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TITLE:

A Study of Shift Control Algorithm without Clutch Operation for Automated Manual Transmission in the Parallel Hybrid Electric Vehicle

Topic:

- (●) FUTURE AUTOMOTIVE TECHNOLOGY
- ( ) INTELLIGENT TRANSPORTATION SYSTEMS
- ( ) USER FRIENDLY AUTOMOBILE
- ( ) ADVANCED PRODUCTION AND LOGISTICS
- ( ) VEHICLES & THE ENVIRONMENT

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Abstract:

A new shift control algorithm without clutch operation for reducing the shift shock and improving accelerating ability of a parallel hybrid vehicle with an automated manual transmission (AMT) is presented in this paper. The engagement of clutch, which is the key point of shift control in general AMT, is sophisticated and very difficult. But in the parallel hybrid vehicle, shift control without clutch operation is possible because both the engine and motor can control the speed of input shaft of gearbox. Consequently, it not only improves the shift quality of vehicle, but also prolongs the life time of clutch. Simulation results indicate that the shift amenity and accelerating ability are improved by using the shift control algorithm without clutch operation.

Place / Date:

1. INTRODUCTION

With the development of power electronics technologies and electric components, parallel hybrid electric vehicles (HEV) have attracted worldwide attention [2]. In parallel hybrid vehicles, both the motor and the gas engine could provide driving torque to the wheels, so the performance of powertrain is different from traditional vehicle. The motor can also be used as a generator to recharge the batteries when the engine produces more power than that need to propel the vehicle or braking energy reclaim system is active. As a result of the torque performance of gas engine and the battery peak power density requirement, the vehicle needs a multi-speed transmission between the motor and the main differential. In present days, several automated transmissions are developed such as automatic transmission, continuously variable transmission, and automated manual transmission (AMT) etc. However power loss of automatic transmission and expensive cost of continuously variable transmission limit the application of them for parallel hybrid vehicles. In opposition to them, AMT is suitable for parallel hybrid electric vehicles because of high efficiency, convenient realization and inexpensive cost.

Generally a gear shift of AMT is performed by disengaging the clutch, engaging neutral gear, shifting to a new gear, and engaging the clutch again. The engagement of clutch, which is the key point of shift control in general AMT, is sophisticated and very difficult. But in the parallel hybrid vehicle, shift control without clutch operation is possible because both engine and motor can control the drive torque and the speed of input shaft of gearbox. Therefore, the clutch is not used during the gear shifting event, but due to the load sharing between the two independent driving sources on the parallel hybrid vehicle, a clutch to separate the internal combustion engine and electric drive from the drive shaft is also required.

2. CONTROL PRINCIPLE OF GEAR SHIFTING

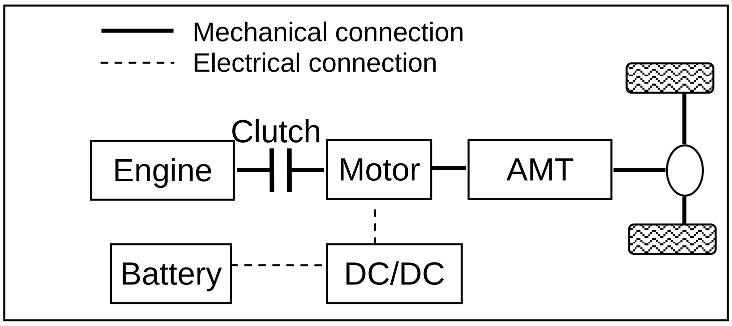

Fig. 1 Schematic block diagram of PHEV powertrain

The schematic block diagram of the parallel hybrid powertrain is illustrated in Fig. 1. This parallel hybrid powertrain is mainly composed of engine, battery, DC/DC inverter, motor, and AMT. The AMT which is a four-speed gearbox is used to transfer the torque of the engine and motor to the wheels. A clutch is used to connect the engine to the motor, so the engine can be engaged to or separated from the powertrain by operating the clutch. Dislike the engine, the motor is always connected to the AMT input shaft. This parallel hybrid powertrain has three different driving modes: engine, motor and hybrid. In this paper, the gear shifting control is discussed just only in the driving mode of hybrid.

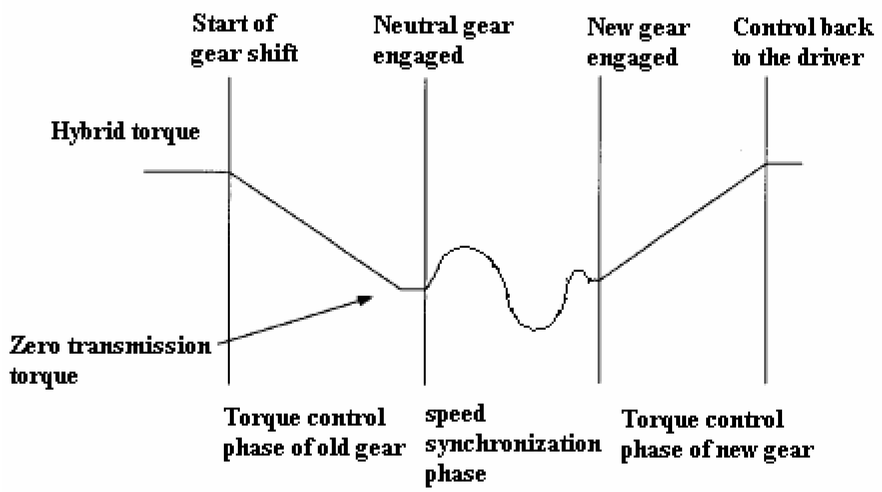

Fig. 2 Dynamic analysis of gear shifting without clutch operation

There are three phases during a gear shift process (see Fig. 2). The first phase is torque control phase of old gear. In order to minimize the wear of the gearbox, the noise, and the shift shock, the most critical part of the shift sequence is the torque control phase of old gear. If a gear is disengaged at a torque level different from zero, a speed impulse will follow which increases the wear of the gearbox and disturbs the driver. So the hybrid torque of the engine and the motor should be controlled to a torque level corresponding to zero before neutral gear is engaged [3]. Since there is no sensor that measures this torque, it is difficult to shift to neutral gear at torque-free state.

The second phase is speed synchronization phase. After neutral gear is engaged, speed synchronization phase is entered. It is important to minimize the total time needed for speed synchronization phase, since the vehicle is free-rolling with zero transmitted. Therefore, it is important to control the speed difference between the input shaft and the output shaft (scaled with the conversion ratio of the new gear) and the drive torque level near to zero as soon as possible at the moment of synchronizer's two sides meshing with each other. In the speed synchronization phase, both the engine and motor can drive the input shaft of transmission, so the total time needed for speed synchronization phase can be minimized and the transit of synchronization phase to new gear engaged can be more smoothly compared with traditional vehicle.

The last phase is torque control phase of new gear. Once the new gear is engaged, torque control phase of new gear is entered. In this phase, the hybrid torque level is transferred from torque-free state back to the level that the driver demands. In order to minimize the time needed for this phase and to improve comfort, the drive torque of the engine and motor can be controlled back to the driver demands in an appropriate way.

3. CONTROL STRATEGY OF GEAR SHIFTING WITHOUT CLUTH OPERATION

According to the analysis of gear shifting without clutch operation, the gear shifting process could be divided into five steps: torque control of old gear, engagement of neutral gear, speed control, engagement of new gear, and torque control of new gear (see Fig. 3).

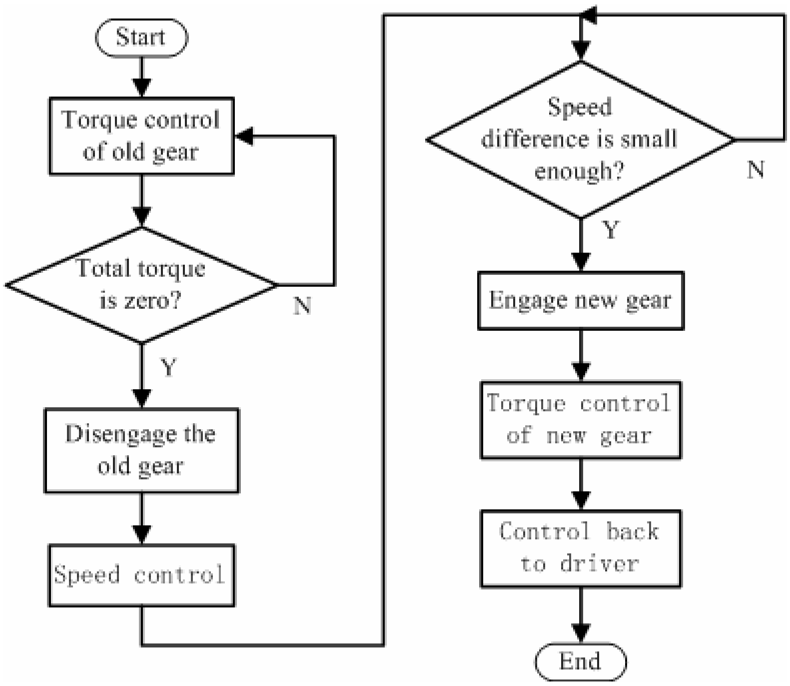

Fig. 3 Flowchart of Shift Control Strategy

The first step is torque control of old gear, which is to reduce the drive torque of transmission to zero. If a gear is disengaged at a torque level different from zero, the following speed impulse will prolong the time needed for speed synchronization, increase the wear of the transmission, and disturb the driver. In this step, the most critical thing is to control the hybrid torque of input shaft to zero quickly and steadily. In order to reduce hybrid torque to zero, more attention must be paid to how to control the drive torque of the engine and motor and how to measure the input shaft torque. In the hybrid mode, both the engine and motor drive the transmission, so the torque control in the torque phase of old gear is different from traditional vehicle. In order to control the transferred torque in the transmission to zero on the traditional vehicle, the oils ejected into cylinder should be reduced quickly to zero, which will bring some bad influence on gas engine. On the hybrid vehicle, because the motor working in braking mode can be used as a generator to recharge the batteries, the oils need not be reduced to zero and the hybrid torque of input shaft can be reduced to zero more quickly and steadily. Since there is no torsion sensor on the parallel hybrid vehicle, a Kalman filter is used to estimate the input shaft torque by taking the measured input shaft speed and wheel speed as input parameters [3].

The second step is engagement of neutral gear. After the drive torque of engine and motor reducing to zero, the transmission engages neutral gear. Because there is no driving torque transferred in the transmission, the engagement of neutral is easily executed.

The third step is speed control, which is corresponding to speed synchronization phase. To achieve speed synchronization, the speed control is performed by controlling motor to adjust the input shaft speed to reduce the difference between the input shaft and the output shaft (scaled with the conversion ratio of the new gear). The most important things are to minimize the total time in the speed synchronization phase and to prevent engine from combusting badly.

The fourth step is engagement of new gear. Once the speed difference between input shaft and output shaft of new gear is within a permissible range, the new gear is engaging. In order to improve shifting quality, the drive torque of engine and motor must be controlled to zero at the time of engaging new gear. Since the speed synchronization and torque control is already achieved, it is possible to engage new gear smoothly and quickly.

The fifth step is torque control of new gear. After the engagement of new gear, the drive torque of engine and motor will transferred back to the level that the driver demands in an appropriate way. Finally control is transferred back to driver.

4. DYNAMIC MODEL

A model integrating all the components of the powertrain was built. Good adaptability of the model is required to analyse and compare the various configurations and technologies. The modelling is thus based on a modular approach allowing the separate definition of each part of the powertrain, which can then be easily connected to create several configurations. Modelling and simulations were carried out with MATLAB and SIMULINK. Fig. 4 shows the block diagram of the powertrain studied in this paper. This powertrain model, depicted in Fig. 4, consists of a hybrid control unit (HCU), integrated starter/generator (ISG), SI ICE engine, engine clutch, traction motor, and a transmission with AMT and final drive integrated (AMT_FD), electric power distribution (EPD), energy storage system (ESS), ABS and vehicle-road dynamics.

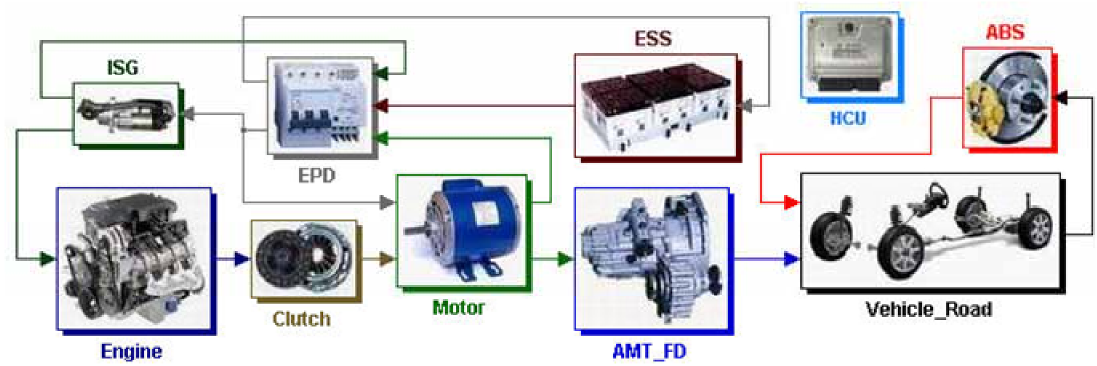

Fig. 4 SIMULINK Model of a Parallel Hybrid Powertrain

<u>Nomenclature</u>

J_e = sum of engine inertia and clutch inertia of engine side, kg-m^2
J_m = sum of motor inertia, clutch inertia of motor side and AMT input inertia, kg-m^2
J_v = total quasi inertia of vehicle mass and all the inertia at and after AMT output side, km-m^2
g = transmission gear ratio
T_e = engine torque, Nm
T_m = motor torque, Nm
T_s = torque transferred by synchronizer, Nm
ω_e = engine rotational speed, rad/s
ω_v = transmission output rotational speed, rad/s
d_e = quasi damping of the engine, Nm-sec/rad

d_m = quasi damping of the motor and transmission input, Nm-sec/rad
$T_v(\omega_v)$ = quasi resistance torque at the output of the transmission, Nm
$\dot{\omega}_x$ = derivative of rotational speed "x", rad/s^2

Driveline Dynamics

The driveline can be simplified as Fig. 5 represents. Vehicle mass can be converted into inertia on output shaft of the AMT and all the resistance force of the vehicle can be converted in to resistance torque exerted on the output shaft of the AMT. Such method can be used for the dynamics simplifying of other components. When the clutch is engaged, the engine inertia couples to the motor inertia and the rotational speed of the engine equals to that of the motor. To study gear shifting without clutch separation in the PHEV, three states of the synchronizer are concerned for the whole driveline: full engaged, slipping and disengaged.

When the gear is in neutral position, the synchronizer is disengaged:

$$(J_e + J_m)\,\dot{\omega}_e + (d_e + d_m)\,\omega_e = T_e + T_m$$

The sign on T_m is positive when the motor is used for traction and negative when being used as a generator. And T_m can also be a dead load when the motor is just acting as inertia.

When the synchronizer is slipping:

$$(J_e + J_m)\,\dot{\omega}_e + (d_e + d_m)\,\omega_e = T_e + T_m - T_s / g$$
$$J_v\,\dot{\omega}_v = T_s - T_v$$

The sign on T_s is the same as $(\omega_e - \omega_v \cdot g)$.

When the synchronizer is full engaged:

$$(J_e + J_m)\,\dot{\omega}_v + (d_e + d_m)\,\omega_v = T_s - T_v$$
$$\omega_e = \omega_v \cdot g$$

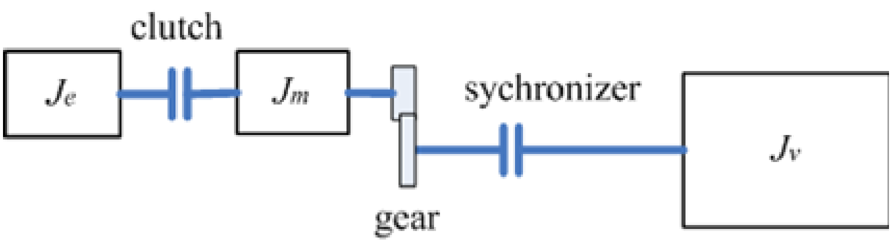

Fig. 5 Simplified Driveline

5. SIMULATION RESULTS

The simulation results, depicted in Fig. 6, show vehicle velocity (km/h), engine throttle (%), acceleration pedal (%), engine rotational speed (rpm), gear, halfshaft torque (Nm), engine and motor torque (Nm) during vehicle amain accelerating and gear shifting without clutch separation.

When the vehicle accelerates from rest, the motor provides the necessary torque before the engine is started and the motor rotational speed meet the proper rotational speed of the engine. Once the clutch is engaged, the vehicle operates in hybrid drive mode for the acceleration pedal is stepped to 100%. Because the clutch is still engaged during gear shifting, the rotational speed of the engine is always equal to that of the motor.

At the beginning of gear shifting, the engine throttle is drawn back and the motor is controlled to provide negative torque to counteract the engine torque at the same time because the dynamic characteristic of the engine is tardier than that of the motor. The sum of the torque of the engine and the motor will be below the reference value in a very short time. Then the gear is shifted to neutral position. Speed control starts at the moment to synchronize velocities of the transmission input/output shafts by the motor as soon as possible. The gear is shift to the target gear after the speed difference between input side and output side of the synchronizer is blow the reference value. When the gear shift is completed, the total output torque of the engine and the motor is controlled to restore gradually in a short time.

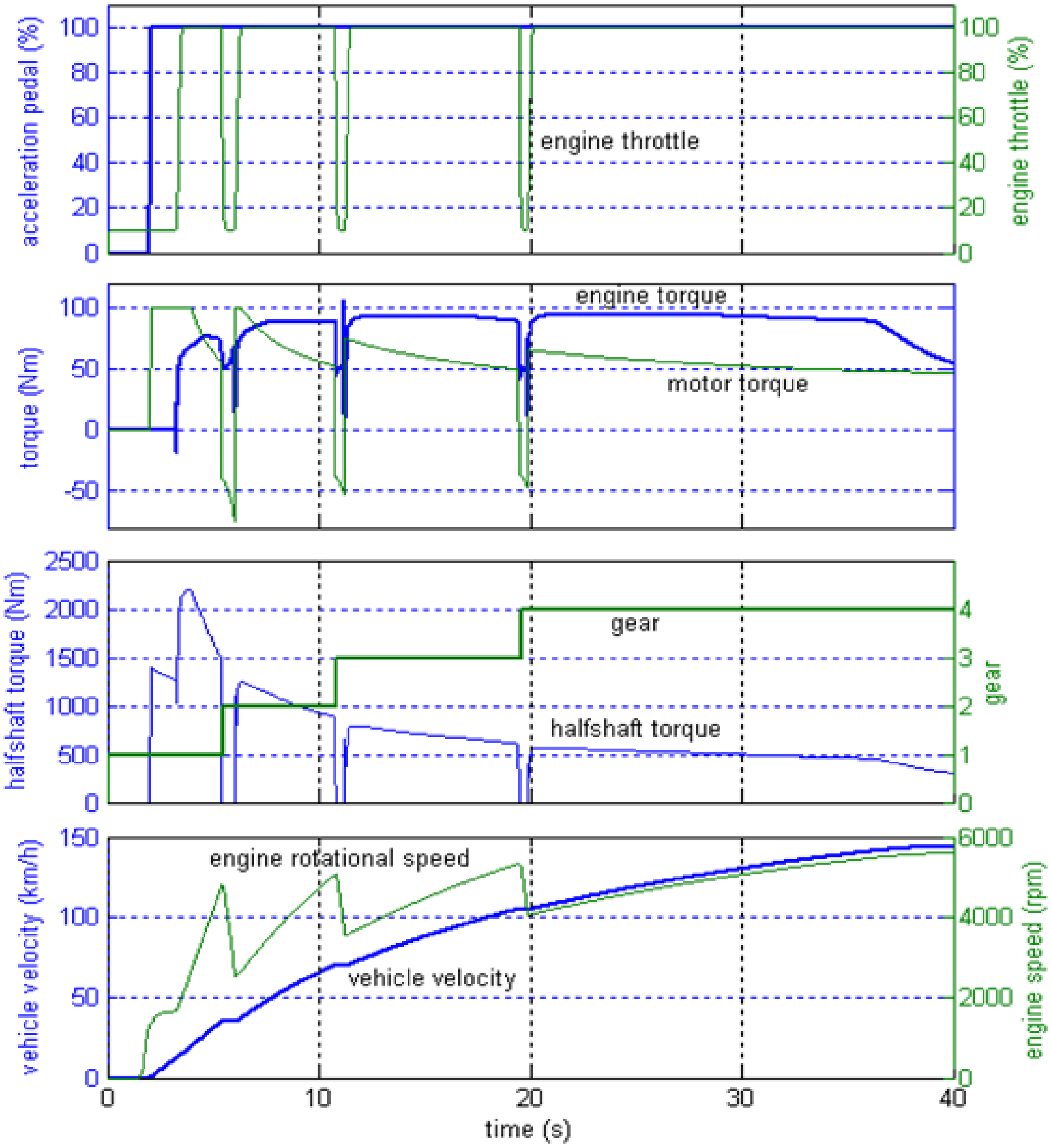

Fig. 6 Simulation Results

6. CONCLUSION

There are three main key points to utilizes automatic gear shifting with a manual transmission but without engaging the clutch during the shift event:

- Torque control which controls the hybrid torque to zero during the torque control phase of old gear;

- Speed control which reduces the speed difference between input shatf and output shaft quickly;

- Torque control which controls the drive torque of engine and motor back to the level that the driver demands in an appropriate way;

Using the above method of shift control without clutch operation, the old gear can be disengaged without shock, the new gear can be engaged with a minimum of time spent in the speed synchronization phase, and thus leading to a minimized time for a gear shift. Simulation results show that the shift amenity and accelerating ability are improved by using the shift control algorithm without clutch operation.

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