Hardware-in-loop Simulation of Energy Management System for Plug-in Hybrid Electric Bus

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Abstract. A hardware-in-loop experiment that integrated controller area network (CAN) monitor and evaluation function for control system is the research content, and a rule-based energy management system of plug-in hybrid electric bus (PHEB) is developed. First, a rule-based energy management strategy is designed for PHEB, which realizes series or parallel mode is determined by a mode clutch. Then, a real energy management system of PHEB was developed based on automatic code generation technology, and the real-time kernel of PHEB model was downloaded into VTSystem platform for the real-time simulation system development, Finally, an driver and energy management system-in-loop experiment was carried out to verify the energy management strategy under the China Transit Bus Driving Cycle (CTBDC), and the CAN bus performance features were evaluated by CANoe software.

Introduction

Plug-in hybrid electric bus is a configuration combined with pure electric vehicles and conventional hybrid electric vehicle characteristics, carrying large capacity power battery can be charged from the grid, with a pure electric vehicle mileage [1]. Because inserted electric hybrid vehicles’ special energy distribution structure, the more traditional control of the power source are, the more complex, leading to that high efficiency and energy saving become study’ key [2]. The energy management strategy algorithm based on the rule is easy to implement with strong practicability, good real-time performance, and is widely used in the practical application of the PHEV energy management system.

The hardware in the loop simulation is a key step in the control system of "V" cycle development process, the hardware in the loop simulation platform can be very close to real vehicle environment, the hardware in the loop simulation can not only verify the developed control system’ effectiveness, but also can realize online matching and optimization of control parameters, so as to improve the design success rate and decrease the risk of development [3]. The hardware in the loop simulation’s main commercial tool chain is LabCar system, dSPACE system and ADRTS system [4]. Because the CAN bus has good real-time performance, reliability and simple protocol architecture, it is widely used in electric vehicle control [5], and the CAN bus simulation tools to integration of professional hardware in the loop simulation, can be more close to the actual conditions.
This paper firstly developed an energy management strategy based on rules which can realize the transformation of CD and CS, and base on the development process of MotoTron control system to realize hardware of the control strategy. Then through Simulink automatic code generation technology to generate PHEB simulation model’s real-time kernel, with CANoe software downloading to VTSytem, so as to establish the real-time simulation model of the controlled object, finally connected the real control system and the real-time simulation machine through the CAN bus, and used CANoe software to monitor and evaluate the CAN bus communication quality. According to such a flow process, we can test and improve the control functions and properties of the energy management system.

**PHEB Energy Management Strategy**

**Powertrain Configuration**

In this paper, the plug-in hybrid electric bus’ powertrain configuration used serial parallel structure, specific as shown in Figure 1, engine and ISG motor is fixedly connected, ISG motor is connected with a drive motor through the model clutch, then the power through the rear axle main reducer and differential to the wheels, driving PHEB.

![Powertrain form](image)

**Figure 1. Powertrain form.**

**Energy Management Strategy**

In general, plug-in hybrid electric bus energy management strategy design obeys power battery depletion principle, minimum principle of energy flow, driving priority principle and maximum energy recovery principle of regenerative braking [6].

For plug-in hybrid electric bus, there are three kinds of energy consumption patterns, namely the EV mode, CD mode, CS mode. In EV mode, drive motor driven vehicle individually, all the energy that vehicle required come from the power battery; in CD mode, the engine and the drive motor driven the vehicle together, power battery SoC decreased gradually; under the CS mode, most of the energy driving the vehicle come from the engine, the power battery SoC maintained in a proper range, until the vehicle stop.

**EV mode.** When SoC>65%, EV (equivalent to pure electric vehicles) mode. Tdstands for demanded torque, Testands for the requirements of the engine output torque, Tmstands for the main drive motor needs output torque, Tgstands for ISG motor demand output torque. At this time power battery provides energy, driving motor is responsible for meeting the driving requirements, at this time due to the higher SoC, charging efficiency is lower, so no
regenerative braking, and reduce the number of low power battery charging efficiency, extend power battery life.

**CD Stage Strategy.** When 30%<SoC<65%, at this time it is CD mode. Control strategy flow chart. When Mode=0 stands for the clutch engagement. Mode=1 stands for the disconnected clutch, according to the speed of clutch it switches modes, and it has the relay characteristics, when speed is low, the clutch is disconnected, in the high speed, the clutch is in engagement.

When the vehicle is at low speed, only use the drive motor to drive the vehicle.

When the car is running in high speed, when the driving demand torque is less than the lower limit of the optimum engine operating region, only provided by the drive motor torque; when the driving demand torque is in optimal working area of the engine, use engine direct drive mode; when the driving demandtorque is larger than the upper limit of the optimal engine working area, both the engine and the drive motor meet drive demand;at this stage, the regenerative braking can be conducted to recycling energy.

**Stage of CS strategy.** When the SoC < 30%, It is CS model. Flow chart of the control strategy, Pd is power demand, Pm is drive motor power, Pmd_max is maximum output power to drive motor, Papu is APU output power, Papu_max is APU maximum output power, Papu_min is APU threshold power, APU work at constant speed, Pchg is power for charging demand (when the Pchg> 0, it do not need to charge, when the Pchg < 0, it needs to charge), Tchg is charging demand torque (Tchg > 0 indicates that don't need to recharge, Tchg < 0 indicates that need to charge).

The control strategy ensure the SoC stability near 30%. The charging demand power is proportional to the maximum charging power Pchg_max, the farther the distance control target 30% SoC, the greater its absolute value, when the battery work window of CS mode in the upper limit, Pchg = Pchg_max; when Work in lower limit, Pchg = - Pchg_max. Charging demand torque can be obtained by the charging demand power.

**The Hardware-in-loop Simulation Test**

To verify the validity of the control strategy, This section use the hardware in the loop simulation platform make the multiple sets of test. At the same time, in order to ensure the pilot control pedal demand closer to coach real running condition, similar to PHEB real-time simulation model, the test download China Transit Bus Driving Cycle, CTBDC into real-time interface card of VTSystem, observing the CANoe can be taken as the basis of the driver's pedal manipulation. the CTBDC is shown in figure 2.

![Figure 2. China bus driving cycles.](image-url)
To better display the results of control strategy, it first run three typical Chinese urban road driving cycles. At the same time, to validate the mode switch of the control strategy, the power battery SoC initial value is set to 85%, the total capacity is set to 10 A, h.

The driver makes the PHEB real-time simulation model of the vehicle speed follow the CTBDC as far as possible by manipulating the throttle and brake pedals. The actual effect is shown in figure 3. The two curves are basically consistent, which shows that the driver hardware-in-loop simulation platform with a high control and response accuracy, thereby laying the foundation for the well-proven energy management strategy.

As can be seen in Figure 4, prior to 870S, the demand for power is not achieved when following the negative. Because the SoC is high, the vehicle is in EV mode and the energy management strategy does not allow for regenerative braking and charging. Therefore only the positive power demand can achieve the following target.

As shown in Figure 5, when SoC is in 65%–80%, this time is in the EV mode. This mode does not allow traffic charging and regenerative braking, so the power did not grow up; When the SoC is below 65%, this time is in the CD mode. Since this mode allows regenerative braking, the situation SoC growth thus appears; When the SoC is below 30%, this time is in the CS mode and SoC swings between 29% ~ 31%. Due to the changes of SoC leads to the CD and CS mode switch, eventually it makes the SoC in the 30% up and down fluctuations. And through the slope of the decline in SoC can be seen, CD and CS mode is slower than the EV model. Because the vehicle energy is no longer only from the power battery, power consumption slows down, which is in line with the actual situation.

The mode switch of the control strategy is shown in Figure 6. In accordance with the change in SoC, EV and CD mode switch cannot be reversed. However, CD and CS mode switching is reversible. As can be seen with the APU to the power battery charging, SoC picks up to a certain level, then switches back to CD mode. As can be seen from the figure, the design of the control strategy in the late period can achieve the CS and CD mode of the
effective switch, that is, the extension of the use of CD mode. This is consistent with the global optimization control objectives, which is beneficial to enhance the fuel saving potential of energy management strategy based on rules.

PHEB 100km energy consumption can be seen in Figure 7. Combining with Table 1, the engine operating point (shown in blue *) is always the best engine work area, indicating that the development of energy management strategies is good with fuel economy.

![Figure 7. The engine working point distribution.](image)

| Performance parameter                     | Control result |
|-------------------------------------------|----------------|
| Fuel consumption (L/100km)                | 14.1           |
| Electric energy consumption (kW·h/100km)  | 11.9           |
| Initial SOC                               | 85%            |
| Termination SOC                           | 31.7%          |

In summary, the controller can accord the driver's intention of the vehicle model to meet the expected energy management based on this verification platform with normal logic functions. It indicates that the control model has the actual vehicle operating conditions, which can be used as part of the controller involved in the future of the real vehicle tests.

**Conclusion**

(1) This paper developed a rule-based energy management strategy. In order to verify the reliability and real-time performance of the developed energy management strategy, the driver's hardware in the loop simulation platform is built. Based on the automatic code generation technology, the use of commercial software (MotoHawk, MotoTune) completed the development of PHEB energy management system. And use the VTSystem to develop PHEB real-time simulation system. Finally, use electronic accelerator pedal and the accelerator pedal to implement pilot in loop operation. At the same time, use canoe software as PC software to complete the hardware in the loop simulation platform of real-time monitoring.
(2) On the bus driving cycles as the target speed, a series of HIL tests were carried out on the driver's control pedal. HIL test results show that the real-time simulation speed and power can follow needs speed and power well, indicating that the development of the energy management system can meet the requirements of dynamic performance. At the same time on the road after the process it can realize switch reversibly of CD model and CS model, which make SOC stable in the vicinity of 30%. That’s to say, in the stability of the SOC extended CD model work effectively at the same time, further enhance fuel economy. This is consistent with the theory of global optimization goal. The initial SoC was 85%, hundreds of kilometers were 13.7 L diesel fuel sales and electrical energy and 10.5 kW · h.

(3) CANoe monitoring results show that the normal bus communication, and HIL platform CAN communication performance parameters are reasonable with no error frame, indicating that the development of PHEB energy management system has good real-time performance and reliability.

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