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Hybrid drive design for minibus by simulation

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Abstract

This paper presents the design method of hybrid drive configuration for the minibus with some limited conditions. The approach of design hybrid drive system is based on the dynamic modelling and simulation of the hybrid minibus with planetary gear system. The main target of the design is to obtain the optimal design with the proper hybrid drive configuration and control for a given set of design constraints. It's necessary to adjust some parameters such as mechanical ratios and parameters of battery pack as well as control by simulation in order to obtain optimal design. The transient operating process can be studied in details with the dynamic model in Matlab/Simulink, and the control strategy can be optimized by running the simulation and monitoring the operation of each components: the operating points of ICE, fuel consumption (energy consumption), the power distribution, the torque and rotary speed of ICE and motor, the operating efficiency of motor, the change of battery State of Charge (SOC), current and voltage.

Keywords: HEV, powertrain, simulation, vehicle performance, energy consumption

1 Introduction

A HEV has two or more sources of on-board power. The integration of these power-producing components with the electrical energy storage components allows for many different types of HEV design. The flexibility in HEV design comes from the ability of the control strategy to manage how much power is flowing to or from each component. This way, the components can be integrated with a control strategy to achieve the optimal design for a given set of design constraints. To obtain the optimal design, the hardware configuration and the power control strategy are designed together. Before a control strategy is implemented, an HEV consists simply of hardware components hooked up electrically and mechanically, with nothing telling them what to do or when to do it. The control strategy brings the components together as a system and provides the intelligence that makes the components work together.

This paper depicts the design of hybrid drive configuration for the minibus with some limited conditions. The approach of design hybrid drive system is based on the dynamic modelling and simulation of the hybrid minibus with planetary gear system. It's necessary to adjust some parameters of hybrid drives such as mechanical ratios and parameters of battery pack as well as control by simulation in order to obtain optimal design. The transient operating process can be studied in details with the dynamic model in Matlab/Simulink, and the control strategy can be optimized by running the simulation and monitoring the operation of each components: the operating points of ICE, fuel consumption (energy consumption), the power distribution, the torque and rotary speed of ICE and motor, the operating efficiency of motor, the change of battery SOC, current and voltage.

2 Required performance of hybrid minibus and limited conditions

2.1 Parameters and technical requirements of hybrid minibus

1) Dimension: 5980(L)×2000(W)×2752(H) mm;
2) Total mass: ≤5000kg;
3) Maximum speed: 100 km/h;
4) Acceleration time from 0 to60 km/h: ≤25s;
5) Maximum Gradeability: 30%; (Option: For maximum Gradeability using Diesel Engine only with additional gearbox)
6) Fuel Consumption Improvement: ≥20%; (Compared with the conventional minibus, according to the proper comparable city driving cycle)

2.2 Requirements of hybrid drive system for minibus:

1) Engine operating mode;
2) Pure electric operating mode;
3) Regenerative braking;
4) High reliability and smooth shift among different operating modes;
5) Being composed of mechanical parts and the corresponding separated controller;
6) Communicating by CAN BUS with main controller;

2.3 Limited conditions

The hybrid minibus will be designed and adjusted according to Fiat IVECO minibus. There are following limited conditions which couldn't be changed.

1) Engine: Rotary speed range 850~4000 rpm, Max output power 87 kW/3600 rpm, Max torque 269 Nm/1900 rpm;
2) The possible selected ratio of main reducer: 3.62, 3.91, 4.18, 4.44, 4.56, 4.88, 5.22;
3) Battery is limited to High Power NiMH provided by Chinese manufacturer.
4) Motor can be selected according to the requirement of hybrid drive design.

3 Designing target of hybrid drive for minibus by simulation

The main target of the design by modelling and simulation is to obtain the optimal design for minibus with the proper hybrid drive configuration and control for a given set of design constraints. The minibus with the hybrid drive system should meet the requirements of vehicle performance such as maximum speed, acceleration, gradeability, at the same time to obtain the minimal fuel and electricity consumption depending on the proper control strategy. The hybrid drive system should meet the requirement of pure engine mode, pure electric mode and regenerative braking.

4 HEV model

In order to achieve the designing target by simulation, it's necessary to make a HEV model. The simulation flow chart of HEV dynamic model in Simulink is shown in Fig.2. The general model of hybrid drivetrian is based on Fig.1. The configuration of hybrid drive system including the dynamic model should be adjusted during simulation to meet the target of design.

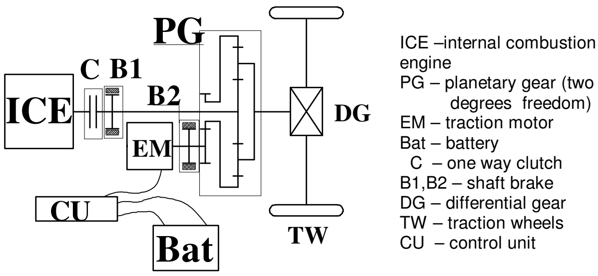


Fig.1. Hybrid drive system with planetary gear [2]

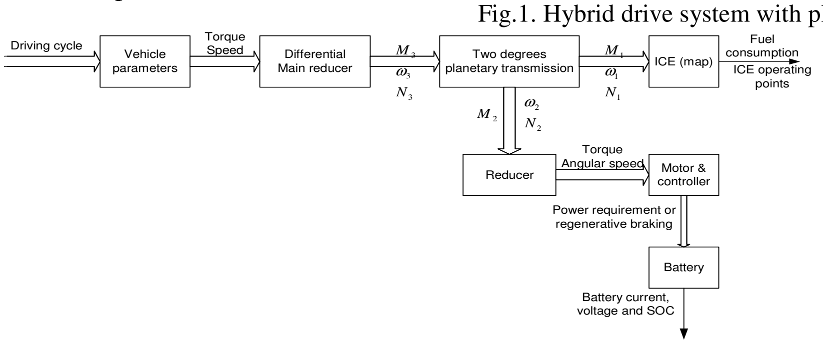


Fig.2. The simulation flow chart of HEV dynamic model in Simulink

4.1 Vehicle model

The mathematical equations used for vehicle model in Simulink are as followings:

$$M\_wheel = (F_f + F_{aero} + F_{acc} + F_g) r_{dyn}$$

$$F_f = mgf \cos\alpha$$

$$F_{aero} = \frac{c_x A}{21.15} v^2$$

$$F_{acc} = \frac{1}{3.6} m \delta_b \frac{dv}{dt} \quad (\delta_b = 1 + \frac{J_s j^2 \eta_m + \sum J_k}{m r_{dyn}^2})$$

$$F_g = mg \sin\alpha \quad (\alpha \text{ - gradient})$$

Where:

m - Vehicle total mass [kg];
g - Acceleration of gravity [m/s^2];
f - Rolling friction resistance;
A - Frontal area [m^2];
c_x - Aerodynamic coefficient;
δ_b - Rotation elements factor;
R_{dyn}- vehicle dynamic radius [m];
j - The amount ratio between engine shaft and driving wheels;
η_m - The efficiency of torque transmission;
J_s - Moment inertia of engine rotor;
$\sum J_k$ - The moment inertia of vehicle wheels, reduced on vehicle shaft;

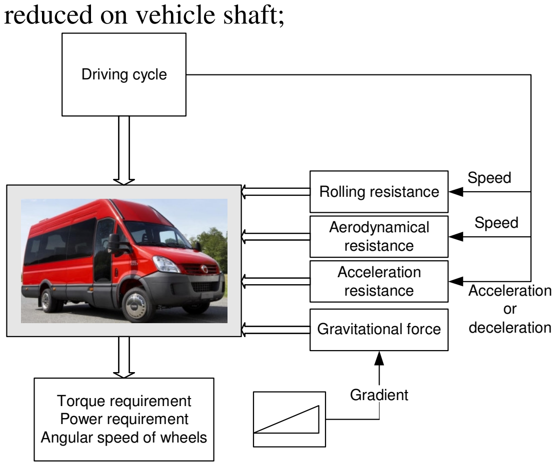


Fig.3. Vehicle model

The function of vehicle model is to calculate torque and power requirements according to vehicle loads and driving cycle (see Fig.3) and then input them into drive system.

4.2 Planetary transmission model

The mathematical equations used for planetary transmission model in Simulink are as followings [2]:

$$\omega_1 + k_p \omega_2 - (1 + k_p)\omega_3 = 0$$

$$J_1 \dot{\omega}_1 = \eta_1 M_1 - \frac{1}{k_p} \eta_2 M_2$$

$$J_3 \dot{\omega}_3 = M_3 + \frac{k_p + 1}{k_p} \eta_3 M_2$$

Where:

J_1 - total inertial torque of sun wheel and connecting elements;
J_3 - total inertial torque obtained from reduction of the vehicle mass, road wheels and gears reducer inertial torques to the carrier shaft;
M_1 - external torque acting on the sun shaft;
M_2 - external torque acting on the sun shaft;
M_3 - external torque acting on the carrier and corresponding to the vehicle motion resistance reduced to the appropriate shaft;
ω_1, ω_2, ω_3 - angular velocity of sun, crown and yoke wheels respectively.
η_1, η_2, η_3 - substitute coefficients of internal power losses.

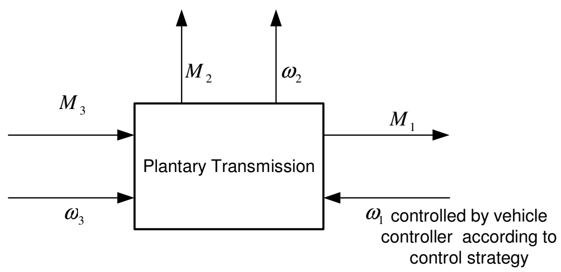


Fig.4. Planetary transmission model

4.3 Battery model

For adjusting the configuration of hybrid drive system and simulating vehicle performance, the testing data of 27Ah 12V NiMH battery module provided by Beijing Institute of Technology EV Centre are used in the simulation. The battery model was developed by Author [3] [6] and following mathematical equations were aggregated in the model:

$$e(k) = -61.805k^6 + 246.72k^5 - 358.34k^4 + 246.03k^3 - 85.246k^2 + 15.389k + 11.369$$

$$r(k) = -0.75178k^6 + 2.2681k^5 - 2.6248k^4 + 1.4629k^3 - 0.40259k^2 + 0.049571k + 0.0083927$$

$$u(t) = e(k) - i(t) r(k)$$

$$P(t) = u(t) i(t)$$

$$k = k_0 - \int i(t) dt$$

The battery model in Simulink is shown in Fig.5

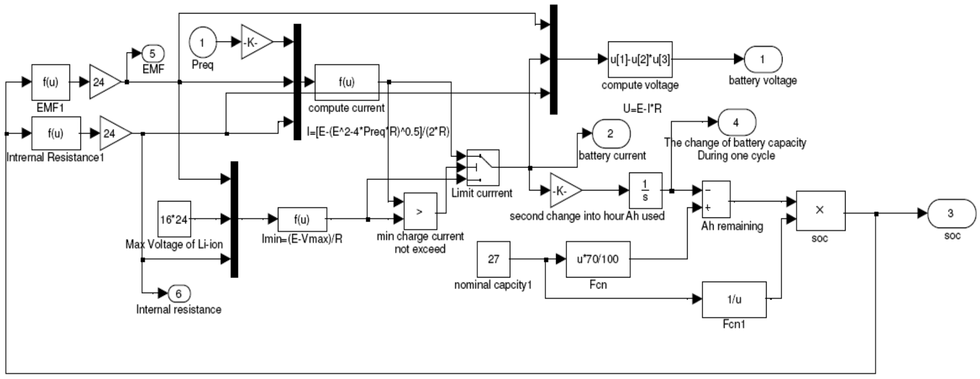


Fig.5. Battery model in Simulink

4.4 Motor model

SR218N Brushless PM Motor/Generator (from UQM Technologies, Inc) and its controller (PowerPhase 75 Traction System) were selected for this hybrid drive system after detailed consideration. The efficiency map of PowerPhase 75 Traction System (motor and its controller) is used for motor modeling in Simulink (See Fig.6)

There are two methods to make motor model: using mathematical equations or using efficiency map of motor. However, there is a very small difference (about 1%) of simulation result by using mathematical equations and efficiency map of motor, which was verified by Dr. P. Piórkowski [1].

The mathematical equations used for motor Simulink model are as followings [2]:

$$\left.\begin{aligned} \frac{d\Psi_d}{dt} - \omega\Psi_q + Ri_{1d} = u_{1d} \\ \frac{d\Psi_q}{dt} + \omega\Psi_d + Ri_{1q} = u_{1q} \end{aligned}\right\}$$

$$J\frac{d\omega}{dt} = M_e - M_l$$

$$M_e = \frac{3}{2}p((L_d i_{1d} + M_{df}\Theta_f)i_{1q} - L_q i_{1d} i_{1q})$$

$$P = \frac{3}{2}(u_{1d}i_{1d} + u_{1q}i_{1q})$$

Where: $\psi_d = L_d i_{1d} + \psi_{fd}$; $\psi_q = L_q i_{1q}$;

$\psi_{fd} = M_{df}\theta_f$ - constant flux of permanent magnet connected with d - axis;

M_{df} - Appropriate mutual inductance;

θ_f - Magnetic potential of the permanent magnet;

L_d, L_q - d - q- axis inductance;

i_d,i_q - d - q- axis currents;

R - Stator resistance,

ω - Rotor angular velocity.

p- Pole pairs number,

M_e - Motor electromagnetic torque,

M_l - External loading torque.

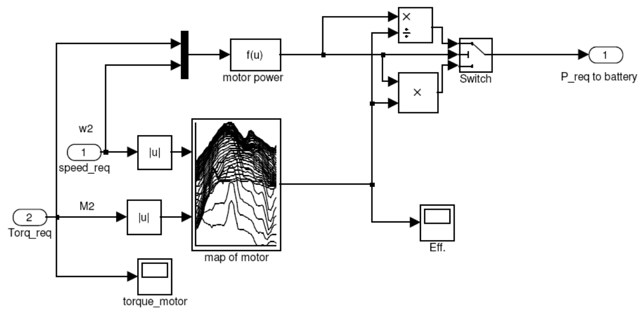


Fig.6. Motor model in Simulink

4.5 Engine model

The engine model in Simulink is shown in Fig.7. The engine model was based on the laboratory test data and engine map

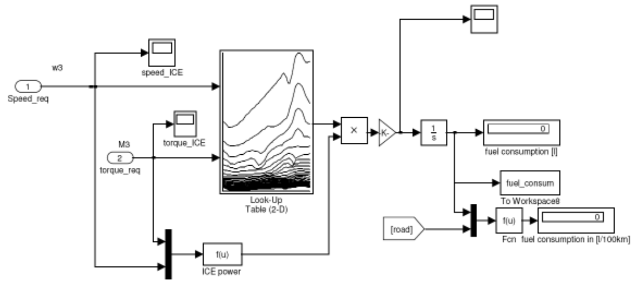


Fig.7. Engine model in Simulink

5 Simulation result

5.1 Configuration and control strategy depiction

The configuration is shown in Fig.8. NEDC driving cycle with limited top speed 100km/h is used for simulating vehicle general performance. Control strategy used in simulation:

1) Engine operation is controlled according to vehicle operating conditions—vehicle speed and vehicle load (torque). During vehicle driving in normal road, engine speed changes according to vehicle speed (the control parameters will not be presented here for secret reason). The control parameters should be adjusted and optimized in order to keep engine operating in the most efficient area. But the factor which affects engine operating is not only vehicle speed, but also the mechanical ratio between drive wheels and engine [5]. During the simulation both of the control parameters and the mechanical ration had to be adjusted trial and error in order to obtain the design target. During vehicle climbing big gradient (at this moment vehicle requires big drive torque), vehicle will switch into pure engine operating mode according to torque signal.
2) Mechanical ratio and vehicle operating mode change: When vehicle speed is lower than 17km/h, vehicle operates in pure electric mode; When vehicle speed is between 17~80km/h, vehicle operates in hybrid mode, three-speed gearbox selected ratio 0.26; When vehicle speed is 80~100km/h, vehicle operates in hybrid mode, three-speed gearbox selected ratio 0.352; When vehicle cruising speed reaches 100 km/h, motor brakes, only pure engine is operating; When vehicle is climbing for big gradient, ratio 1.26 of three-speed gearbox is selected and vehicle operates in pure engine mode.
3) About battery pack. During simulation, 300V 15Ah NiMH battery pack is used. When the initial value of battery SOC is in the range 0.5~0.8, there is no big difference of influence on battery performance and vehicle operating performance; If the initial value of SOC is selected out of this range, there will be a big difference: the SOC of battery couldn't keep the same at the beginning and the end of simulation; vehicle energy consumption will increase because the battery efficiency will decrease out of this range. Usually the internal resistance of battery out of this range is bigger [4] [6].

5.2 Minibus parameters and some simulation results

Table 1 shows the minibus parameters used in the simulation and some simulation results such as energy (including fuel and electricity) consumption, all mechanical ratios and the parameters of battery pack which were properly adjusted to meet vehicle required performance during simulation.

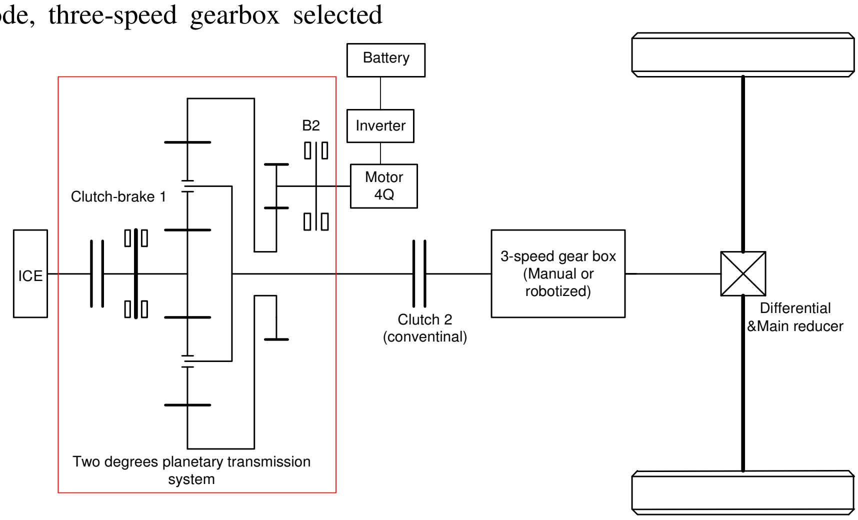


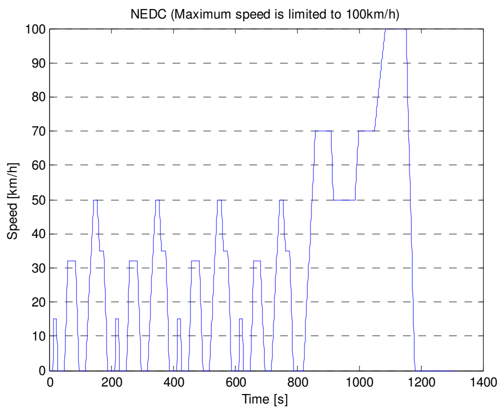
Fig.8.Configuration of hybrid divetrain

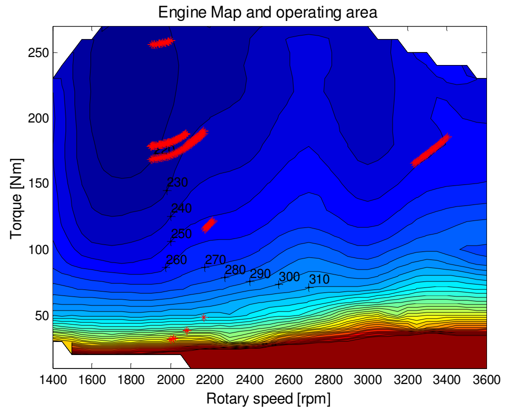
Table 1: vehicle parameters for simulation and some simulation results

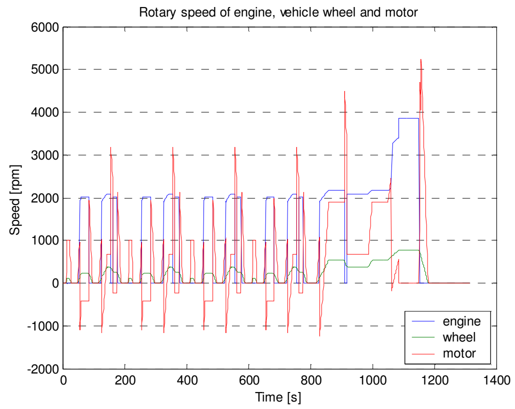
Battery	300V 15Ah NiMH battery pack
Main reducer ratio	4.88
The basic planetary transmission ratio	2.98
Reducer ratio between PM motor and planetary transmission	3.8
Three-speed gearbox between differential and planetary transmission	1.26 (For climbing big gradient) 0.352(For speed 0~80km/h) 0.26(For speed 80~100km/h)
Vehicle mass	5,000 kg
Vehicle front area	4.64 m2
Drag coefficient c_x	0,35
Dynamic tire radius index r_{dyn}	0,348 m
Fuel consumption (pure electric start)	10.54 l/100km
NEDC driving cycle (with top speed limited)	100km/h
Engine: Volume: 2.8 l Rotary speed range 850~4000 rpm; Maximum output power 87 kW/3600 rpm; Maximum torque 269 Nm/1900 rpm;	PM Motor: 240 Nm peak torque; 75kW peak, 30kW continuous power; Regenerative braking; Full power @ 250~400 VDC input

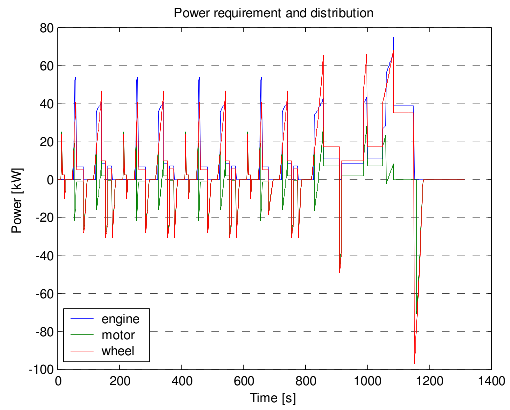
5.3 Vehicle simulation results with NEDC (limited top speed 100 km/h)

Control strategy of vehicle start: Pure Electric Start

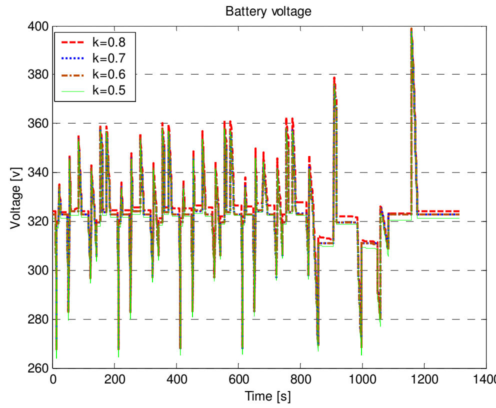


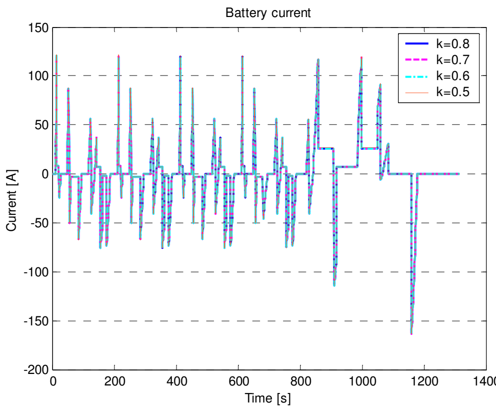




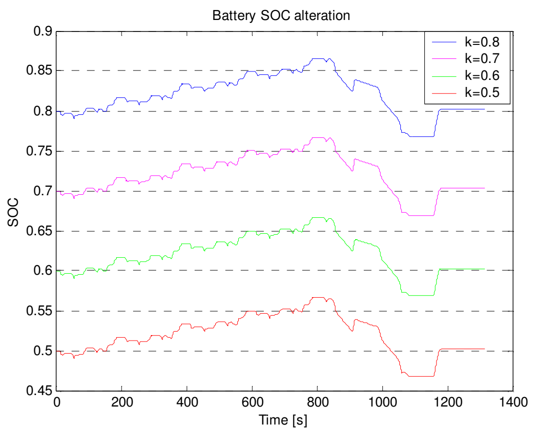


Battery voltage operating range 275V~400V, 400V is too big and it can be controlled by limiting battery charging current.

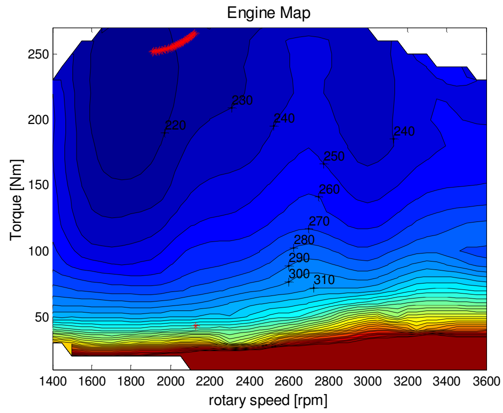


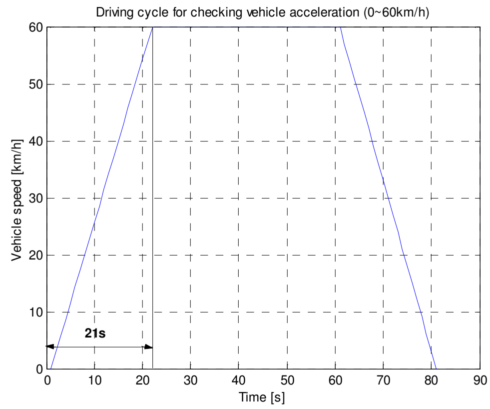


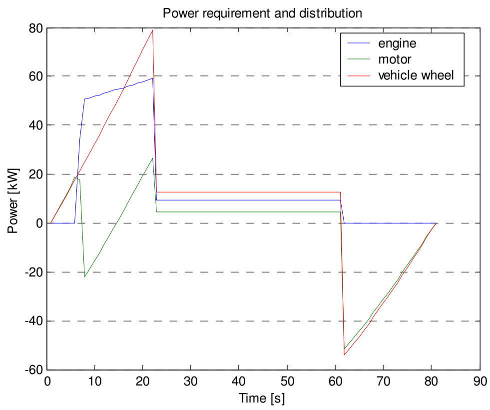
Battery current operating range is –165A~125A, corresponding to –11C~8.3C. The regenerative braking current is too big, which results in battery voltage rapidly increasing. It should be limited by BMS



5.4 Vehicle ability of acceleration (0~60km/h) simulation







5.5 Simulation result of minibus with conventional drive

In order to compare the fuel consumption of hybrid drive and conventional drive, the simulation for minibus with conventional drive was also made. During simulation, the NEDC driving cycle was used. The gear change was adjusted according to the optimal way in proper time. The simulation result of fuel consumption for the conventional drive is 15.93 l/100km

6 Conclusion of simulation result

The designed hybrid drive system has achieved the design target

1) Vehicle acceleration time from 0 to60 km/h 21s ≤25s;
2) Maximum speed: 100 km/h;
3) Maximum Gradeability: 30%;
4) Fuel consumption improvement is 33.8% (for the same driving cycle, hybrid drive system is 10.54 l/100km and conventional drive system is 15.93 l/100km). For hybrid drive system, the fuel consumption means energy consumption (fuel consumption + electricity consumption) because the SOC of battery keeps in balance at the beginning and at the end of driving cycle. Electricity has been transferred into engine fuel consumption.
5) The hybrid drive system can have the following operating mode: pure engine operating, pure electric operating, hybrid operating and also the function of regenerative braking is considered.
6) This system is simple and can be easily adjusted based on the conventional vehicle.

References

[1] Antoni Szumanowski, Chang Yuhua, Piotr Piórkowski, Arkadiusz Hajduga *Hybrid Electric Vehicle Drives Design (Edition based on URBAN BUSES)*, ISBN 83-7204-456-2, Radom, 2006.

[2] Szumanowski A., *Fundamentals of Hybrid Vehicle Drives,* Monograph Book, ISBN83-7204-114-8, and Warsaw-Radom 2000.

[3] Antoni Szumanowski, Jakub Dębicki, Arkadiusz Hajduga, Piotr Piórkowski, Chang Yuhua, *Li-ion Battery Modeling and Monitoring Approach for Hybrid Electric Vehicle Applications*, EVS 20 Los Angeles 2003.

[4] Szumanowski A., Chang Yuhua, Piórkowski P., Jankowska E., Kopczyk M., *Performance of city bus hybrid drive equipped with Li-ion battery*, EVS 21 Monaco 2005.

[5] Antoni Szumanowski, Chang Yuhua, Piotr Piórkowski, *Analysis of Different Control Strategies and Operating Modes of Compact Hybrid Planetary Transmission Drive*, 2005 IEEE VPPC in Chicago, Illinois, USA;

[6] Antoni Szumanowski, Chang Yuhua, Piotr Piórkowski, *Method of Battery Adjustment for Hybrid Drive by Modeling and Simulation,* 2005 IEEE VPPC in Chicago, Illinois, USA;

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