POWERTRAIN SLIDING MODE CONTROL IN SHEV FOR IMPROVEMENT OF FUEL ECONOMY AND ESS LIFETIME

Xi Zhang and Chengliang Yin

National Engineering Lab for Automotive Control Electronics, Shanghai Jiao Tong University, Shanghai, China

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Abstract: This paper proposes a powertrain sliding mode control strategy for a series hybrid electric vehicle (SHEV) aimed at improving fuel economy and energy storage system (ESS) lifetime. An ESS charging curve considering positive factors for ESS lifetime extension is predetermined, and two robust sliding mode controllers using the fixed boundary layer technology are designed. One is in charge of engine speed control, and the other is for torque control. Thus the powertrain control system could not only reduce emissions due to engine efficiency enhancement but extend ESS lifetime. Finally, simulation results using ADVISOR confirm validity of the proposed strategy.

1 INTRODUCTION

Electric power as the only propulsion power for a series hybrid electric vehicle (SHEV) comes from the ESS and the engine/generator set that converts the energy from fuel into electricity. In SHEV, Engine optimal operation region could be located properly due to the particular structure.

Recently, appropriate control of the SHEV powertrain for emission reduction has been a research hotspot. A modified instantaneous equivalent consumption minimization strategy (ECMS) into the SHEV powertrain control system was introduced (Plsu and Rizzoni, 2005). Wang et al., (2008) introduced a simulated annealing (SA) algorithm to optimize the operational parameters for SHEV fuel economy and emissions. Unfortunately, these SHEV powertrain control strategies fail to sufficiently address the highly nonlinear parameter variations and sudden external disturbances during the vehicle operation.

Sliding mode control (SMC) is very suitable for automotive applications due to its low sensitivity to disturbances and plant parameter variations (Kachroo and Tornizuka, 1996; Utkin et al., 2009). In this paper, powertrain controller design uses the chattering-free fixed-boundary-layer technology for chattering elimination. To locate the engine operation in the optimal efficiency region, two proposed sliding mode controllers responsible for engine speed and torque respectively work together due to the simultaneous speed and torque magnitude constraints in such an area.

So far, few manufacturers concern the systematic electrical solutions for battery lifetime extension under the present battery technology. It's available to analyze some stress factors which induce ageing and influence the rate of ageing (Svoboda, 2007). Consequently, comparison between two ageing processes with a couple of different stress factors (e.g. SOC, charge rate, temperature, etc.) is possible as long as other operating conditions are similar.

Some problems which affect battery lifetime such as surge current, persistent high power, low SOC and so on in conventional powertrain control have to be concerned. To solve these, this paper presents an ellipse-like-based battery charge scenario. When the engine starts, the battery keeps charging at a high rate from the low SOC level, and its SOC increases fast. The charge current gradually drops to zero when the SOC approaches to the predetermined maximum level. The chaotic and fast-variable current almost disappears, which is very good for battery lifetime extension.

Finally, simulation results by modifying the original SHEV model in Advanced Vehicle Simulator (ADVISOR) confirm that the proposed strategy is valid and efficient.

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2 POWERTRAIN STRUCTURE

The structure of the studied SHEV powertrain is shown in Figure 1. An internal combustion engine (ICE) linked to a permanent magnet synchronous generator (PMSG) provides main power in hybrid mode. The ESS (battery pack) serves as the only power source in the pure-electric-vehicle (EV) mode and also absorbs the energy in the regeneration process (braking or deceleration). In addition, the battery pack will be charged by the engine when its state of charge (SOC) drops to a predetermined level, as determined by the control strategy.

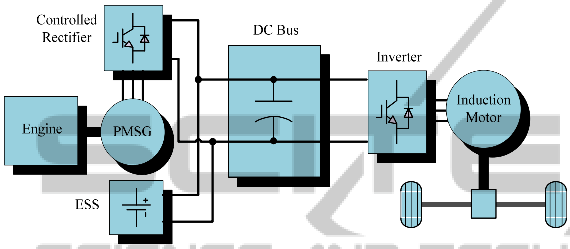


Figure 1: Studied SHEV powertrain structure.

3 POWERTRAIN CONTROLLER DESIGN

The block diagram of the proposed powertrain control system is shown in Figure 2. Definitions of variables in this figure are given as follows: SOC, state of charge; V_B, battery output voltage; I_B^r, calculated battery charging current; P_L, load demand; P_B^r, required power for battery charging; $\hat{P}_E^r$, engine output power with limitations; $\hat{\omega}_E^r$, calculated engine speed; ω_E^*, calculated engine speed with limitations; ω_E, actual engine speed; $\hat{T}_E^r$, calculated engine torque; T_E^*, calculated engine torque with limitations; T_G^*, final required generator torque; and T_G, actual generator torque.

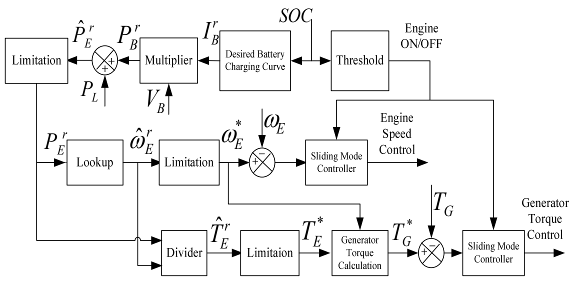


Figure 2: Proposed powertrain control system.

3.1 Engine Speed Control

The engine operation state function can be expressed below

$$\frac{\mathrm{d}\omega_E}{\mathrm{d}t} = \frac{1}{J_s} u T_{\max}(\omega_E) - \frac{1}{nJ_s} T_G \tag{1}$$

where $T_{\max}(\omega_E)$ stands for the maximum torque at speed ω_E, $n \approx 1$ denotes speed ratio between the engine and generator, J_s is moment of inertia of the engine/generator set, and u represents the engine throttle angle (considered as the control variable) and could be delineated as follows.

$$u = A_n^{-1}(u' - B_n) \tag{2}$$

where $A = -\frac{1}{nJ_s} T_G$, $B = -\frac{1}{J_s} T_{\max}(\omega_E)$, the subscript n stands for the nominal value, and u' is considered as a new control variable.

Let the sliding surface $s = e + \lambda \int_0^t e \mathrm{d}t$, where $e = \omega_E^* - \omega_E$ and λ is a constant, and the new control variable can be obtained using the fixed boundary layer sliding mode control technology, expressed below

$$\begin{aligned} u' = & -\hat{\theta}_e(\omega_E) + \frac{\mathrm{d}\omega_E^*}{\mathrm{d}t} + \lambda e + \\ & (F(\omega_E) + \eta) m sat(\alpha(\omega_E), s, \phi) \end{aligned} \tag{3}$$

where $\eta > 0$ is a predetermined constant and satisfies $s\dot{s} < -\eta|s|$; $\phi > 0$ is the width of sliding mode layer. The error function $\theta_e(\omega_E)$ is given by

$$\theta_e(\omega_E) = -\frac{1}{nJ_s} T_G + \frac{T_{\max}(\omega_E)}{T_{\max}(\omega_E^*)} \cdot \frac{1}{nJ_s} T_{Gn} \tag{4}$$

3.2 Engine/Generator Torque Control

The state functions of the PMSG can be delineated as follows:

$$\begin{cases} T_G = K_{trq} i_q \\ \frac{\mathrm{d}i_q}{\mathrm{d}t} = -\frac{R}{L} i_q - \omega_G i_d + \frac{\omega_G}{L} \lambda_m - \frac{u_q}{L} \\ \frac{\mathrm{d}i_d}{\mathrm{d}t} = -\frac{R}{L} i_d + \omega_G i_q - \frac{u_d}{L} \end{cases} \tag{5}$$

where i_d and i_q, stator direct-axis and quadrature-axis currents; L_d and L_q, stator direct-axis and quadrature-axis inductances; λ_m, flux of the permanent magnet; R, stator winding resistance; $\omega_G \approx \omega_E$, generator speed (replaced by ω_E in the following analysis); K_{trq}, torque constant; u_d and u_q, stator direct-axis and quadrature-axis voltages, as control variables in the system.

Let the sliding surface $s_i = e_i + \lambda_i \int_0^t e_i \mathrm{d}t, \quad i = 1,2$, where $e_1 = i_q^* - i_q$, and $e_2 = i_d^* - i_d$. Similar to derivation process in engine speed control, new controls can be obtained as

$$u_1 = -\hat{\theta}_{e1}(X) + \frac{\mathrm{d}i_q^*}{\mathrm{d}t} + \lambda_1 e_1 - \left(F_1(X) + \eta_1\right) msat(\alpha_1(X), s_1, \phi_1) \tag{6}$$

and

$$u_2 = -\hat{\theta}_{e2}(X) + \frac{\mathrm{d}i_d^*}{\mathrm{d}t} + \lambda_2 e_2 - \left(F_2(X) + \eta_2\right) msat(\alpha_2(X), s_2, \phi_2) \tag{7}$$

where $\eta_i > 0 \ (i = 1,2)$ is a predetermined constant and satisfies $s_i \dot{s}_i < -\eta_i |s_i| \ (i = 1,2)$, and $\phi_i > 0 \ (i = 1,2)$ are the widths of the two sliding mode layers. Derivation of the error function is similar to that in engine speed control.

Thus, the required stator direct-axis and quadrature-axis voltages can be finally obtained to guarantee desired generator torque.

3.3 Battery Charging Scenario Design

Although several options (e.g., parabola, ellipse, line, trigonometric, etc.) exist for such a charging scenario, only ellipse could satisfy all the fore-mentioned requirements. In the meantime, the ellipse curve is easy to calculate and easy to be implemented in microprocessors. Consequently it is possible to realize it in real time and real applications. In this paper, a combination of line and ellipse (see Figure 3) is eventually selected because one wants the battery SOC to reach the “healthy” low threshold SOC1 in the beginning phase (Phase I) and then approaches to the maximum value SOCmax in Phase II.

It has to be noted that the engine may not meet the calculated power requirement that is the sum of battery charging power and the peak driving power demand at some instants. Thus constraints have to be added.

When the calculated engine power is located in the high-efficiency region, the battery can be charged along the pre-set curve. If the calculated engine power exceeds the high-efficiency region, the driving power demand is first satisfied while the battery charging points may not lie on the pre-set one. Whichever case happens, the dynamics of the entire SHEV will not be influenced at all, the engine always runs in the optimal region, and the requirement of choosing a high-power engine could also be avoided.

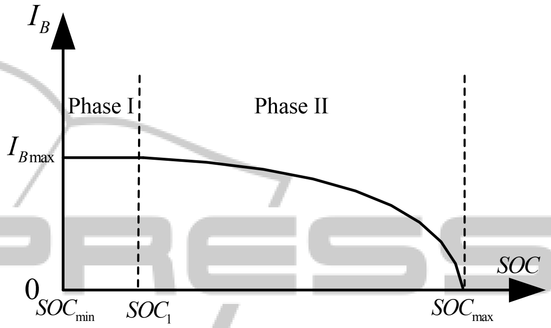


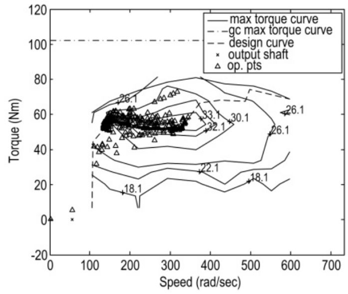
Figure 3: Desired battery charging curve.

4 SIMULATION RESULTS

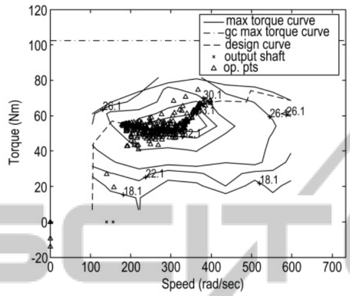
This study employs ADVISOR for verification. The original SHEV model is modified to embed the proposed control system into the powertrain. In this simulation, a Geo Metro 1.0L engine is selected. A PMSG rated with 41kW-power and 95%-efficiency is linked with the engine, and an induction motor rated with 75kW-power and 95%-efficiency acts as a traction motor. 100 Ovonic M70 cells compose the battery pack where 50 are in series and 2 in parallel. The inverter and controlled-rectifier both own the structure of three IGBT/diode bridges.

The Orange County Cycle (OCC) is chosen as the drive cycle for analysis. This is because the OCC comprises of considerable acceleration/deceleration processes and is capable of sufficiently validating SHEV advantages on possible improvement of system efficiency. The constants in the above analysis are set as follows: $\lambda_1 = 3540$, $\lambda_2 = 650$, $\eta_1 = 2.03$, $\eta_2 = 2.46$, $SOC_{\min} = 0.6$, $SOC_{\max} = 0.8$, $SOC_1 = 0.68$.

Figure 4 shows the engine operation efficiency map. It is obvious from comparison between Figure 4(a) and 4(b) that most operation points using the proposed strategy are located in the optimal region while most points using the conventional method are beyond such an area.



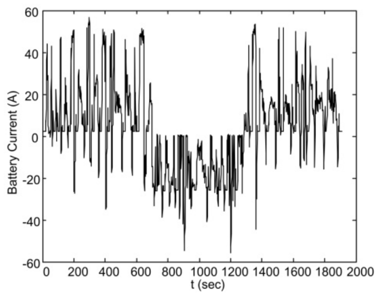
(a) Conventional method



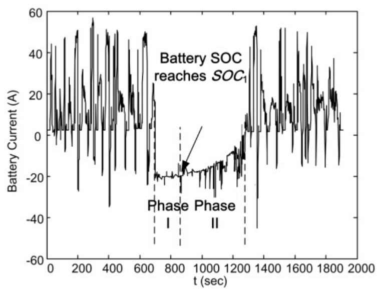
(b) Proposed method

Figure 4: Engine operation efficiency map.

The battery current curves using the conventional and proposed methods respectively are depicted in Figures 5(a) and 5(b). It is clear that chaotic and surge currents using the proposed method in the normal (engine is ON) mode almost disappeared compared to those using the conventional method, which does good to the battery lifetime extension.



(a) Conventional method



(b) Proposed method

Figure 5: Battery current during OCC.

Table 1 gives some index including MPG, emissions, efficiency resulting from simulation using two methods. It is obvious that the proposed method performs better fuel economy, lower emissions and higher efficiency.

Table 1: Performance comparison between two methods.

Method / Index	Conventional Method	Proposed Method
MPG	37.8	40.9
Emissions (g/mile)	HC:0.783, CO:3.234, NOx:0.838	HC:0.781, CO:2.158, NOx:0.820
Average Engine Efficiency	0.301	0.322
Overall System Efficiency	0.0720	0.0782

5 CONCLUSIONS

This study presents two sliding mode controllers for SHEV powertrain on basis of a predetermined optimal ESS charging scenario to improve fuel economy and ESS lifetime. The engine speed and torque could be located in the high-efficiency region. Meanwhile the ESS lifetime extends due to the designed charging curve avoiding negative charging status, chaotic and surge currents, or persistent high power. ADVISOR-based simulation results validate the proposed powertrain control system.

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