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# Development of the Electric Control Unit for a Full Hybrid Power-train Structure

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**Abstract**

A function modularization control system is established for the vehicle with a new full hybrid power-train structure consisting of two electric motors and a set of coupling device. Control strategies based on ICE optimized operation schedule are utilized to improve the power-train efficiency and to reduce fuel consumption. With the development tool of MATLAB/SIMULINK and special debugging tool, a prototype of multi-energy control unit is completed. Over 5,000 kilometers road test of the vehicle shows the feasibility and reliability. And the performance of the vehicle has been improved.

*Keywords: Full hybrid power-train, double motors, control strategy, function modularization*

## 1. Introduction

Hybrid electric vehicle (HEV), who combines the advantages of traditional automobile and electric vehicle, is still an important research topic for the world automobile industry in early 21st century[1][2], since nowadays battery technology as the bottleneck of the development of electric vehicle has not obtained a breakthrough. In recent years, hybrid vehicles have been greatly developed[3][4], and well-known car manufacturers such as Toyota, Honda, Ford has introduced commercial models.

Powered by two or more power sources, HEV requires a separate control unit to manage the energy needed for vehicle to be allocated rationally among each source[1]~[6]. As one of the key technology, multi-energy control unit (HECU) responses for signals acquisition, driver's intention recognition, control strategy realization, control command output, etc. Its performance directly affects the vehicle economic and dynamic properties. The HECU receives the status signals of the vehicle and other subsystems, the driver's command input, that is, key status, gears and pedals position. With certain control strategy, it coordinates motors, engine and battery pack taking into account vehicle dynamic performance and fuel economy requirements[7]~[9]. Based on the analysis of a certain full hybrid power-train structure, this paper focuses on the energy management strategy. Furthermore, a CAN-based multi-energy power-train control unit was realized with modular design method. Also, a prototype was built to validate the feasibility and reliability.

## 2. Power-train Structure

The hybrid structure researched in this paper shown in Figure 1. In this figure, thick solid line indicates mechanical transmission path, thin solid line power transmission path, dashed line CAN bus. The system includes the engine, two sets of permanent magnet synchronous motor (PM1 and PM2), the driver operation input bench, and nickel hydrogen batteries pack. The driver operation input refers to key statuses, gears, acceleration and braking pedals position, and some necessary buttons. PM1 drives the vehicles directly through the main reducer, and works as a generator to transfer the vehicle's kinetic energy into electric energy stored in the power batteries when deceleration and braking. PM2 is connected to the engine through the gear transmission and works as the starter, and also as the generator to transfer mechanical energy of the engine into electricity.

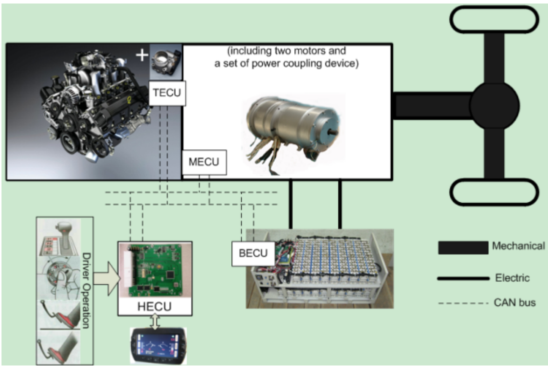



Fig.1 structure of the power train system

This parallel-series HEV has removed the traditional 12V starter motor, and replaces the traditional mechanical throttle by an electronic actuator. A throttle control unit (TECU) was designed, and the engine was re-calibrated and optimized. Other control unit in the vehicle includes multi-energy control unit (HECU), energy electric control unit (ECU), battery pack management unit (BECU), and two motor control units (MECUs), which communicate through the CAN bus.

Here, the PM1 can drive the vehicle alone when in low vehicle speed. When acceleration or uphill is needed, the PM1 outputs curtain torque as an auxiliary to achieve the demand. The PM1 works as a generator in deceleration and downhill to regenerate the energy and store in the battery bank.

In this structure, the PM2 works as a starter in the process of starting the engine and as a generator when the engine outputs power. When the engine is needed to be started, the PM2 outputs the necessary torque and drives up the engine crankshaft speed to the preset point. The PM2, as a generator, determines the output power of the engine and makes its output following the so-called optimized operation line (OOL) [7].

# 3. Energy Management Strategy

The control strategy was developed in the traditional 'V' development mode. Control program was realized in MATLAB/Simulink/Stateflow, and debugged with MicroAutobox of dSPACE Corporation. The test bench was shown in Figure 2. The monitor and debug interface was realized with ControlDesk software of DSPACE Corporation, as shown in Figure 2.

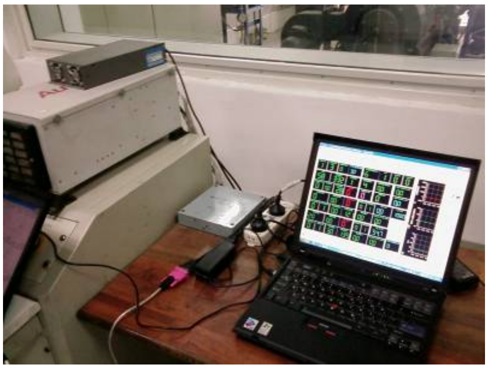


Fig.2 Test bench

## 3.1 Control function modulization

The control function is divided into several parts and realized with modules. The main modules include signal trimming, logic control, parameters calculation, coordinate control, and output control, emphasized with solid line box in Figure 3.

And several modules can be further subdivided into parts. The control logic module also includes mainly vehicle status determination module, system power on control module, fault dealing module, cooling system control module, and engine start/stop control module. The coordinate control module contains parking mode control module, driving mode control module, and reverse mode control module to produce different control commands in various vehicle modes.

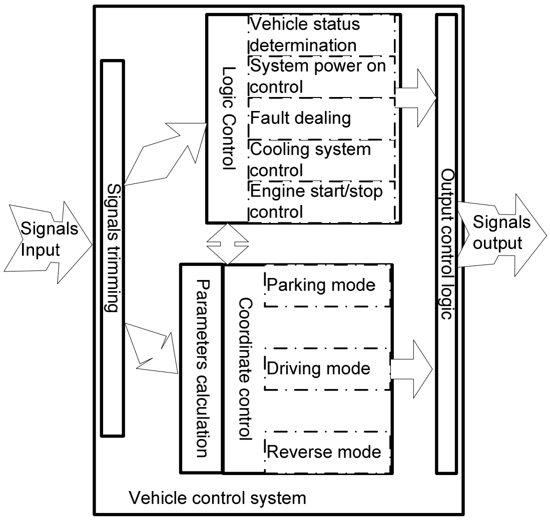



Fig.3 Function modules

## 3.2 Logic control modules

### 3.2.1 Vehicle status and power control logic

Figure 4 shows the realization of vehicle status determination and power on/off control logic with logic language.

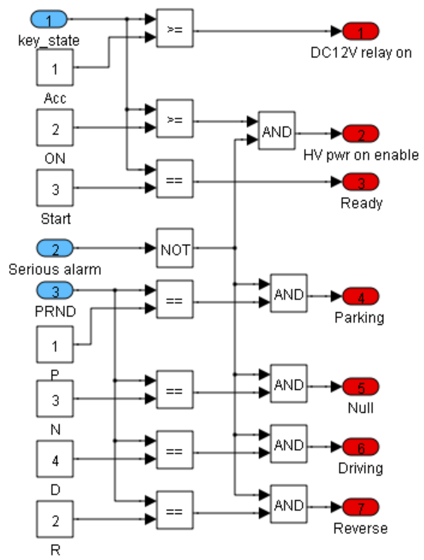



Fig.4 Vehicle status and power on control logic

The key status of ACC, ON and START are replaced with 1, 2, and 3, respectively. When the key is in ACC position, the low voltage power 12VDC of each control system is powered on. Once the key status in ON mode without serious alarm, the high voltage control relay is on and the capacitors in the inverters are pre-charged and then the process of powering on is completed. Now if START mode is active, the vehicle ready message will be shown in IOP and the vehicle can be driven forward or backward up to the shift status.

The shift status includes four modes, that is, parking (P), neutral (N), driving (D), and reverse (R), which is the same as the traditional automatic transmission (AT). The modes are also determined with serious alarm signal. The four modes are replaced with 1 to 4, respectively, as shown in figure 4. Here, the P mode and N mode are dealt in the same way.

### 3.2.2 Fault processing logic

Fault processing relates to the reliability of the system. All the main subsystems perform self-test and send fault codes to the HECU. All the fault codes are unified and divided into three levels. Level III alarms will only be displayed on the IOP, and level II alarms will lead to lower output power. Level I alarm is the most serious ones. Once the level I codes emerge, the output will be disabled.

### 3.2.3 Engine start/stop control logic

The engine will be started and stopped if it is necessary. Figure 5 shows the control logic. There will be many possible factors which could affect the engine status. The main inputs often include the SOC signal, the vehicle speed vehicle signal, and the acceleration pedal signal. Here, hysteresis loop is introduced to overcome the fluctuation of the signals, such as relay1, relay3, and relay5. Allowing for the performance in low vehicle speed, the ST1 signal is TRUE only when the outputs of relay1 and relay2 are TRUE simultaneously. When the SOC of the battery pack is larger than the preset upper of relay4, the ST4 signal will never be TRUE, which can prevent over-charging of the battery in long down still or frequently brake and deceleration. If the signal ST is TRUE, and there are no level 1 alarm, the signal ST_cmd will be TRUE after a certain interval for the engine off.

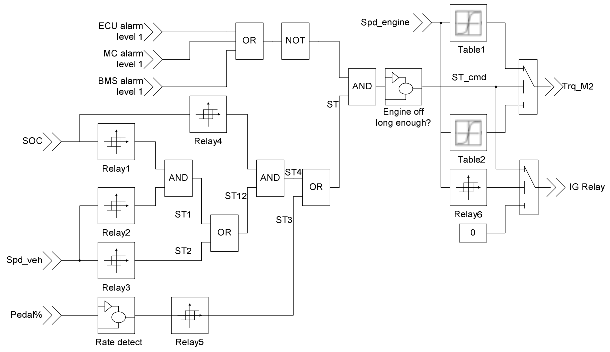
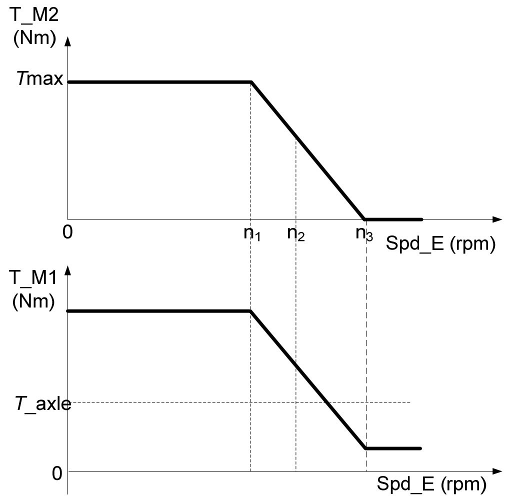



Fig.5 engine start/stop control logic

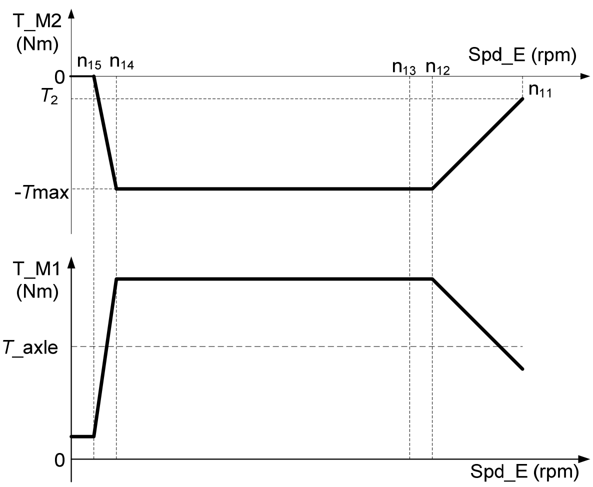
The signal ST_cmd works as a control command. If it is TRUE, the signal Trq_M2 will output according to table1. Else, it will output according to table2.

In table1, the torque output is to run the axle of the engine to certain speed, as shown in Figure 6(a). Here, the torque of M2 varies according to the speed of the engine and it works as a starter. If the real speed of engine is lower than preset $n1$, the motor M2 output is $T$max. When the speed is higher than $n1$, the torque will decrease linearly. Till the speed reaches $n3$, the torque is zero. To reduce the vibration when to start the engine, the torque in the transmission axle $T$_axle should remain unchanged. The output torque of M1 is forced to be changed to compensate it. In Figure 6(a), a type of possible variation of the T_M1 is shown. As a result, the $T$_axle is constant during the interval to start the engine, which will improve the NVH performance of the vehicle.

In table2, the aim of the output of M2 is to stop the engine. The torque output variation curves of M2 and M1 also shown in Figure 6(b). In the process, the M2 is a generator and the torque is express with negative value. The absolute value increase linearly from $n11$ to $n12$, and is equal to $T$max finally. When the speed of the engine reaches $n14$, the absolute value of the torque will begin to decrease linearly. It could avoid the engine rotating reversely. At $n15$, it is zero. After that, the engine will stop freely and rapidly. The $n15$ often be set to 30~50 revolutions per minute (rpm). Similarly, the output torque of M1 is also modified to compensate the possible variation of the torque in the axle.




(a) Torque output variation curve to start the engine




(b) Torque variation to stop the engine

Fig.6 Schematic diagram of torque variation curve

To control the start and stop of the engine, the ignition (IG) relay is controlled. As shown in Figure 5, the output of relay6 are use to control it. If the speed of the engine is larger than the upper of relay6, that is, $n2$ in Figure 6(a), the IG relay is on and ignition coil sparks and fire the mixed gas in certain cylinder. The hysteresis loop relay6 is used to assure the successful ignition process. Likewise, when to stop the engine, the IG relay is set off if the speed reaches the lower of relay6, that is, $n13$ in Figure 6(b). The point of $n2$ and $n13$ are set in the stable operation region. For example, the $n2$ can be set 950 rpm, and $n13$ 850 rpm. The method to make the relay be on and off in the stable operation region of the engine has improved the Noise Vibration and Harshness (NVH) performance of the vehicle highly when to start and stop the engine.

### 3.2.4 Output control logic

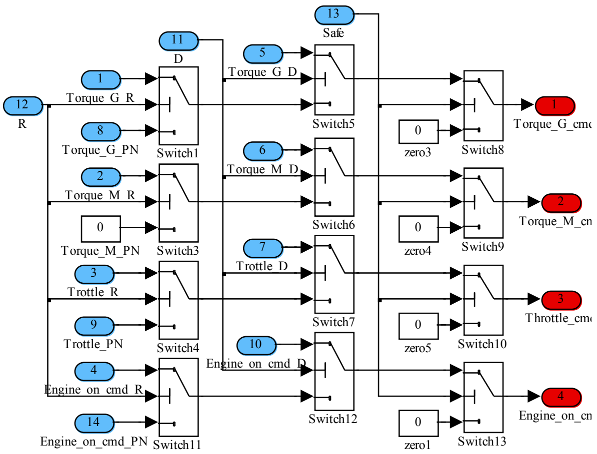



Fig.7 Output control logic

Fig.7 gives the output control logic with logic language. Since the output of the two motors, the throttle position, and the engine start/stop control command are derived in different modes simultaneously. The shift status determines the selection of the outputs. When it is R mode, the output computed will be the real control commands. And it is the same in D mode. The N mode output will appear when it is neither R mode nor D mode. When level I alarms appear, all the control command will be set to zero, which means there is no power out.

## 3.3 Coordinate control modules

### 3.3.1 N mode

When the vehicle is in N mode, the vehicle stands by and there is no torque out in the transmission axle. But there is still something you can do. On the one hand, when you want to prepare for running the vehicle, you must put the shift status in N mode. In N mode, the control system is power on with 12VDC when the key is on the $1^{st}$ or $2^{nd}$ position. Self-testing of each subsystem is performed automatically. If there is no serious alarm and the key is on the ON status, the high voltage control relays are switched on and the inverters are powered on. On the other hand, if the battery pack is in very low level and cannot start the vehicle, you can force to start the engine in N mode to charge the batteries. The method is realized when you keep the key on the $3^{rd}$ position over 3 second. However, the energy efficiency is very low and work time is limited strictly.

### 3.3.2 D mode

The output power required on the axle is determined by the acceleration pedal position. On the other words, the output power in the transmission axle $P_{\text{axle\_out}}$ is expected to be equal to the $P_{\text{req}}$=k*$pedal\%$.

And it can be expressed in exp(1).

$$P_{\text{req}} = kP_{\text{E}} + \eta P_{\text{M1}} \quad (1)$$

Here, $P_{\text{E}}$ refers to the output of the engine, $P_{\text{M1}}$ the output of the M1. And $k$ and $\eta$ are the coefficient respectively. Since the output of the engine cannot change rapidly when acceleration or deceleration suddenly, the $P_{\text{M1}}$ is used to compensate the difference between $P_{\text{req}}$ and $P_{\text{axle\_out}}$. In this case, the engine can operate in its optimized operation zone. As a result, the vehicle could achieve lower emission and lower fuel consumption. When the SOC of the assembled battery pack deviates from the target value, $P_{\text{Batt}}$ is needed to modify the output of the engine and the M1. The derivation process of the control command to throttle position $Tps_{\text{\_cmd}}$, $T_{\text{M2\_cmd}}$ and $T_{\text{M1\_cmd}}$ is shown in Figure 8.

When there is no difference between the real value and the target value of SOC, that is, ΔSOC is zero, the $P_{\text{E\_req}}$ is equal to $P_{\text{2\_req}}$ and can be looked up in Table2. Else, if theΔSOC is not zero, an extra power is required and $P_{E\_req}$ is determined by $P_{2\_req}$ and $P_{1\_req}$. The $P_{1\_req}$ can be derived with Table1. If the ΔSOC is a positive value, the $P_{1\_req}$ will be negative, and vice versa.

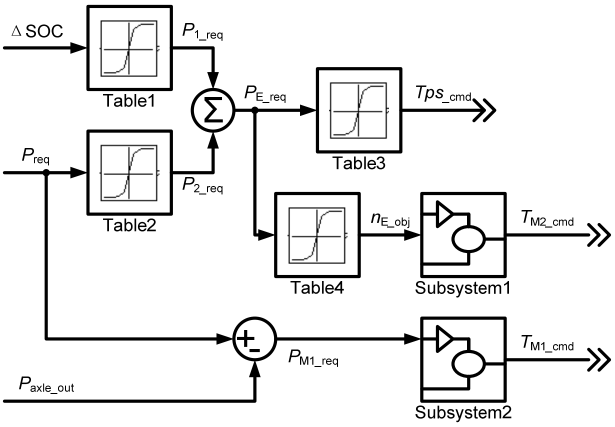



Fig.8 Derivation process of the control command

In Table3 and Table4, the relative parameters of the optimized operation line are presented. With the input of $P_{E\_req}$, you can get the object values of the throttle position $Tps_{\_cmd}$ and the axle rotate speed $n_{E\_obj}$. The former will be output as the control command of the throttle position of the engine directly. And the latter works as the input of Subsystem1 and the reference value of the torque of M2 can be regulated and derived. In certain work point, if the feedback of the speed of the engine is larger than $n_{E\_obj}$, the absolute value of the torque output of M2 will be increased to slow down the engine. Otherwise, the absolute value of $T_{M2\_cmd}$ will be decreased.

The output power of M1 $P_{M1\_req}$ is the difference of the $P_{req}$ and $P_{axle\_out}$. With Subsytem2 you can get the torque command values $T_{M1\_cmd}$ with certain control strategy. In most cases the difference is not zero because the echo of the engine is slow and the required power fluctuates rapidly. If the difference is positive, the M1 works as a general motor to transfer the electric energy from the battery to mechanical energy. And when the vehicle is decelerating the difference will be negative and the M1 is a generator and restored the regenerated energy in the batter pack.

In the control subsystem Subsystem1, the proportional plus integral controller (PI controller) is used. For the robust of the system, incremental PI control algorithm is employed, which is expressed in exp (2).

$$\Delta T(k) = k_p(error(k) - error(k-1)) + k_i error(k) \quad (2)$$

Here, the main controller parameters $K_p$ and $K_i$ are the coefficient of proportion and integrator, respectively. The $K_i$ is a constant in the process, but the $K_p$ is a variable. The $K_p$ varies with the speed of engine, as shown in exp(3).

$$k_p = \begin{cases} k_1 & n_1 \le spd\_E \le n_2 \\ k_2 & n_2 < spd\_E \le n_3 \\ k_3 & n_3 < spd\_E \le n_4 \\ \ldots & \end{cases} \quad (3)$$

The parameter $K_p$ could be obtained in more segments. The reason why to modify it is that the model of the engine is a nonlinear model and is very complex and volatile.

If the engine is off and the vehicle is only driven by the motor M1, the control strategy will be very simple. The throttle position controller is disabled and the throttle valve is free. The torque of M2 is zero and it rotates freely. The output power of M1 $P_{M1\_req}$ is the difference of the $P_{req}$ and $P_{axle\_out}$. With Subsytem2 you can get the torque command values $T_{M1\_cmd}$ with certain control strategy.

When the vehicle is in D mode and the brake is free, a low speed of the vehicle is often expected for the driver. It is realized with the limitation of the minimum value of $P_{req}$. With the prototype, the minimum value of $P_{req}$ is set to 1 kilowatt and the speed of the vehicle is about 5 km/h.

### 3.3.3 R mode

In R mode, the engine is off and the vehicle is only driven by the motor M1. Also, the throttle valve and M2 are free. With Subsystem2 we can obtain the value $T_{M1\_cmd}$. Since there are no gears to change the rotation direction of the wheels, the rotation direction of M2 must be set to be reverse in this mode. Also, the low running speed of the vehicle is achieved.

## 4. Prototype and Part of Results

A prototype vehicle has been assembled. Figure 9 shows a photo in the process of assembling the powertrain. And the vehicle has been performed road test over 5,000 kilometers to verify the feasibility and reliability of the HECU.

Fig.9 A photo of the assembled power train

The results show that the performances of the vehicle have been improved. The acceleration time from 0 to 100km/h has been improved from 17sec of the counterpart traditional vehicle to less than 12sec. The grade degree is over than 25%, which is almost the same the counterpart. Fuel consumption reduced from 10.3L per 100 km to 8.7L/100km in multiple operating modes. In China city cycle, the saved ratio is larger.

Figure 10 shows part of experimental results. In the process, the engine was almost on except in the startup and at the end. The SOC was maintaining in the range of 55±5%. If the vehicle is driven only by the motor M1, the SOC will be less than 45% before the engine start automatically in low speed. The Spd_E changes not sharply, but the torque of M1 Trq_M varies rapidly. It causes the current in the battery fluctuates sharply. It is must admitted that this condition may optimize the operation zone of the engine but will worsen the operation of the battery, which can decrease the lifecycle somewhat. Furthermore, while the signal of Acc_pedal (%) decreases, the torque of M1 also reduces and sometimes it was a negative value. Especially at the end of the process, it is obvious and the SOC increased. In other words, the regenerative brake energy was restored. In the test process, all the functions described above are realized and verified. The major aim is to optimize the relative parameters and to improve the performance further.

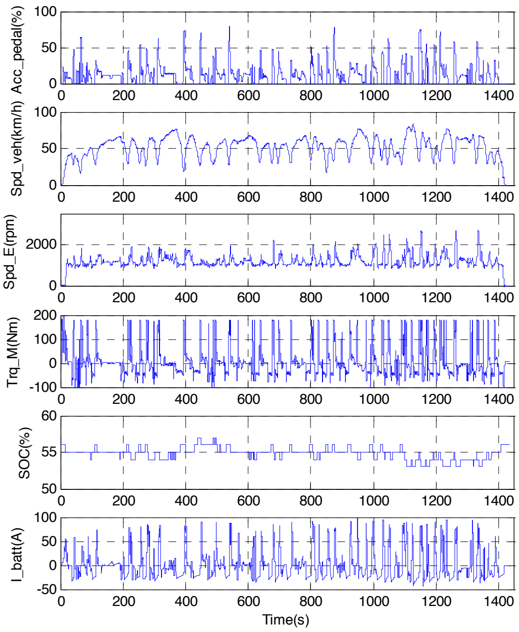



Fig.10 Experimental curves on the rural road

## 5. Conclusions

In this paper, the control function module was divided into several modules. The main modules are logic control module and coordinate control module. The two modules are described. Especially, the engine start/stop control logic and control strategy in D mode are presented in detail. Finally, the test results of the prototype were gave. It shows that the performance of the vehicle has been improved. And the control system is valid and reliable.

## References

[1] Andreas S, Franz Z, Johannes S. *Powertrain*

*Hybridization of a Full Size SUV-A Multifunction Electric 4WD Traction Module*. EVS23, 2008

[2] Delprat S, Guerra T M, Rimaux J. *Optimal Control of a Parallel Powertrain: From Global Optimization to Real Time Control Strategy*. EVS 18, 2001.

[3] Zhu Yuan, Cben Yaobin, Chen Quanshi. *Analysis and Design of an Optimal Energy Management and Control System for Hybrid Electric Vehicles*. EVS 19, 2002.

[4] Seiler J, Schroder D. *Hybrid Vehicle Operating Strategies*. EVS 15, 1998.

[5]Vollmer Thomas, Hfihn Bemd—Robert. *Operational Strategy and Control of the Autark Hybrid of the TU Mtlnchen*. EVS 15, 1998.

[6] Amano Masahiko, Gopal Ram V, Matsuo Takes}ti, et a1. *Practical Optimization of Energy Management for Parallel Hybrid Electric Vehicles*. EVS 20, 2003.

[7] Mehrdad Ehsani, Yimin Gao, Ali Emadi. *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design (2nd Edition)*. CRC press, 2009

[8] NAGASAKA A. *Development of the Hybrid/Battery ECU for the Toyota Hybrid System*. SAE Paper 981122, 1998.

[9] PHILLIPS A M． *Vehicle system controller design for a hybrid electric Vehicle*, IEEE International Conference on Control Applications，Alaska, 2000, pp: 297-302.

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