World Electric Vehicle Journal Vol. 3 - ISSN 2032-6653 - © 2009 AVERE

EVS24

Stavanger, Norway, May 13-16, 2009

Integrated Design of Powertrain Controllers in Series Hybrid Electric Vehicles for Efficiency Enhancement and Battery Lifetime Extension

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Abstract:

In this study, a control strategy for the series hybrid electric vehicle (SHEV) powertrain, based on the design of fixed-boundary-layer sliding mode controllers (FBLSMCs) and a battery charge scenario, is presented to enhance engine efficiency as well as extend battery cycle life. An appropriate battery charge scenario is designed to remove surge charge current, keep the battery staying in a high state-of-charge (SOC) region and avoid persistently-high charge power, which are positive factors to the battery lifetime extension. To locate the engine operation in the optimal efficiency area, two robust FBLSMCs against uncertain disturbances are configured in the powertrain control system, responsible for engine speed control and engine torque control, respectively. Simulation results are obtained for comparison between the proposed and conventional powertrain control schemes by using the Advanced Vehicle Simulator (ADVISOR). Through these simulations, the effectiveness and superiority of the FBLSMC-based SHEV power train control strategy are validated.

Keywords: Series hybrid electric vehicle (SHEV), fixed-boundary-layer sliding mode controllers (FBLSMCs), battery charge scenario, optimal efficiency area.

I. INTRODUCTION

Hybrid electric vehicles (HEVs), combining a conventional propulsion system with an energy storage system (ESS), achieve better fuel economy than conventional vehicles. Due to their higher fuel efficiency and environmental advantages, HEVs have been studied and commercially developed by more and more institutes and enterprises [1]-[3].

In a series hybrid electric vehicle (SHEV), the electric power as the only propulsion power comes from the ESS and the electric generator that converts energy from fuel into electricity [4]-[6]. Although a SHEV has some unsatisfactory characteristics i.e., the requirement of larger power capacity for the traction motor and the utilization of one more electric machine than a parallel HEV, the simple and decoupled mechanical structure brings some advantages. By using the traction motor for propulsion, the operating noises can be reduced, which provides a stealth function for certain military

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applications. In addition, high engine operating efficiency can be obtained with optimization of engine operation.

In this study, the powertrain of a SHEV consists of an engine generator set, a battery pack, a traction motor and two power converters for driving the generator and traction motor respectively. Recently, various researchers have been focusing on the control issues of the SHEV powertrain. Reference [7] introduced a modified instantaneous equivalent consumption minimization strategy (ECMS) into a SHEV powertrain control system. A simulated annealing (SA) algorithm was proposed to optimize the operational parameters for SHEV fuel economy and emissions [8]. Reference [9] presented a knowledge-based control strategy for fuel consumption minimization using information of the engine efficiency map, vehicle battery behavior and some overall parameters characterizing the expected trip. A power-flow management algorithm considering a normal operation mode and an electric vehicle (EV) operation mode appeared in [10]. However, 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 an efficient tool to control complex high-order dynamic plants operating under uncertain conditions due to the order reduction property and low sensitivity to disturbances and plant parameter variations [11]-[13]. Consequently, it's very suitable for automotive applications. The chattering-free fixed-boundary-layer sliding mode controller (FBLSC) is utilized in this paper with the advantage that the boundary width is kept fixed so that the area where the system trajectories are attracted toward the boundary will not vary unexpectedly at all. To locate the engine operation in the optimal efficiency region, two proposed FBLSCs, responsible for engine speed and torque respectively, work together due to the simultaneous speed and torque magnitude constraints in such an area. As a result, strong system robustness can be achieved against the nonlinear parameter variations and external disturbances.

The battery technology attracts more and more attentions from researchers involved in HEV research since it is considered as the key technology to the future HEVs [14]. Considerable battery manufacturers dedicate themselves to the breakthrough of barriers on the cost, size, life and energy density of batteries [15]-[17]. Unfortunately, to the authors' knowledge, few HEV researchers are focusing on the systematical solutions for battery lifetime extension under the present battery technology. In fact, it is very difficult to predict the battery lifetime by using chemical or electrical variables and to test the batteries for the full range of applications in which batteries are used. However, it's possible to analyze some stress factors which induce aging and influence the rate of aging [18]. Consequently, comparison between two aging 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.

The vehicle operation studied in this paper is that, the engine starts when the battery SOC drops to the predetermined lower threshold and it stops as soon as the SOC increases to the desired upper threshold. In most SHEVs, the battery charge current is determined by the engine output power and load requirements together during the engine operation process. In general, it is chaotic and varies rapidly, and surge current exists, which does great harm to the battery life [19]. In the meantime, the battery SOC usually cannot reach a high level in a short time while the low SOC is unfavorable to the battery durability in the long term.

To solve the above problems, a smooth battery charge curve of current vs SOC is needed, and this curve has to be ordinate-large at low SOC so that the SOC can increase as quickly as possible. Additionally, persistently-high power should be relatively avoided because it has potential negative influence to battery life [19]. Considering these aspects, this paper presents an ellipse-like-based battery charge scenario. In other words, the curve of the charge current vs battery SOC is like an ellipse. 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. In this case, an average high SOC can be guaranteed while the persistently-high power can also be avoided. Most importantly, the chaotic and fast-variable current almost disappears, which is very good for battery lifetime extension. Nevertheless, it has to be noticed that in the proposed powertrain control method, the power of the engine during its operation is determined by power requirements of the battery and traction motor, which is an inverse power derivation process compared to that used in other SHEV powertrain control strategies.

Integration of the proposed FBLSCs and ellipse-like-based battery charge scenario is implemented by modifying the original Advanced Vehicle Simulator (ADVISOR) SHEV model. Simulation results verify that the proposed design strategy of SHEV powertrain controllers is valid and is more efficient compared with the conventional methodology.

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II. System Configuration And Drive Cycle Selection

A. *Powertrain Structure and Component Specifications*

The structure of the studied SHEV powertrain is shown in Fig. 1. In this study, the gasoline engine is a Geo Metro 1.0L SI engine whose maximum power is 41kW @ 5700 rpm. The speed- and torque- independent PMSG generates rated 41kW output power with approximately 95% efficiency. A Westinghouse AC induction motor (IM), output power rated at 75kW with 92% efficiency, acts as the traction motor for the vehicle propulsion. The ESS consists of 50 M70 NiMH cells connected in series, manufactured by Ovonic Inc. The capacity and nominal voltage of each cell are 28 Ah and 6V, respectively. Consequently, the nominal voltage of the battery pack is 300V. In addition, the IM/inverter design is appropriate for a 300 V system.

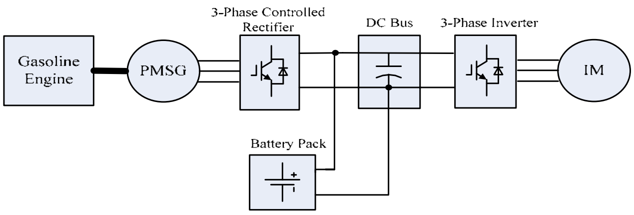

Fig. 1. Powertrain structure of SHEV.

B. *Drive Cycle Selection*

In a SHEV, requirements for the engine are not directly linked to vehicle speed, which gives more freedom in engineering. Thus, the ICE can be operated at a constant and efficient rate, even as the car changes speed. At low or mixed speeds, this could result in dramatic increase in overall efficiency. Consequently, the Orange County Cycle (OCC) is taken into consideration as the emulation drive cycle since it consists of considerable acceleration and deceleration processes. Although the OCC may not be the most typical drive cycle for a commercial SHEV, it does a good job in showing advantages on overall efficiency. Moreover, the OCC, as a well-known drive cycle, offers a common standard for comparison between the proposed and conventional SHEV powertrain methodologies.

III. Establishment of Control System

The vehicle operation process during the OCC is highly nonlinear, resulting in highly-nonlinear and uncertain engine dynamics. Meanwhile, some parameters of the engine, generator and even the controlled rectifier may vary during the engine operation due to the variations of external conditions such as temperature, pressure and so on. An effective and efficient engine control methodology is in great need for enhancement of the overall system efficiency. Therefore, the requirement arises for strong robustness needs against parameter variations, external disturbances, and highly-nonlinear system dynamics. Simple control models cannot handle complicated engine dynamics well because they need accurate information and lack of robustness that is essential to the control objective. The sliding mode control (SMC) is well known for its advantages in providing a systematic approach to the problem of maintaining stability and consistent performance facing modeling imprecision. In SMC, the system trajectory is maintained to stay on the sliding surface for subsequent time once it is driven onto this surface. The imperfect implementation of the control switching leads to chattering, which is a major drawback of the SMC. The advantages of the fixed-boundary-layer sliding mode controller (FBLSMC) are that, not only chattering phenomenon is removed, but also the boundary width is kept fixed so that the area where the trajectories are attracted toward the boundary is not changed, avoiding the instability of normal chattering-free sliding mode controllers. Therefore, the FBLSMC strategy is employed in this study as an effective tool for enhancement of engine efficiency to locate the engine speed and torque into the optimum area.

The proposed powertrain control strategy is based on the engine on/off status alternation. When the engine is turned on, it supplies the requested power from the load. In the meantime, battery pack is charged by the engine power and possible regenerative power. So the battery SOC increases as expected. This is called the normal operation mode. Once the battery SOC reaches the predetermined maximum level, the engine controller receives a stop signal and is turned off. The operation changes to electric vehicle (EV) mode, in which only the battery pack serves as the power source for the load and also receives the regenerative braking power. As soon as the battery SOC drops to the given minimum level, the engine starts again preventing the battery from depletion.

In this paper, an ellipse-like-based battery charge current curve (current vs SOC) is decided considering the fore-mentioned advantages. Then the engine output power is calculated as the approximate sum of the battery power and load demand. Based on the expected engine operation curve and optimum region definition, the desired engine speed and torque can be obtained. As a matter of fact, the engine torque depends on the generator torque which is adjusted by the PWM signals for the controlled rectifier. So the objectives for

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powertrain control are changed to the control of the engine speed and generator torque to constrain the engine operation in the optimum region. Two FBLSMCs respectively responsible for the engine speed and generator torque are utilized against the parameter variations, external disturbances, and highly-nonlinear system dynamics. The whole control process is shown in Fig. 2. The variables in this figure are defined as follows: SOC, state of charge; V_B, battery voltage; I_B^r, required battery current; P_L, load profile; P_B^r, required battery power; $\hat{P}_E^r$, original required engine power; P_E^r, required engine power with thresholds; $\hat{\omega}_E^r$, original required engine speed; ω_E^*, required engine speed with thresholds; ω_E, real engine speed; $\hat{T}_E^r$, original required engine torque; T_E^*, required engine torque with thresholds; T_G^*, final required generator torque; T_G, real generator torque.

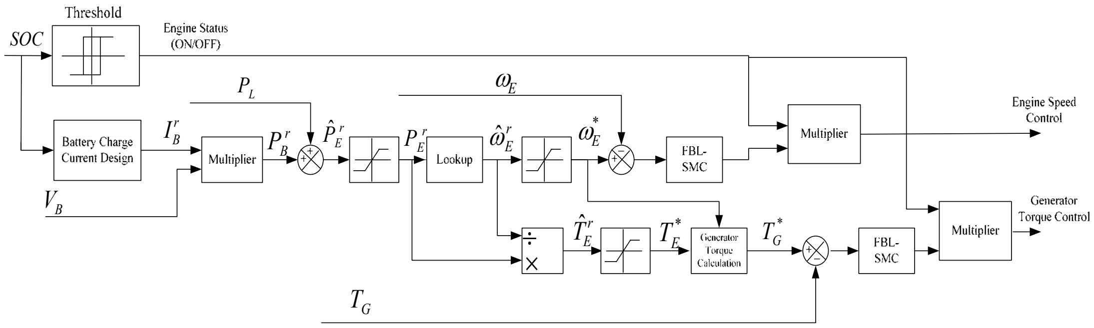

Fig. 2. Block schematic of the proposed SHEV powertrain control strategy.

The state equation of the engine is expressed as:

$$\frac{\mathrm{d}\omega_E}{\mathrm{d}t} = \frac{1}{J_s} u f(\omega_E) - \frac{1}{nJ_s} T_G \qquad (1)$$

where $f(\omega_E)$ is the maximum engine torque at a certain ω_E; n is engine/generator speed ratio ≈ 1; J_s is the inertia of the engine/generator set; u represents the engine throttle angle and acts as a control variable for the engine speed FBLSMC.

The state of the generator employed in the SHEV is described as:

$$\begin{cases} \dfrac{\mathrm{d}i_q}{\mathrm{d}t} = -\dfrac{R}{L} i_q - \omega_G i_d + \dfrac{\omega_G}{L} \lambda_m - \dfrac{u_q}{L} \\ \dfrac{\mathrm{d}i_d}{\mathrm{d}t} = -\dfrac{R}{L} i_d + \omega_G i_q - \dfrac{u_d}{L} \\ T_G = K_{trq} i_q \end{cases} \qquad (2)$$

where i_d, i_q are direct- and quadrature- axis stator currents, respectively; L_d, L_q are direct- and quadrature-axis inductances, respectively; λ_m is amplitude of the flux linkages established by the permanent magnet; R is stator resistance; $\omega_G \approx \omega_E$ is generator speed; K_{trq} is a torque constant; u_d, u_q, considered as control variables for the generator torque FBLSLC as well as the engine torque control, represent direct- and quadrature- axis stator voltages, respectively.

IV. Simulation Results

Advanced Vehicle Simulator (ADVISOR) is employed as the simulation tool in this study. The proposed powertrain control strategy is embedded in the modified SHEV model originated from ADVISOR as shown in Fig. 3. The results are shown in Fig. 4 through Fig. 7.

From the comparison between Fig. 4 and 5, it is clear that most engine operation points using the proposed method concentrate in the optimal area (the circle indicated by "33.1" percent) of the engine efficiency map while the majority of the engine operation points using the conventional method is located beyond such an area. In other words, the proposed method can boost the engine efficiency as a result.

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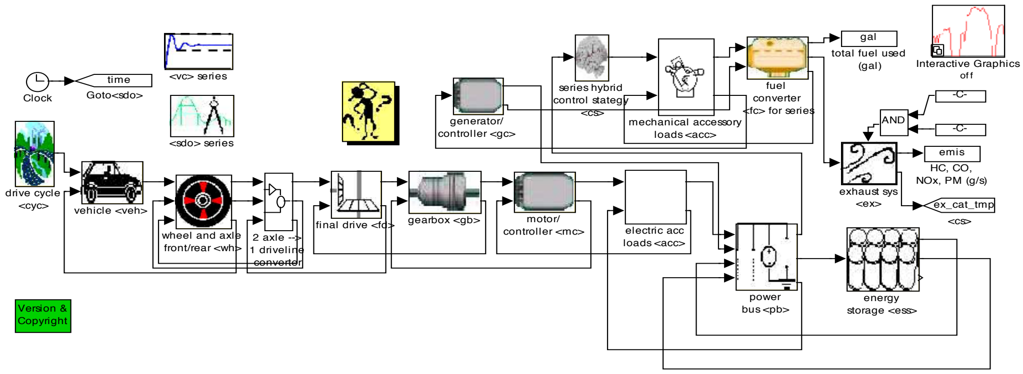

Fig. 3. Modified SHEV model for algorithm implementation

To verify the validity of the proposed battery charge scenario, the simulated results of the battery current are obtained, related to the conventional and proposed methods respectively. As shown in Fig. 6, the conventional method fails to avoid the transient surge current to the battery, which is not good for the battery lifetime extension in the long term. It is depicted in Fig. 7 that by using the proposed powertrain control strategy, the chaotic and fast-variable current almost disappears, which is beneficial to the battery lifetime. The battery SOC increases as quickly as possible, and the persistently-high power is avoided.

Some indexes such as miles per gallon (MPG), emissions, engine efficiency and overall system efficiency using the two methods are listed in Table I. Obviously, the proposed method shows better MPG, less emissions and higher efficiency than the conventional one.

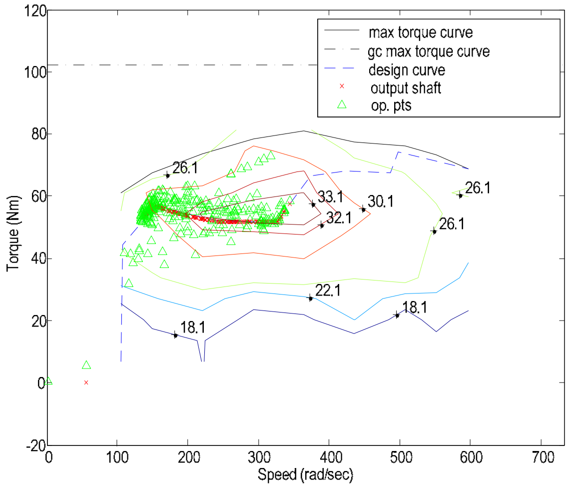

Fig. 4. Engine operation (conventional method).

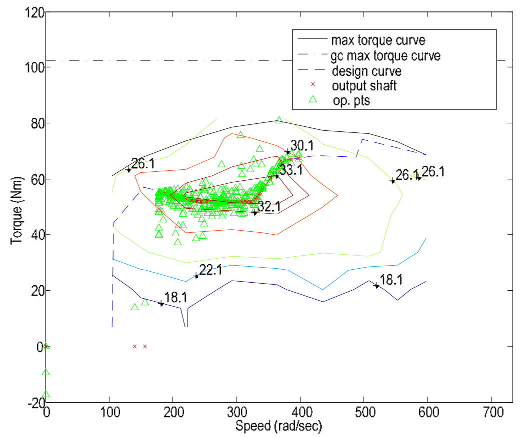

Fig. 5. Engine operation (proposed method)

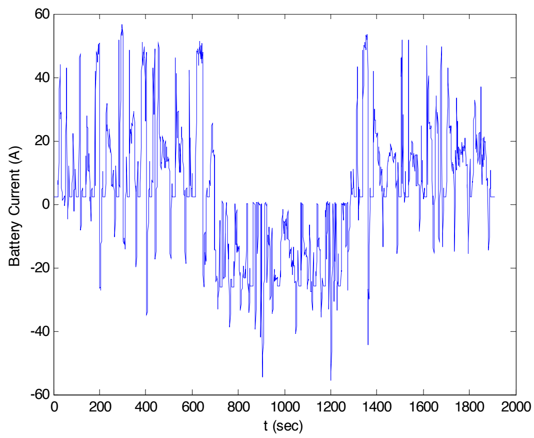

Fig. 6. Battery current during OCC (conventional method).

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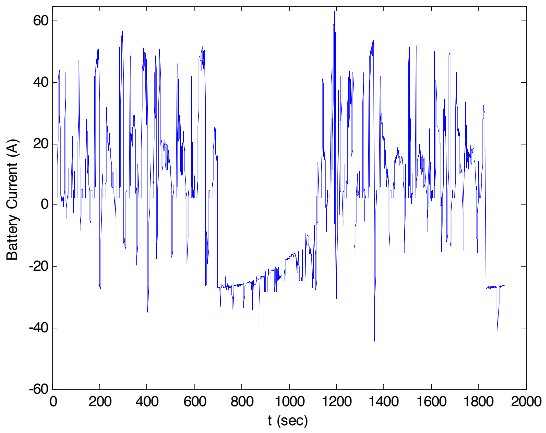

Fig. 7. Battery current during OCC (proposed method).

TABLE I PERFORMANCE COMPARISON BETWEEN CONVENTIONAL AND PROPOSED METHODS

Index Method	Conventional Method	Proposed Method
MPG	37.8	40.6
Emissions (g/mile)	HC:0.783, CO:3.234, NOx:0.838	HC:0.794, CO:2.161, NOx:0.821
Average Engine ency	0.30	0.32
Overall System ency	0.072	0.078

V. CONCLUSION

Two fixed-boundary-layer sliding mode controllers (FBLSMCs) are proposed for the powertrain controller design in the SHEV for the purpose of efficiency enhancement and battery lifetime extension. The two FBLSMCs are in charge of the speed control and torque control for the engine, respectively, against the parameter variations and disturbances. A battery charge scenario avoiding the chaotic current is designed for battery life extension with the consideration of some stress factors. Simulated results using ADVISOR show that the proposed strategy provides better fuel economy, emissions and efficiency than the conventional strategy. Through these simulations, the effectiveness and superiority of the proposed SHEV powertrain control strategy are validated.

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