MODELING AND SIMULATION OF TORQUE DISTRIBUTION CONTROL STRATEGY FOR A SERIES-PARALLEL HYBRID ELECTRIC BUS

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Series-parallel hybrid electric bus, Control strategy, Modeling, Simulation, analysis.

ABSTRACT

Combined with the characteristics of vehicle operation, a torque distribution control strategy based on logic threshold method for a series-parallel hybrid electric bus is proposed to improve the vehicle's fuel economy. And the simulink model of this strategy is built. Then the simulation is completed under the selected cycle condition. Compared with the real vehicle test data, the control strategy can reduce the fuel consumption by 6.2% on the basis of guaranteeing the vehicle's dynamic performance, which achieves the design goals. And the charge balance of the super-capacitor is also well maintained. The validity and feasibility of the torque distribution control strategy has been verified.

INTRODUCTION

With good fuel economy and low emission, the series-parallel hybrid electric bus(SPHEB) has become an important new energy vehicle to deal with the increasingly serious energy crisis and environmental problem, and has great market value (Mingze Gao 2013; Niassar A. H. et al. 2005). As the core of the energy management for the SPHEB, the vehicle control strategy is the core technology to realize the energy saving and emission reduction, and it is also the focus of the present study(Lqbal Husain. 2012). Gong Xianwu etc. designed a logic threshold control strategy based on the principles of meeting the power demand and improving the engine's fuel economy, and the simulation analysis was carried out to study the control effect(Xianwu Gong and Dejun Wu et al. 2014). Abdelsalam A. A. proposed a fuzzy logic control strategy for PMSM-EVT hybrid electric vehicle and designed the controller with velocity, total drive torque, power required and battery's state of charge(SOC) as control variables, which optimized the work status of the engine and improved the vehicle's fuel economy(Abdelsalam A. A. and Shumei Cui 2012). Wassif Shabbir etc. studied a real-time optimization control strategy with real-time efficiency maximization of hybrid power system as the goal, which achieved a lower fuel consumption of the vehicle(Wassif Shabbir 2014). With the advantages such as simple in design and easy to implement, the logic threshold control strategy is widely used in the actual control of the SPHEB.

In this paper, a type of SPHEB is the study object. Based on the structure analysis of its powertrain and combined with the characteristics of the vehicle operation, a torque distribution control strategy on the base of logic threshold method is proposed with a major control object to improve the vehicle's fuel economy. The simulink model of the strategy is built in Matlab. To verify the validity and feasibility of the torque distribution control strategy, the simulation analysis is completed.

STRUCTURE ANALYSIS OF THE SERIES-PARALLEL HYBRID POWERTRAIN

The prototype of the SPHEB studied in this paper is a rear wheel drive city bus with 12 m class, which is equipped with a powertrain mainly composed by a six-cylinder engine, a traction motor, an integrated/starter-generator(ISG), an automatic clutch, a super-capacitor and a vehicle controller, as shown in figure 1. Using the coaxial arrangement, the engine crankshaft is connected to the ISG spindle directly. The swhich between series mode and parallel mode can be realized by opening and closing the clutch installed between the traction motor and the ISG. The CAN (controller area network) bus control mode is used in the vehicle controller to implement the control of the engine, the traction motor, the ISG and the automatic clutch.

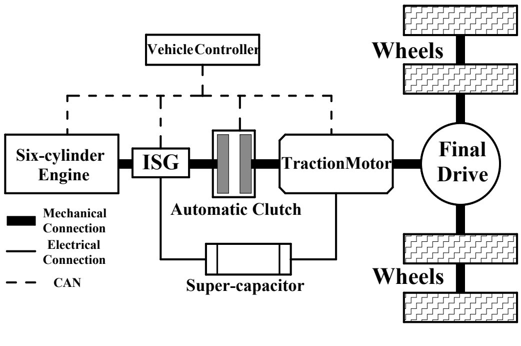

Figure 1: Structure of the Hybrid Powertrain

The series-parallel hybrid powertrain has advantages of both the series and the parallel structure, which has

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great flexibility for the energy flow and control. And many different working modes can be achieved. Combined with the actual characteristics of the vehicle operation, 5 kinds of working modes can be implemented: the pure electric mode, the engine-only driving mode, the engine and traction motor combined driving mode, the engine driving and charging mode and the energy recovery mode.

TORQUE DISTRIBUTION CONTROL STRATEGY OF SPHEB

Since the SPHEB has many working modes, during its working, the working mode and the distribution of the drive torque or braking torque among various power components should be determined by the torque distribution control strategy. So in the design of this control strategy, the determination and control of the SPHEB's working modes and the development of the torque distribution rules are necessary to be done.

Determination and Control of the Working Modes

According to the operation characteristics of the SPHEB studied in this paper, the working modes are determined by the driving or braking signals from the accelerator pedal or the brake pedal operated by the pilot and the super-capacitor's SOC. The determine processes and conditions of the different working modes are shown in figure 2. According to whether there is a driving or braking signal, the working modes can be divided into driving mode and regenerative braking mode. Then the driving mode is determined in detail according to the super-capacitor's SOC and the required torque calculated by the driving signal. Taking the high limit of the super-capacitor's SOC as SOC_*high*=0.9, the low limit as SOC_*low*=0.4.

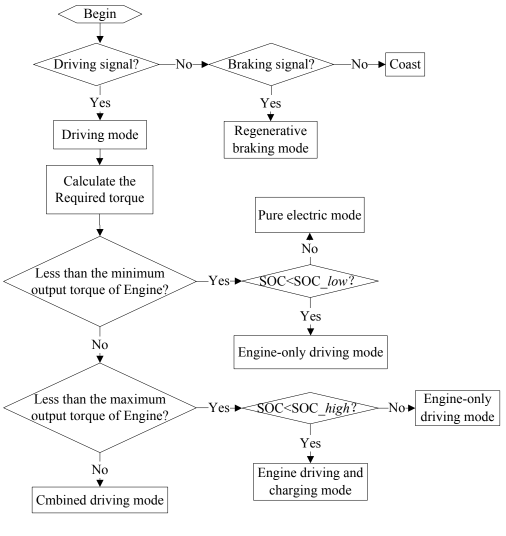


Figure 2: Determination Flow-chart of Working Modes

Driving Torque Distribution Rules

The method of electric power auxiliary control is used in the distribution of the driving torque. The traction motor is used as a flexible power component to assist the engine's working and to optimize the engine's working condition for a better fuel economy and keeping the super-capacitor's SOC in a good range.

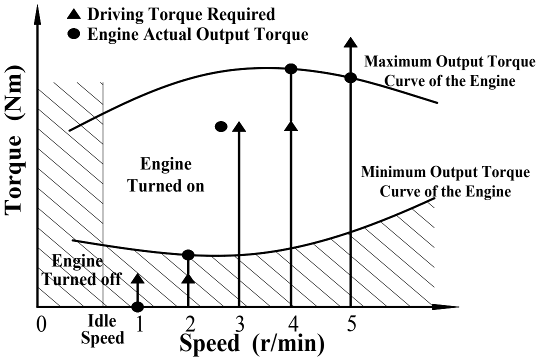


Figure 3: The Distribution of the Driving Torque

The distribution of the driving torque is shown in figure 3. According to the size of the driving torque required, there are 5 kinds of circumstances corresponding to the different torque distribution rules:

1) If $T_{req} < T_{e\_min}$ and SOC≥SOC_*low*, the SPHEB is working in the pure electric mode. The clutch is disengaged, and the engine is turned off. Control $T_e=T_{isg}=0$, $T_m=T_{req}$.

2) If $T_{req} < T_{e\_min}$ and SOC<SOC_*low*, the SPHEB is working in the engine driving and charging mode. The clutch is closed, and the engine is turned on. Control $T_e=T_{e\_min}$, $T_m= 0$, $T_{isg}= T_{req}-T_{e\_min}$.

3) If $T_{e\_min} \leq T_{req} < T_{e\_max}$ and SOC≥SOC_*high*, the SPHEB is working in the engine-only driving mode. The clutch is closed, and the engine is turned on. Control $T_e=T_{req}$, $T_m= T_{isg}=0$.

4) If $T_{e\_min} \leq T_{req} < T_{e\_max}$ and SOC<SOC_*high*, the SPHEB is working in the engine driving and charging mode. The clutch is closed, and the engine is turned on. Control $T_e=T_{e\_max}$, $T_m= 0$, $T_{isg}= T_{req}-T_{e\_max}$.

5) If $T_{req} \geq T_{e\_max}$, the SPHEB is working in the engine and traction motor combined driving mode. The clutch is closed, and the engine is turned on. Control $T_e= T_{e\_max}$, $T_m= T_{req}-T_{e\_max}$, $T_{isg}=0$.

In the above rules, T_{req} is the driving torque required. T_{e_min} is the minimum output torque of the engine. T_{e_max} is the maximum output torque of the engine. T_e is the actual output torque of the engine. T_m is the actual output of the traction motor. T_{isg} is the actual output torque of the ISG Their units are N·m.

Regenerative Braking Torque Distribution Rules

The energy utilization can be improved by the regenerative braking of the SPHEB, which is one of the most important ways of the energy saving(Guozhu Zhao 2012). Mechanical energy can be turned into electrical energy and stored in the super-capacitor by the regenerative braking, which can narrow the gap of the super-capacitor's electricity before and after the SPHEB's start and stop for a good balance of power.

The opening degree of the brake pedal and the super-capacitor's SOC value is used for the distribution of the regenerative braking torque. The emergency degree of braking is determined by the opening degree of the brake pedal , which can also determine the size of the braking torque required. For a good power balancing feature of the super-capacitor, it should be determined that whether the engine needs to start or not for auxiliary power generation and maintaining the super-capacitor by the super-capacitor's SOC. The distribution rules of the regenerative braking torque designed in this paper are as follows:

1) If SOC≥SOC_*high*, the super-capacitor is fully charged. The regenerative braking is not needed to charge the super-capacitor. Otherwise, it may cause overcharge and affect the service life of the super-capacitor.

2) If SOC_*mid*≤SOC＜SOC_*high* and the opening degree of brake pedal≥0.5, the braking is urgent, but it needn't to turn on the engine for auxiliary power generation. Control $T_m=-T_{m\_max}$.

3) If SOC_*mid*≤SOC＜SOC_*high* and the opening degree of brake pedal＜0.5, the braking is not urgent, and it needn't to turn on the engine. Control $T_m=-T_{m\_max}$×the opening degree of brake pedal.

4) If SOC＜SOC_*mid* and the opening degree of brake pedal≥0.5, the braking is urgent, and it needs to turn on the engine for auxiliary power generation. Control $T_m=-T_{m\_max}$， $T_e=-T_{isg}=T_{e\_max}$.

5) If SOC＜SOC_*mid* and the opening of brake pedal ＜0.5, the braking is not urgent, but it needs to turn on the engine. Control $T_m=-T_{m\_max}$×the opening degree of brake pedal， $T_e=-T_{isg}=T_{e\_max}$.

SOC_*mid* is the middle level of the super-capacitor's SOC, and SOC_*mid*=0.6. The opening degree of brake pedal has a range of 0~1.

Modeling of the Torque Distribution Control Strategy

In this paper, the simulink model of the torque distribution control strategy based on the logic threshold method is built in Matlab, as shown in figure 4. This model is mainly composed of 5 submodules: the input signal processing module, the working mode selection module, the driving torque distribution module, the regenerative braking torque module and the coast control module. With these submodules, the control strategy model can control the working conditions of the clutch, the engine, the traction motor and the ISG.

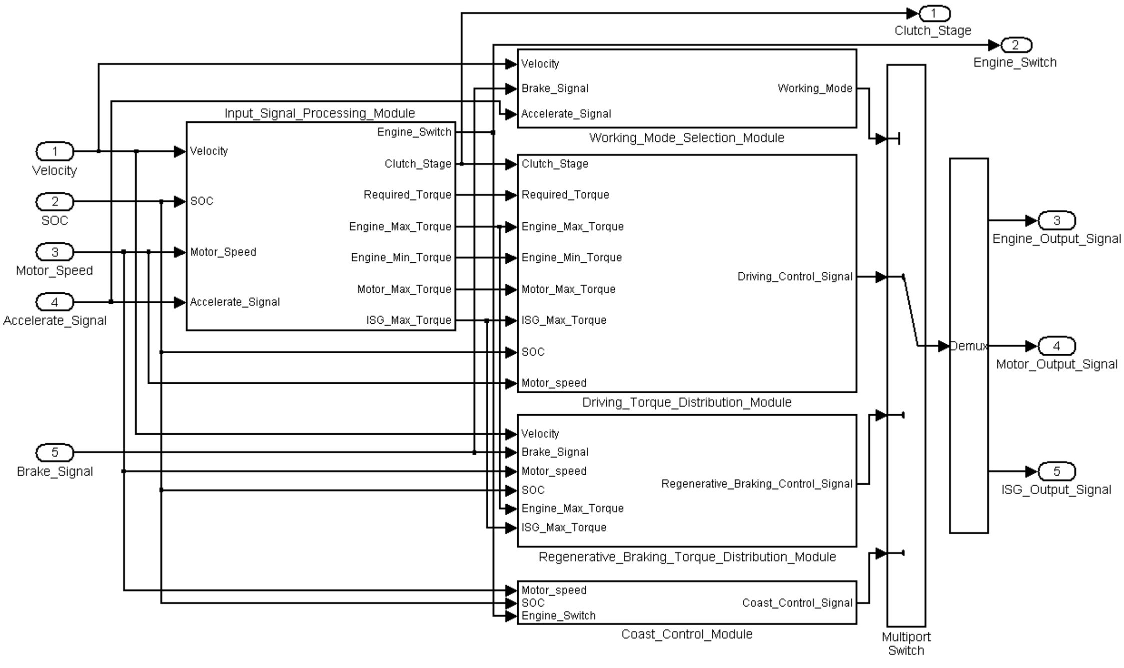


Figure 4: Simulink Model of the Torque Distribution Control Strategy

According to the inputs including the vehicle velocity, the SOC, the traction motor's rotation speed and the opening degree of the accelerator pedal, the parameter values and control signals such as the engine on/off signal and the control signal of the clutch status used in the subsequent modules can be getted by a series of look-up tables and numerical calculations in the input signal processing module. And the input signal processing module is composed of the clutch/engine status control module and the torque caculation module.

The clutch/engine status control module is shown in figure 5. And the status of the clutch and the engine are mainly determined by the vehicle's velocity and the super-capacitor's current SOC.

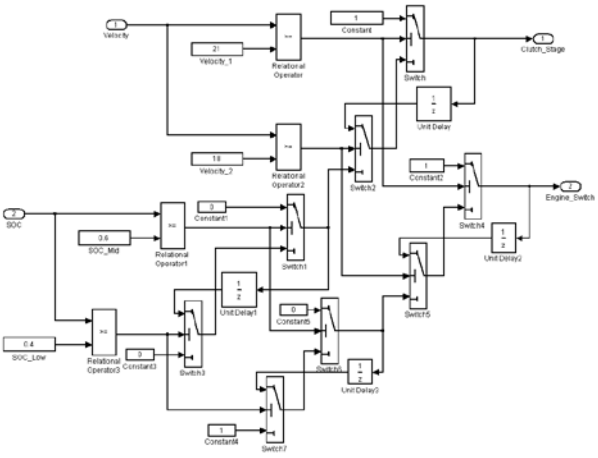


Figure 5: Model of Clutch/Engine Status Control Module

The torque caculation module which used as a caculator to get 5 torque siganls by a series of look-up tables and numerical calculations is shown in figure 6. The speed of motor is the key of this module. These look-up tables are defined by real torque datas of the related components.

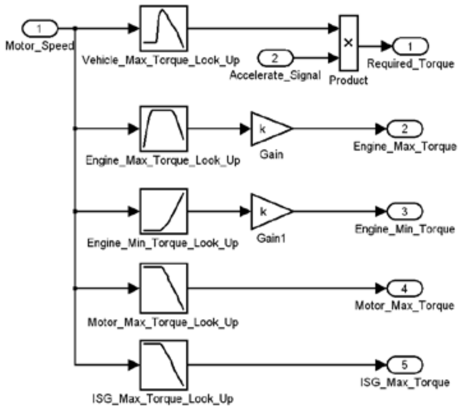


Figure 6: Model of the Torque Caculation Module

The current working mode of the SPHEB is determined by the working mode selection module according to the velocity, the opening degree of the accelerator pedal and the opening degree of the brake pedal. As shown in figure 7, the model of the working mode selection module is built on the basis of the working mode selection process introduced above. Then the signals determined and controlled by the driving torque distribution module or the regenerative braking torque distribution module are outputted to the engine, the traction motor, the ISG and other power output components to get the actual output torque.

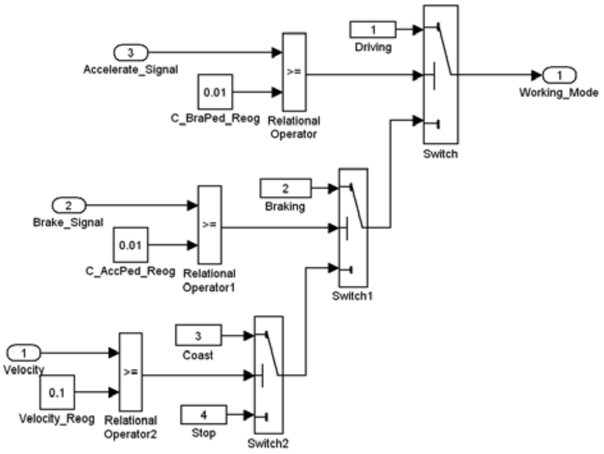
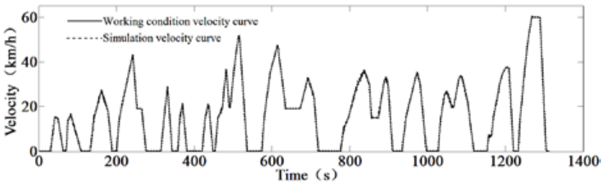


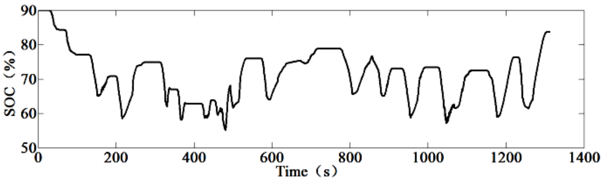
Figure 7: Model of the Working Mode Selection Module

SIMULATION ANALYSIS

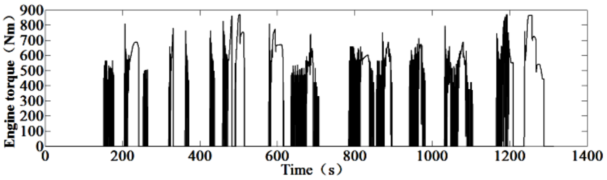
Based on the simulation model of the SPHEB's powertrain established in Cruise, the typical city driving cycle in China is chosen as the test cycle for the simulation. The simulation results of the vehicle's velocity, the SOC of the super-capacitor and the output torque curves of the engine, the traction motor and the ISG changing over time are shown in figure 8.



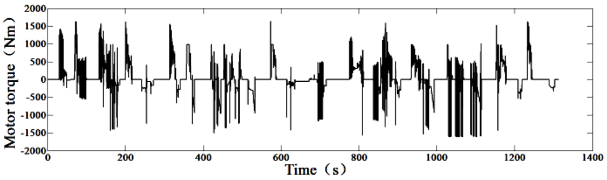
(a) the changing curves of the velocity



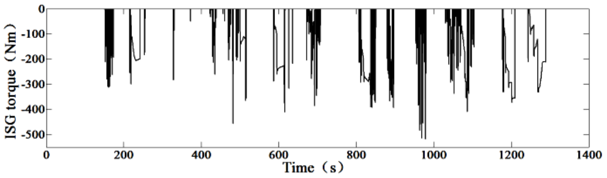
(b) the changing curve of the SOC



(c) the torque changing curve of the engine



(d) the torque changing curve of the traction



(e) the torque changing curve of the ISG

Figure 8: Simulation results

As shown in figure 8(a), the simulation velocity is followed with the actual driving cycle curve closely and can meet the requirements of the actual working condition of the velocity and acceleration. Figure 8 (b) is the curve of the super-capacitor's SOC and it can be seen that with the velocity changing of the driving cycle, the SOC curve is changed in regular fluctuations, which shows that the super-capacitor can be charged or discharged reasonably. Besides, the initial value of SOC is 90% and the end value is 83.6%, which means its power balance is good. With the changing curves of the output torque shown in figure 8(c)~(e), when the vehicle starts up or is driven at a low speed, the driving torque required is provided by the traction motor only, and the SOC drops. With the increase of the vehicle's veloxity, the engine turns on and the driving torque required is provided by both the engine and the traction motor during the acceleration. When the SOC is very low, the super-capacitor is charged by the electricity generated from the ISG with producing negative torque. When braking, the braking energy is recycled by the traction motor which outputs negative torque and the SOC is rising. All of these are in accordance with the proposed vehicle control strategy as well as the designed torque distribution rules, which are also showing that the control strategy designed in this paper is correct and effective.

As shown in table 1, the simulation results of the SPHEB's dynamic performance and fuel economy are compared with the actual vehicle test data. The simulation result of the acceleration time for 0~50 km/h is shorter than the actual vehicle test data and the fuel consumption is 6.2% lower than the actual vehicle test, which means that with the control strategy built in this paper, the fuel consumption has been decreased on the premise of a good dynamic performance. And on the other hand, it also indicates that there is a good control effect of the torque distribution control strategy proposed in this paper. The vehicle's fuel economy has been improved and the design goal of the control strategy has been achieved.

Table 1: Results of the dynamic performance and the fuel economy

	Simulation Results	Actual Test Date
Maximum Speed ($km \cdot h^{-1}$)	77.8	78.0
Acceleration Time of 0~50 $km \cdot h^{-1}$ /(s)	15.4	17.2
Fuel Consumption (L/100km)	22.23	23.70

In addition, in order to verify the control effect on maintaining the electric power balance of the super-capacitor of the torque distribution control strategy designed in this paper, a comparation with a common control strategy without the distribution of the regenerative braking torque is made. With the same initial value of the SOC(90%), the end value simulated by the torque distribution control strategy designed in this paper is 83.6%, while the end value simulated by the common control strategy is 80.4%. That indicates that the super-capacitor has a better electric power balance feature with the torque distribution control strategy designed in this paper. Figure 9 shows the comparison of the simulation cueves of the super-capacitor's SOC

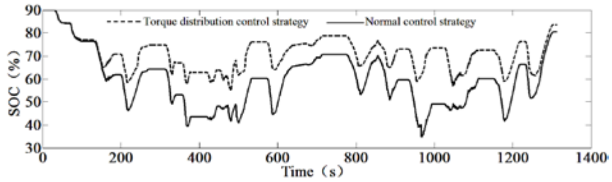


Figure 9: Comparison of the SOC Curves

CONCLUSIONS

Combined with the actual operations and based on the structure analysis of a SPHEB's powertrain, a torque distribution control strategy is designed with a major control object to improve the vehicle's fuel economy. And the simulink model of the control strategy is built. The control effect of the torque distribution control strategy proposed in this paper is got by the joint simulation analysis. The simulation results show that:

(1) Under the typical city driving cycle in China, the velocity of the simulation can meet the velocity of the actual driving cycle closely and the dynamic performance of the simulation can match the actual vehicle test data.

(2) The fuel consumption of the SPHEB is 6.2% lower than the actual vehicle test and the SOC of the super-capacitor is more smooth with a better electric power

balancing feature, which has indicated that the torque distribution strategy proposed in this paper can not only improve the vehicle's fuel economy and achieve the design goals effectively, but also can maintain the electric power of the super-capacitor in a better way. The torque distribution strategy has a good control effect. The simulation results have verified the validity and feasibility of the torque distribution strategy proposed in this paper.

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