TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 12, No. 9, September 2014, pp. 6673 ~ 6681
DOI: 10.11591/telkomnika.v12i9.6398

Research on the Regenerative Braking Control Strategy Considering Battery/Motor/CVT Joint High Efficiency for CVT Hybrid Electric Vehicle

Tao Deng[1], Chunsong Lin[1], Bin Chen[2]
[1]School of Mechatronics & Automotive Engineering, Chongqing Jiaotong University, Chongqing, P.R.China
[2]The State Key Lab of Mechanical Transmission, Chongqing University, Chongqing, P.R.China
Corresponding author, e-mail: d82t722@163.com

Abstract

The traditional regenerative braking control strategies for hybrid electric vehicle just only considers to ensure motor to work along with the battery/motor joint optimal efficiency curve, but not consider the influence of continuously variable transmission (CVT) efficiency to the system synthetic efficiency, yet in fact that the CVT efficiency varies with the operating condition between 70% and 95% variation, which can not be neglected for the synthetic efficiency of regenerative braking system. Based on the analysis of the relationship among the synthesis efficiency of regenerative braking system and the efficiency of the NiMH battery, ISG motor and CVT, the battery/motor/CVT joint high efficiency are calculated, then the battery/motor/CVT joint high efficiency optimum working curve is drawn, finally the regenerative braking control strategy adopted with the battery/motor/CVT joint high efficiency optimum working curve is proposed. Compared to the offline simulation and hardware-in-the-loop(HIL) test results adopted with the battery/motor joint high efficiency optimum working curve, the motor average generating efficiency increases by 2.23%, braking energy recovery rate increases by 4.09% through offline simulation, and the average generating efficiency increases by 1.13% through HILS test. Both results show that the proposed regenerative braking control strategy can realize the NiMH battery, ISG motor and CVT to work with joint high efficiency which fatherly enhances braking energy recovery rate under guaranteeing entire vehicle braking security condition.

Keywords: *hybrid electric vehicle, regenerative braking, efficiency optimization, control strategy, hardware-in-the-loop (HIL)*

1. Introduction

The regenerative braking is one of the important working modes of hybrid electric vehicle. Under the premise to guarantee the entire vehicle safe braking, the optimization of regenerative braking control strategy and the realization of the greatest degree of braking energy recycling are the important research contents of regenerative braking for hybrid electric vehicle.

For regenerative braking control strategy, international research has an early start, and many control strategies have been proposed. Y. M. Gao et al. [1] have proposed three kinds of braking force distribution control strategies to appraise regenerative braking energy recovery efficiency, and given overall consideration to the friction braking, regenerative braking and ABS control, but have not consider the motor efficiency and the CVT efficiency. S. R. Cikanek and K. E. Bailey [2] have taken the improvement of the entire vehicle energy recovery efficiency and the optimization on the driver perception as the design goals of the braking force distribution strategy, but also have not considered the synthesis efficiency of regenerative braking system. Domestic research on regenerative braking control strategy is in the infancy. J. M. Zhang et al. [3] have taken the average regenerative braking force as the goal, and selected key point coordinates on the braking control strategy curve as the control variables, then optimized and designed the regenerative braking control strategy. T. Deng et al. [4] have proposed battery/motor joint high efficiency working method, and formulated the CVT ratio control strategy

Received April 28, 2014; Revised June 18, 2014; Accepted July 10, 2014

and regenerative braking control strategy, but have not considered the influence of the CVT efficiency to the synthesis efficiency of regenerative braking system.

By adjusting ratio continuously, CVT hybrid electric vehicle not only can guarantee the engine or motor to obtain the optimum energy consumption under each driving mode, but also forces the motor to work in the high efficiency region to enhance regenerative braking energy recovery rate under vehicle deceleration and braking mode.

For CVT hybrid electric vehicle, the CVT efficiency is assumed to be constant (η_{cvt} =0.85) in the general regenerative braking control strategies. However, the CVT actual efficiency varies with its working condition between 70% and 95%, which obviously influences system synthesis efficiency. Therefore, it's not enough to only ensure the motor to work with high efficiency or the battery/motor to work with the joint high efficiency, but the entire powertrain efficiency including the battery, the motor, and the CVT.

In this paper, the mild hybrid electric Changan Antelope vehicle with the ISG (integrated starter/generator) motor taken as the research object, and based on the analysis of the influence of each driveline component to system synthesis efficiency, the CVT ratio control strategy with battery/motor/CVT joint high efficiency working method during regenerative braking is proposed, the regenerative braking system simulation model is established and analyzed to lay the foundation for HEV regenerative braking system research and development.

Nomenclature

η η_m NiMH battery/ISG motor/CVT joint efficiency
η_b η_{cvt} ISG motor efficiency
η_e η_k NiMH battery efficiency
E CVT efficiency
U the battery electric efficiency the coulomb efficiency electromotive force
battery terminal voltage
I battery current
R battery inherent resistance
I_{dis} battery discharging current
I_{chg} battery charging current

t_{dis} battery discharging
t_{chg} time battery charging
P_b T time motor power
n ω_m motor torque
i_f motor speed
v motor target speed
final drive ratio
vehicle speed
r wheel radius
z braking severity
i_{max} the maximum CVT ratio

2. Battery/Motor/CVT Joint Efficiency Model

2.1. NiMH Battery/ISG Motor/CVT Joint Working Efficiency

By the bench test, the NiMH battery, the ISG motor, and the CVT efficiency characteristic map are shown as Figure 1-3 [4].

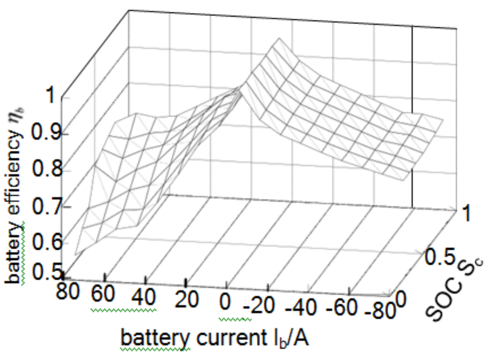

Figure 1. NiMH Battery Charging and Discharging Efficiency Characteristic Map

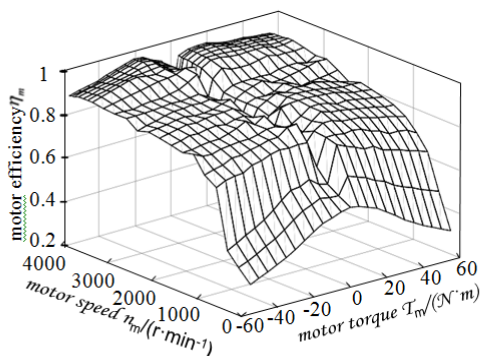

Figure 2. ISG Motor Efficiency Characteristic

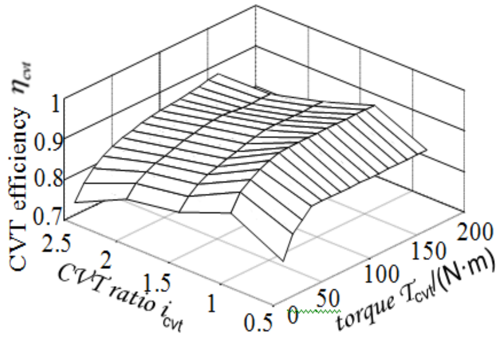

Figure 3. CVT Efficiency Characteristic Map

The NiMH battery/ISG motor/CVT joint efficiency is equal to the product of the three efficiencies, namely:

$$\eta = \eta_m \cdot \eta_b \cdot \eta_{cvt} \quad (1)$$

The NiMH battery efficiency η_b includes the battery electric efficiency η_e and the coulomb efficiency η_k. η_e is described to be the loss electric energy quantity due to battery inherent resistance and η_k is described to be the quotient of discharging capacity and charging capacity under some di scharging condition, as following:

$$\eta_b = \eta_e \cdot \eta_k \quad (2)$$

$$\eta_e = E/U = E/(E+I \cdot R) \quad (3)$$

$$\eta_k = (I_{dis} \cdot t_{dis})/(I_{chg} \cdot t_{chg}) \times 100\% \quad (4)$$

Because the formula of ISG motor power is as follow: $P_b = U \cdot I = T \cdot n / 9549 \cdot \eta_m$. Then the joint working efficiency map of NiMH battery/ISG motor/CVT can be obtained under different SOC and different CVT ratio by setting series of ISG motor speed and torque values, which means each CVT ratio can be corresponded to a battery/motor/CVT joint working efficiency map.

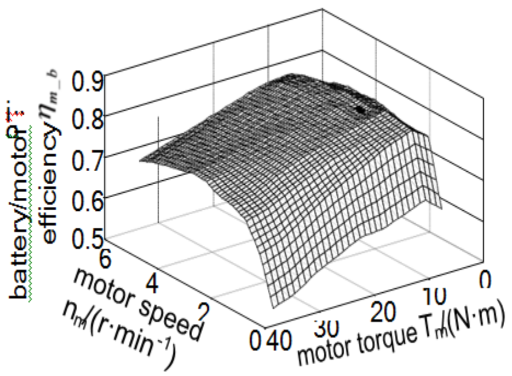

Figure 4. The NiMH Battery/ISG Motor Joint Efficiency Map when SOC=0.3

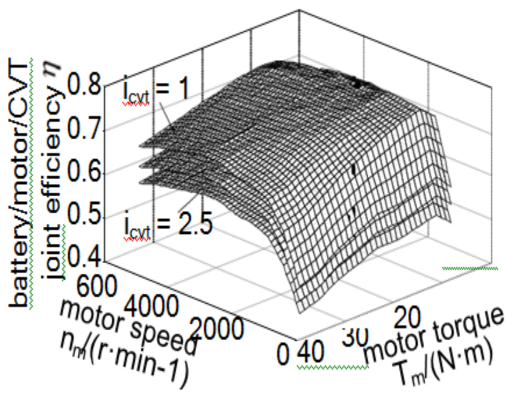

Figure 5. The NiMH Battery/ISG Motor /CVT Joint Efficiency Map when SOC=0.3

As known from the comparison the Figure 4 with Figure 5, the biggest difference between the battery/motor joint working efficiency map and the battery/motor/CVT joint working efficiency map is that the efficiency of the high speed and high torque region is much lower than the efficiency of the high speed and low torque region in the battery/motor joint working efficiency map, but not obviously in the battery/motor/CVT joint working efficiency map, which shows that the battery/motor joint high efficiency region is not equivalent to the battery/motor/CVT joint high efficiency region. Therefore, the regenerative braking control strategy should be formulated considering the battery/motor/CVT joint high efficiency, which ensures the highest working efficiency for the CVT-HEV system. As known from the battery/motor/CVT joint working efficiency surfaces under the different CVT ratio in Figure 5, the NiMH battery/ISG motor/CVT joint efficiency surfaces firstly increase along with CVT ratio to the highest efficiency value until i_{CVT}=1, then the joint efficiency surfaces decrease along with the increasing CVT ratio.

In addition, the values of NiMH/ISG motor/CVT joint working efficiency surfaces vary drastically between 40% and 80%. Therefore, the energy recovery efficiency for the regenerative braking system can be fatherly enhanced by controlling CVT-HEV to work in the battery/motor/CVT joint high efficiency region.

2.2. Defining the Battery/Motor/CVT High Efficiency Optimum Working Curve

During the regenerative braking, the regenerative braking system should works in the battery/motor/CVT joint high efficiency region in order to realize the most energy recovery.

Therefore, it is crucially important to obtain the joint optimum working line which guarantees the synthesis efficiency of the NiMH battery, ISG motor and CVT to be highest.

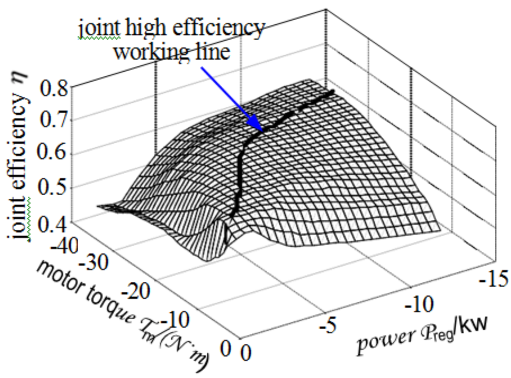

Figure 6. The Three Dimension Map for NiMH Battery/ISG Motor/CVT Joint Optimum Working Line when i_{CVT}=1

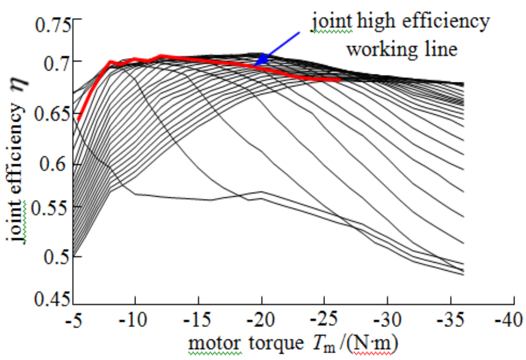

Figure 7. The Contour Map for NiMH Battery/ISG Motor/CVT Joint Optimum Working Line when i_{CVT}=1

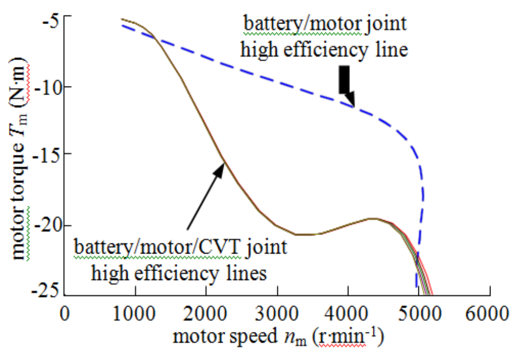

Figure 8. The NiMH Battery/ISG Motor/CVT Joint High Efficiency Optimum Working Line under Different CVT Ratio when SOC=0.3

During regenerative braking, the ISG motor torque is determined according to the braking power by regenerative braking system. In order to convenient to obtain the battery/motor/CVT joint optimum working curve, the joint efficiency-motor speed-motor torque 3D map in Figure 5 can be converted to be the joint efficiency-motor torque-braking power 3D map in as shown in Figure 6 (taken i_{cvt}=1 as example), in further, the joint efficiency-motor speed-braking power 3D map can be converted to be the joint efficiency-motor torque 2D contour map as shown in Figure 7 (taken i_{cvt} =1 as example). As known from the Figure 6 and Figure 7, each highest efficiency point corresponds to each constant power line, which are cascaded as joint high efficiency optimum working curve.

For different i_{cvt}, different battery/motor/CVT joint high efficiency optimum working curve can be obtained by the above method as shown in Figure 8. As known from Figure 8, the battery/motor/CVT joint high efficiency working lines under the different CVT ratio i_{cvt} value vary slightly, but with similar overall tendency. At the meanwhile, the battery/motor joint high efficiency working curve does not coincide with the battery/motor/CVT joint high efficiency working curve, which is hard to realize the most braking energy recovery with high efficiency. Only to control ISG motor to work along with the battery/motor/CVT joint high efficiency optimum working curve, the entire synthesis efficiency of regenerative braking system can be highest, and then can recover the more regenerative braking energy.

2.3. The Battery/Motor/CVT Joint High Efficiency Optimum Control Strategy

During regenerative braking of CVT hybrid electric vehicle, the ideal motor torque can always be found in the joint high efficiency optimum working curve under the certain regenerative braking power, current battery SOC value and CVT ratio value, and the corresponding motor speed can be computed, then the CVT ratio can be determined. Moreover, the computed motor torque value and motor speed value are unique corresponding to the certain regenerative braking power, which can be as target values to control the ISG motor to work along with the battery/motor/CVT joint high efficiency optimum curve and guarantee the NiMH battery, ISG motor and CVT gearbox to work into the joint high efficiency optimum region.

2.4. CVT Ratio Control Based on the Battery/Motor/CVT Joint High Efficiency Optimum Working Curve

During regenerative braking, the regenerative braking force F_{reg} can be interpolated and obtained according to braking severity z, which multiplied with the vehicle speed to obtain the regenerative braking power [3]. Then, the motor speed can be interpolated with the battery/motor/CVT joint high efficiency optimum working curve. Finally, the CVT target ratio value i_{cvt} can be computed according to the above obtained vehicle speed and the driveline ratio as shown in Figure 9, which is function of brake intensity z and the vehicle speed v, namely:

$$i_{cvt} = \omega_m \cdot r / (v \cdot i_f) \quad (5)$$

According to CVT target ratio, the working radius RDR of the primary belt wheel and required working pressure PDN of the secondary belt wheel cylinder can be computed [5].

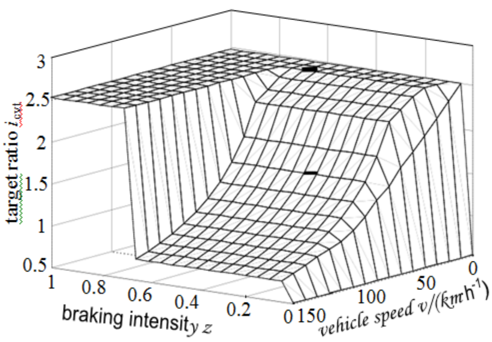

Figure 9. CVT Target Ratio Control Map

The acceptable charging power of NiMH battery must be considered in CVT ratio control by taking the minimum between the regenerative braking power provided by ISG motor and the battery acceptable charging power of NiMH battery as the actual required regenerative braking power. In additional, the braking severity limit must be considered during CVT ratio control, namely when braking severity z >0.7, regenerative braking can not be used due to security factors, the ratio can be adjusted to the maximum i_{max}, and in order to be easy to start, the CVT ratio also should be adjusted to maximum value i_{max} when the vehicle speed is lower than critical value v_0 [4].

2.5. Regenerative Braking Control Strategy Research

Based on the analysis and computation of entire vehicle regenerative braking control strategy, regenerative braking force distribution control model is established. According to the constitution and working characteristics of HEV braking system, the braking forces computed by braking force distribution strategy are distributed as follow several kinds of situations to avoid battery to overcharge [5-7]:

(1) The SOC value is firstly judged. If SOC >0.8, the traditional friction braking and the engine braking work together, but no motor regenerative braking; If SOC ≦0.8, the ISG motor can provide the regenerative braking force;

(2) The braking severity z is computed according to the actual vehicle speed obtained from the wheel and the braking intention, which is used to judge the braking control as follows:

a) When the braking severity $0 \leqq z \leq 0.1$, only the motor regenerative braking is adopted;
b) When the braking severity $0.1 < z < 0.7$, the motor regenerative braking and the traditional friction braking work together, and the engine braking taking part in when required;
c) When the braking severity $0.7 \leqq z \leqq 1$, the traditional friction braking and the engine braking work together, but no motor regenerative braking.

3. Research on Regenerative Braking System Modeling and Simulation Analysis

3.1. Regenerative Braking System Modeling

Combined with the theory modeling method and the numerical modeling method, the entire forward simulation models (as driver intention, vehicle control, controller models) for CVT hybrid electric vehicle have been established under Matlab/Simulink simulation environment, including the vehicle models (the driver intention model, working mode transition, and vehicle parameters computing), control modules (clutch engaging/disengaging control, CVT ratio control, regenerative braking control), and the subsystem models (engine model, NiMH battery model, ISG motor model, final drive model and wheel model) [4].

3.2. Regenerative Braking System Simulation and Analysis for CVT Hybrid Electric Vehicle

In order to confirm the superiority, the proposed regenerative braking control strategy are respectively simulated and compared under the battery/motor/CVT joint high efficient optimum working region and the battery/motor joint high efficient working region. As the result shown in Figure 10, all the characteristic indexes are improved under the battery/motor/CVT joint high efficiency optimum working region comparing with the battery/motor joint high efficiency optimum working region. Under the battery/motor joint high efficiency optimum working region, the SOC value reduces from the start value 0.7 to the end value 0.6693, the average motor generation efficiency is 72.64%, and the braking energy recovery rate is 47.52%. Under the battery/motor/CVT joint high efficiency optimum working region, the SOC value reduces from the start value 0.7 to the end value 0.6746, the average motor generation efficiency is 74.87%, and the braking energy recovery rate is 51.61%. Comparing to the battery/motor joint high efficiency optimum working curve, the SOC increases with 0.792%, the motor average generation efficiency increases by 2.23%, and the braking energy recovery rate increases by 4.09%, as shown in Table 1.

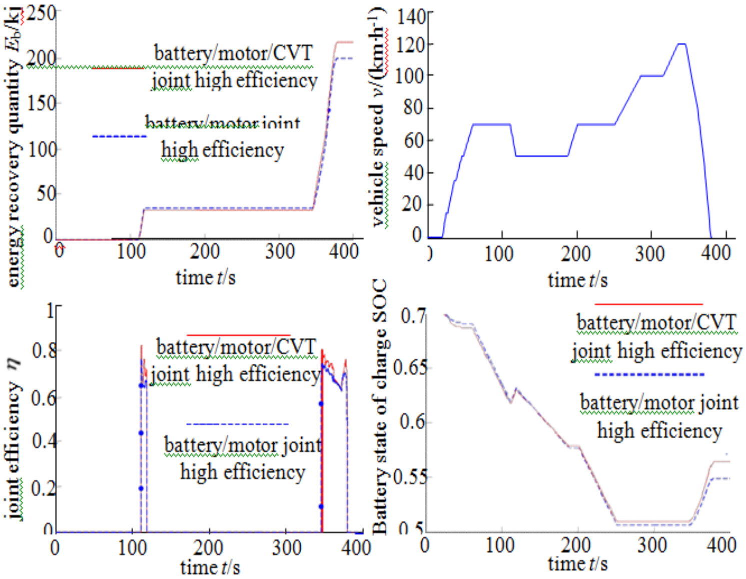

Figure 10. EUDC Cycle Simulation Results

Table 1. EUDC Cycle Simulation Results

	SOC	average generating efficiency	energy recovery rate
battery/motor joint high efficiency	0.6693	72.64%	47.52%
battery/motor/CVT joint high efficiency	0.6746	74.87%	51.61%
difference value	0.0053	2.23%	4.09%

4. Hardware-in-the-loop (HIL) Test Research

To prove availability of the proposed regenerative braking control strategy and the effective of battery/motor/CVT joint high efficiency optimum working curve to the braking energy recovery rate, the hardware-in-the-loop test system is developed for the battery/motor joint high efficiency optimum working curve and the battery/motor/CVT joint high efficiency optimum working curve, as shown in Figure 11 [6]. The hardware-in-the-loop test system includes JL475Q1 engine, 10kw ISG motor, NCVT (0.498-2.502), clutch, cone gear driveline box, brake, driveline box, electric eddy current dynamometer, inertia flywheel, NiMH battery and so on. The hydraulic braking system is controlled by the braking pedal, the pressure of the front wheel braking system is controlled by the duty cycle of the two high-speed switching valves, and the input pressure of the main braking pump is adjusted by the loading sensing pressure proportioning valve. The control system includes the ISG motor controller-IPU, battery management system-BCM, CVT controller-TCU, and the HEV controller-HCU replaced with the dSPACE/AutoBox during test. The HIL electric/electronics system includes the two speed-torque sensors, two current sensors, pressure sensor of the hydraulic system, three pedal stroke sensors, etc. The speed-torque signals is read through the speed-torque meter installed in the IPC, and transmitted to dSPACE/AutoBox through the serial communication, but the other signals are converted A/D through the I/O interface of the DS1103 card installed in the dSPACE/AutoBox. dSPACE/Autobox is high-speed LAN connected with a notebook through network cable with 100M bandwidth.

Figure 11. The HIL Test Bench Diagram

Under the initial condition that the SOC is 0.7, the braking speed is 60km/h and the braking severity is 0.3, the proposed regenerative braking control strategy is verified on the HILS test bench, the test results are shown in Figure 12. During regenerative braking, when adopting with the battery/motor joint high efficiency optimum working curve, the SOC value reduces to be 0.6916, and the motor average generating efficiency is 87.63%. However, when adopting with the battery/motor/CVT joint high efficiency optimum working curve, the SOC value reduces to be 0.6944, the average generating efficiency is 88.76%, as shown in Table 2. Obviously, the energy recovery rate adopting with the battery/motor/CVT joint high efficiency optimum working curve is higher compared with the battery/motor joint high efficiency optimum working curve.

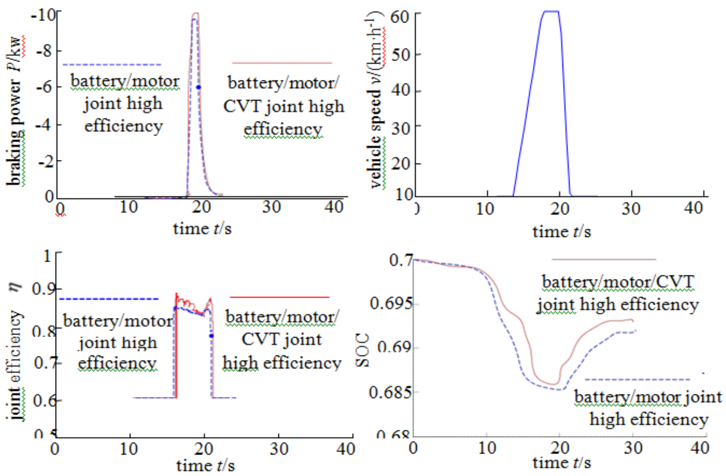

Figure 12. The HIL Test Results under 60km/h, z=0.3, SOC=0.7

Table 2. The HIL Test Results when SOC=0.7, Braking Speed is 60km/h, and z=0.3

	SOC	average generating efficiency
battery/motor joint high efficiency	0.6916	87.63%
battery/motor/CVT joint high efficie ncy	0.6944	88.76%
difference value	0.0028	1.13%

5. Conclusion

(1) The influence of NiMH battery, ISG motor and CVT efficiency in regenerative braking system to system synthetic efficiency has been analyzed, the battery/motor/CVT joint high efficiency model has been established, and the battery/motor/CVT joint high efficient optimum working curve has been drawn.

(2) Based on the battery/motor/CVT joint high efficiency optimum working curve, the regenerative braking control strategy for CVT HEV has been proposed, and the forward simulation model of regenerative braking system for CVT HEV has been established.

(3) Under EUDC cycle, the regenerative braking control strategy adopted with the battery/motor joint high efficiency optimum working curve and the battery/motor/CVT joint high efficiency optimum working curve has been simulated and compared respectively. The simulation results show that the motor average generating efficiency increases by 2.23% and the braking energy recovery rate increases by 4.09% adopted with the battery/motor/CVT joint high efficiency optimum working curve compared to the battery/motor joint high efficiency optimum working curve.

(4) The hardware-in-the-loop (HIL) test results show that the average generating efficiency increases by 1.13% adopted with the battery/motor/CVT joint high efficiency optimum working curve compared to the battery/motor joint high efficiency optimum working curve.

Acknowledgements

This work was supported by National Natural Science Foundation of China (Grant No. 51305473), China Postdoctoral Science Foundation Funded Project (Grant No. 2014M552317), Foundation and Advanced Research Program General Project of Chongqing City, China (Grant No. cstc2013jcyjA0794), Board of Education Science and Technology Research Project of Chongqing City, China (Grant No. KJ120421), and Automobile Engineering Key Laboratory Open Fund Project of Jiangsu Province, China (Grant No. QC201206).

References

[1] YM Gao, LP Chen, Ehsanl Mehrdad. Investigation of the effective of regenerative braking for EV and HEV. *SAE Technical Paper*. 1999; 1999-01-2910.
[2] SR Cikanek, KE Bailey. Regenerative braking system for a hybrid electric vehicle. *Proceedings of the American Control Conference*. 2002(4): 3129-3134.
[3] JM Zhang, SHM Cui, BY Song. An advanced regenerative braking control strategy optimization. *Journal of Jiangsu University*. 2009; 30(3): 246-250.
[4] T Deng, DY Sun, DT Qin. Regenerative braking simulation for hybrid electric vehicle with continuously variable transmission. *Journal of Mechanical Engineering*. 2009; 45 (9): 214-220.
[5] H Yeo, D Kim, S Hwang. Regenerative braking algorithm for a HEV with CVT ratio control during deceleration. *04CVT-41*. Japan, 2004; 53-60.
[6] T Deng. Forward modeling and simulation for regenerative braking system of CVT hybrid vehicle, *Chongqing University*. 2010.
[7] B Chen. Regenerative braking research of pure electric vehicle. *Chongqing University*. 2011.