, and SOC of charge. This HEV drivetrain system can run by the sample controller, and the sample controller units attain the fuel economy, 41.44 mpg. We modify the sample controller units, and challenge to the higher fuel economy by using the online HEV drivetrain system.

3. ON-LINE HEV POWERTRAIN CONTROL WITH SEMI-OPTIMIZATION GAINS AND EXTREMUM SEEKING ALGORITHM

The strategy of power division via ICE, EM1, and EM2 are important for a decreasing of fuel economy from the power flows. Thus, we add the output gain of sample controllers, and then the controller gains are designed using the information of convexity of the index function, i.e., fuel economy. Figure 4b indicates the structure of our proposed controller. The proposed HEV powertrain system uses the sample controllers, and the proposed system sets gains on each sample controller unit. Let $K = [k_1\ k_2\ k_3\ k_4\ k_5\ k_6]^T$ be a vector entries corresponding to the controller gains that are connected to controller units shown in figure 4b. k_1 k_2 k_3, and k_4 correspond to the reference speed in engine controller unit, the torque required to the EM1, the torque required to the EM2, and the electrical power to charge the battery in battery controller unit, respectively.