Research on Torque Control Distribution between Motor and Engine in P2.5 Hybrid Vehicle

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Abstract. The normal torque distribution of the P2.5 hybrid system is based on the strategy of open-loop engine control, dynamic engine torque estimation and the motor torque compensation. To meet the rapid acceleration and the deceleration, the motor torque is compensated according to the estimated engine torque to satisfy the driver torque request first, and then satisfy the battery charge torque. Other torque distribution strategies are defined according to the special working conditions below: 1) To improve the efficiency of the engine and the response of the system and to avoid the drop of engine speed, the motor compensation enabled condition and torque distribution strategy is defined. 2) To enhance the performance of fuel consumption and emission during the catalyst heat phase, the catalyst heat phase is divided into two phases and the torque distribution strategy is defined. 3) To decrease the battery heat time and extend the battery health life, the battery heat enabled condition and torque distribution are defined. The vehicle results are conducted and show that the normal torque distribution control can meet the acceleration and deceleration goal and drivability performance. The motor compensation can meet the driver torque by the motor and avoid the drop of the engine speed. The control of the catalyst heat phase can do good to the emission and fuel consumption.

1. INTRODUCTION
The hybrid systems and pure electric systems are two good solutions of the global energy crisis and environmental problems. However, battery technology is still immature and lots of charging stations are needed, so hybrid systems have attracted a great attention from researchers. To satisfy various objectives, the torque distribution strategies below are defined. Xibo Yuan et al. [1] presented a torque distribution scheme for a four-wheel EV to improve drive train efficiency over a wide torque and speed range. Ying Xu et al. [2] presented an optimal torque distribution strategy for four-motorized-wheel electric vehicle aiming at improving the tractive efficiency and braking energy recovery performance. Hu Jianjun et al. [3] analyzed the influence of different wheel torque distributions on vehicle stability and energy economy during vehicle steering. Jianfei Zhao et al. [4] studied the deadbeat current prediction vector control system of axial flux permanent magnet synchronous motor for electric bus based on the optimal torque distribution method. Yafei Wang et al. [5] proposed an optimal torque distribution algorithm for longitudinal motion by considering the transfer of weight between front and rear axles and motor losses. Lie Guo et al. [6] delivered a torque distribution algorithm under emergency conditions according to the characteristic that the torque of each wheel can be distributed independently. Kaibin Cao et al. [7] developed a multi-objective optimal torque distribution strategy by considering the front and rear axle load transfer and the variations of adhesion characteristics. Stefano De Pinto et al. [8] defined a “torque-fill” controller that varies the motor torque on the axle not involved in the gearshift. Cheng Lin et al. [9] designed a multi-objective controller to minimize the drivetrain power loss while ensuring the vehicle...
stability. Ling Yuan Hsu et al. [10] proposed an automated vehicle trajectory following system that uses four constrained wheel torques to regulate a vehicle on a reference trajectory.

Considering all the design goals and development concerns, Geely has developed a torque distribution strategy based on conditions in P2.5 system control system which has a compact structure and good fuel consumption performance. The torque distribution strategy can accurately meet the driver behavior, the energy management system and other the vehicle sub-systems' demands. Base on the normal torque distribution strategy and working conditions of engine and battery, the rest of the paper will be focused on the torque distribution of the three special working conditions. The real vehicle test results show the torque control strategy can improve drivability goal, fuel consumption performance and other objectives successfully. The strategy is successfully implemented to support the launch of the 2021 Geely Lynk & Co 01 HEV with the hybrid system.

2. P2.5 HYBRID SYSTEM

The P2.5 hybrid system includes the engine, the motor, the battery, the transmission and controllers, which is shown in figure 1. The main parameter of vehicle and the motor are shown as table I and table II. The motor which is connected to the even input shaft of transmission includes three torque output paths-ISG path, EFAD path and disengaged path. The ISG path is that the motor is connected to the C2 clutch and cannot propel the wheels. The EFAD path is that the motor can propel the wheels and disconnected with the C2 clutch. The main functions of the hybrid system are as follows:

1) Driver torque calculation
   When the driver presses the acceleration pedal and selects the drive mode which includes the eco mode, the power mode, the normal mode and the altitude mode, the driver torque request can be calculated based on the vehicle speed and acceleration pedal.

2) Energy management
   The energy management is basically responsible for controlling SOC of the high voltage battery, calculating power limits of the high voltage electrical system and handling the overall energy consumption for the hybrid system.

3) The engine start and engine stop function
   The engine start methods of P2.5 hybrid system includes the clutch start, the motor start and the 12V start. The engine stop methods of P2.5 hybrid system includes the normal stop, and the motor assisting stop method.

![Figure 1. P2.5 hybrid system overall layout](image)

| TABLE I. THE MAIN PARAMETERS OF VEHICLES |
|----------------------------------------|
| Engine                                 |
| 3 cylinders,1.5T,95kw/5500rpm          |
| Gearbox                                |
| 7DCT                                   |
3. NORMAL TORQUE DISTRIBUTION

The normal torque distribution is to process the driver torque request and the charge torque request based on the strategy of open-loop engine control, dynamic engine torque estimation and the motor torque compensation, which is shown in figure 2.

![Figure 2. Normal torque distribution strategy](image)

3.1 Normal Torque Distribution Strategy

The normal torque distribution is to deal with the driver torque and the charge torque. The driver torque request is based on the acceleration pedal and the vehicle speed. The charge torque request is based on the load point shift, vehicle speed and SOC difference between actual SOC and the target SOC. The normal torque distribution is the combination of the open-loop engine control, dynamic engine torque estimation and the motor torque compensation. The total torque request is the driver torque request minus the charge torque request. The total torque request is distributed to the engine first and the engine torque request is sent to the engine controller. After the open-loop engine control and the dynamic engine torque estimation, the difference between the total torque request and the estimated engine torque request is distributed to the motor.

4. MOTOR COMPENSATION TORQUE DISTRIBUTION

When the engine coolant temperature is below -5°C for the car heating or the power mode is selected for fast response in winter, the engine is requested to keep running. In this condition, the engine speed may drop for the reason that the engine combustion is insufficient and the engine torque is not stable.

| Motor Main Parameter                  |
|--------------------------------------|
| Motor Peak Power                     | 60kw       |
| Peak Torque                          | 130Nm      |
| Inverter Peak Power                  | 60kw       |
| Voltage Range                        | 250V-420V  |
| The Highest Speed                    | 12000rpm   |
| The Cool Mode                        | Water Cooling |
| Ratio                                | 1.59       |
| Max System Efficiency                | 88%        |
when the vehicle creeps for the reason that it is hard to control the engine torque and clutch torque and the engine efficiency is low.

To improve the efficiency of the engine and the response of the system and to avoid the drop of engine speed, the driver requested torque is prior to distributing to the motor when the motor compensation mode is active. The motor compensation enabled condition is defined when some conditions below are met:

1) The engine status is running.
2) The vehicle speed is below 8km/h,
3) the driver request torque is low,
4) The battery SOC is not low.
5) The EFAD path is enabled.

When the motor compensation mode is active the motor compensation torque distribution shown in figure 3 is triggered and the motor torque charge request is override by the requested motor compensation torque request which is dependent on the requested driver torque and the vehicle speed. The motor compensation torque is distributed to the motor and the difference between the driver torque and the motor compensation torque is distributed to the engine.

Figure 3. Motor compensation torque distribution strategy

5. TORQUE DISTRIBUTION DURING CATALYST HEAT PHASE

For hybrid electric vehicles, the motor can drive the vehicle alone when some conditions are met. When the engine is cold started, the engine can be kept at idle condition for a certain time to heat the catalytic converter, which can minimize the deterioration of the engine's original exhaust caused by fluctuation of engine working conditions. The catalytic converter heat phase is divided into two phases. The first phase is the engine low load phase and the second stage is the engine high load phase.
5.1 The former catalysts heat phase

Figure 4 and figure 5 are the sketch and torque distribution strategy in the former heating stage of the catalytic converter. Firstly, When the engine is started, it enters the first heat stage of catalytic converter and the time of entering the second stage is determined if the model temperature of catalytic converter is below temperature threshold(300℃). When the battery SOC is not below critical low threshold and battery maximum discharging power limit is not low, the driver's demand torque is allocated to the motor during the heating of front-stage catalytic converter if the driver’s requested torque is less than the torque max capability provided by the motor. By limiting the minimum air intake and the minimum target speed of the engine, the engine can work at a stable idle operating point, which can not only realize the rapid heating of the pre-stage catalytic converter, but also avoid the engine torque changes caused by too many transient working conditions which are not conducive to fuel consumption and emissions.

Figure 5. Catalyst heat first phase torque distribution strategy
5.2 The rear catalysts heat phase
When the temperature of catalytic converter is above some threshold (300°C), the catalytic converter will exit the heating stage and enter the second stage. The goal of the second stage is to heat the catalytic converter. When the second phase is finished, the temperature of catalytic converter is more than 500°C and the conversion efficiency can be more than 90%. During the second phase, engine is requested to keep running and start to propel the vehicle for better power performance and SOC balance of high voltage battery. The engine torque is limited in a relatively stable load by adjusting the motor assisting torque or generating torque to meet the driver's demand. In this way, the engine torque is limited to a stable and economical load range which improves the overall efficiency of the hybrid system and avoids the conditions below:

1) Many transient conditions caused by the changed driver torque demand.
2) Too high engine load conditions which are challenges to fuel consumption and emission.
3) Too low engine load conditions which can increase the engine heat time.

At this stage, the torque distribution strategy of the hybrid power system is:
1) The engine torque is limited in a relatively stable torque which is dependent on the rear catalyst temperature and the coolant temperature;
2) When the driver's demand for torque exceeds the upper limit of the engine's torque range, the motor can assist the torque to supplement the driver's demand.
3) When the driver’s demand torque is below the lower limit of engine torque range, the motor is requested to charge the battery to increase the engine load.

![Figure 6. The rear catalysts heat phase torque distribution sketch](image)

6. BATTERY HEAT TORQUE DISTRIBUTION
When the battery temperature is below 0°C, the battery max charge power and discharge power is limited severely, which has a negative influence on the below conditions:

1) It has a negative influence on the fuel consumption because there is not enough motor torque to transfer the engine load point.
2) It has a great influence on the condition of rapid acceleration which requires motor torque to assist, such as motor assist after clutch start or the torque phase of power on up shift.
3) Because the motor torque is limited and it has weak regeneration capacity. When stepping on the brake pedal, the most of the brake torque is distributed to the friction torque, which has an impact on the recovery of braking energy.

4) The battery temperature increases very slowly when the normal distribution is used, which has bad influence on the battery health.

Based on the above reasons and the cost will increase and the system space will be occupied if PTC and other components for battery heat are used, the battery heat mode enabled condition and torque distribution strategy are defined. When the below conditions are met, the battery heat mode is active:

1) The battery SOC is above the threshold.
2) The battery temperature is below 0 ℃ and the battery max discharge power is below the low threshold.
3) The engine coolant temperature is above the threshold to ensure that the engine status is warm.
4) The vehicle speed is above the threshold. When the vehicle speed is low, the battery heat time is increased.

When the battery heat mode is active, the battery heat torque distribution shown in figure 6 is triggered and the motor torque charge request is override by the requested discharge torque which is calculated from the discharge power. The driver requested torque is first distributed to the motor, then the engine is dragged. When the battery SOC is below the threshold and then heat mode is inactive, the normal torque distribution is applied. When the battery SOC is above the threshold and battery heat torque distribution is again triggered. The motor charge and discharge cycle is triggered and the battery temperature increase rapidly during the motor charge and discharge progress.

![Battery heat torque distribution strategy](image)

**Figure 7. Battery heat torque distribution strategy**

### 7. TEST RESULT

#### 7.1 Normal torque distribution test

The normal torque distribution test is shown in figure 8. At 16m12s, the driver presses the acceleration pedal to 40%, the requested driver torque is based on the vehicle speed and the acceleration pedal. When the motor torque cannot satisfy the driver torque and the engine is dragged by the motor. The total torque request which includes the driver torque and the charge torque is first assigned to the engine, the motor torque is compensated based on the estimated engine torque. When the estimated engine torque capacity is big enough to meet the driver request torque and the charge request, the motor torque is decreased to charge the battery. At 16m20s, the driver presses the brake pedal, the estimated negative engine capacity is so weak that the brake torque request from the brake controller is allocated to the motor to satisfy the deceleration goal.
7.2 Catalyst heat phase torque distribution test
The catalyst heat phase torque distribution test is shown in figure 9. At 3m55s, the former catalyst heat phase is enabled, the clutch is disengaged and the vehicle is propelled by the motor in EFAD path. The engine is in idle mode and keeps in a low load, which is good for the emission and the fuel consumption. At 4m35s, the clutch is engaged and the requested driver torque is first assigned to the engine which is limited around best fuel consumption line. At 4m36s, the vehicle is during acceleration and the motor assists to avoid the excessive engine load when the driver torque is above the max engine torque limit. At 4m42s, the vehicle is during deceleration, the engine keeps stable by the motor generating. According to the torque distribution function, the engine torque is not varied with the change of the driver request torque sharply, so the lambda ratio is not fluctuated by the dramatic change of load. The original row is minimized and the rate of exhaust flow is increased as well as the heat of the catalyst are increased by maintaining the engine torque stable.

Figure 8. Vehicle test of normal torque distribution control progress

Figure 9. Catalyst heat phase torque distribution test
7.3 Motor compensation torque distribution test

The test of creep test without motor compensation is shown in figure 10, in contrast, the test of creep test without motor compensation is shown in figure 11. In figure 10, the requested driver torque is all assign to engine when the vehicle creeps with the normal torque distribution strategy. The engine speed drops from 1107rpm to 784rpm because the engine torque is not stable at low temperature. In figure 11, the requested driver torque is all assign to motor when the vehicle creeps with the motor compensation torque distribution strategy. The engine speed is stable because the engine torque is low.

![Figure 10. Creep with no motor compensation torque distribution test](image1)

![Figure 11. Creep with motor compensation torque distribution test](image2)
8. CONCLUSION
The normal torque distribution strategy is defined based on the estimated engine torque, the open loop engine control, the motor compensation. And the torque distribution strategies based on special working condition of engine and battery are also defined to improve the fuel consumption performance, the drivability performance and some other objectives. At last, real vehicle tests are performed to testify the torque distribution control strategies successfully.

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