Engine-start Control Strategy of P2 Parallel Hybrid Electric Vehicle

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Abstract. A smooth and fast engine-start process is important to parallel hybrid electric vehicles with an electric motor mounted in front of the transmission. However, there are some challenges during the engine-start control. Firstly, the electric motor must simultaneously provide a stable driving torque to ensure the drivability and a compensative torque to drag the engine before ignition. Secondly, engine-start time is a trade-off control objective because both fast start and smooth start have to be considered. To solve these problems, this paper first analyzed the resistance of the engine start process, and established a physic model in MATLAB/Simulink. Then a model-based coordinated control strategy among engine, motor and clutch was developed. Two basic control strategy during fast start and smooth start process were studied. Simulation results showed that the control objectives were realized by applying given control strategies, which can meet different requirement from the driver.

1. Introduction
As the energy security and environmental pollution issues are getting increasingly severe in the world, it’s imperative to develop hybrid electric vehicles (HEVs), which can reduce the greenhouse gases emission and enhance the vehicle’s system efficiency \cite{1}. HEVs must shift working modes frequently to accommodate the complex road condition and enhance the driveline’s efficiency. So the engine-start process is of vital significance, as it affects the vehicle’s drivability and driving comfort. Studies have been made to use a single electric motor (EM) to start the engine, while some challenges exist in this process. The single EM must meet the torque demand for driving wheels and simultaneously provide an extra torque to start the engine by an engine-disconnect clutch (EDC) within an acceptable level of noise, vibration and harshness (NVH).

Several contributions have been made in this areas. Zhonghua Lu took the jerk as the single objective, and developed a coordinated control strategy about automatic clutch, ISG and engine, which is proved to be effective to reduce the jerk of vehicle \cite{2}. Anthony Smith devoted to applying a closed-loop slip control and an open-loop torque control to EDC, but ignored the internal combustion engine (ICE) speed under different conditions \cite{3}. Dongsuk Kum used Dynamic Programming to solve the nonlinear constrained optimal control problem, which meant to minimize engine-start time while accurately supplying the driver torque demand simultaneously \cite{4}. Another research conducted by Koos van Berkel presented a new controller design with a single calibration parameter which was used to tradeoff between fast and smooth clutch engagement \cite{5}.

This paper built a physic model in MATLAB/Simulink, then developed a coordinated control method among ICE, EM and EDC, which included the torque compensation of EM, the torque...
adjustment of ICE, speed modification of ignition, and the pressure to torque control of EDC. This model-based controller dedicated to optimizing the tradeoff between comfort and drivability according to various engine-start condition. It’s proved that the controller successfully reduced vibration within an applicable start time by means of adjusting the main control objective under a certain situation. Which is of great importance to improve both stability and drivability of engine start process.

2. P2 configuration construction
Figure 1 shows the powertrain architecture of HEV P2 configuration, including an internal combustion engine (ICE), engine-disconnect clutch (EDC), a dual mass flywheel (DMF), an electric motor (EM), an automatic transmission (AT) without torque converter, and a transaxle and wheels.

![Figure 1. HEV P2 Configuration](image)

ICE is mechanically connected to EDC hub through DMF, while EM is connected to EDC friction disc. Both ICE and EM can output torque to the front shaft (drive shaft) of the vehicle through AT. When the EDC is separated with ICE, the vehicle works under the pure electric mode, with EM as the only power source. When there is a need to switch mode, EDC engages and transfers torque form EM to ICE, dragging the engine to ignition speed. During this engine-start process, it is hard to control the engine output torque, especially when igniting, so a dual mass flywheel is employed to decrease vibration in the front of EDC. After start-up, the vehicle may enter the engine-drive mode or the parallel drive mode, as well as the battery-charge mode.

3. Engine-start dynamic analysis
During the engine start process, the resistant torque is consist of three parts: rotary inertia torque ($T_r$), gas compression torque ($T_g$), and friction torque ($T_f$).

3.1. Rotary inertia torque
The rotary inertia resistant torque results from the reciprocating movement of the piston and linkage, and it equals to [6]

$$T_r = rF_i (\sin \theta + \frac{\sin \theta \cos \theta}{\sqrt{r^2 - \sin^2 \theta}}) \quad (1)$$

Where, $r$ is the radius of crank (m), $\theta$ is the crank rotary angle (°), $F_i$ is the inertia force, and $l$ is the length of the linkage (m).

3.2. Gas compression torque
The compressed gas in the cylinder mainly acts on the top of the piston and pushes the piston to do the reciprocating movement. During the compression stroke and exhaust stroke, the compressed gas does negative work, serving as a resistant torque of engine-start; during the intake stroke and power stroke, the compressed gas does positive work, driving the piston to move. The gas compression resistant torque ($T_g$) is calculated by

$$T_g = (P_{gas} - P_0)S_p rK \quad (2)$$

In equation (2), $P_{gas}$ is the pressure of compressed gas in the cylinder (Pa), $P_0$ is the atmosphere pressure (Pa), $S_p$ is effective area of the piston top ($m^2$), and $K$ is a conversion factor, which equals to
3.3. Friction torque

The friction torque results from the friction between the piston ring and cylinder, the piston skirt and the cylinder, also the other frictions among the attachments.

3.3.1. Piston ring. During start process, the friction resistant torque can be calculated by

\[ T_{frh} = a_2 \left[ \mu v (P_e + P_{gas}) w \right]^{0.5} d(n_0 + 0.4n_c)r[K] \]  

Where, \( \mu \) is the kinetic viscosity coefficient of lubricating oil \([kg/(m \cdot s)]\), \( v \) is the speed of piston \((m/s)\), \( P_e \) is the pre-tightening force \((Pa)\), \( w \) is the width of the piston ring \((m)\), \( d \) is the diameter of the cylinder \((m)\), \( n_0 \) is the number of oil rings, \( n_c \) is the number of gas ring, and \( a_4 \) is a shape coefficient of piston rings.

3.3.2. Piston skirt. The friction between cylinder liner and piston skirt is much smaller than that resulted from the piston ring, and is calculated by

\[ T_{fs} = a_2 (\mu v \frac{d}{n_0}) dMr[K] \]  

In which, \( M \) is the length of the piston skirt \((m)\).

3.3.3. Attachment friction. The attachment friction of the engine operation includes the resistance from water pump, oil pump, fuel pump, etc. The resistant torque is proportioned to the speed of the crankshaft, and can be expressed by

\[ T_a = a_3 \mu w \]  

Where \( w \) is the speed of the crankshaft \((rad/s)\).

4. Engine-start control strategy

As shown in Fig.2, ICE is controlled by engine control unit (ECU), and EM is controlled by motor control unit (MCU). The actuation of AT and EDC are both controlled by transmission control unit (TCU). While, all the ECU, MCU and TCU coherently follow the order of hybrid control unit (HCU), which is determined by an explicit control law according to the operating condition.

Fast responsiveness and driving comfort are the two major objectives of the engine start control. A large engine-start torque is needed to ensure fast responsiveness, however, to meet the comfort demand, it’s necessary to avoid the sharp increase of the input torque on AT shaft. So a coordinate control strategy among the engine, motor and clutch is applied to a certain extent.

Two basic control methods were developed in this paper, both of them are divided into five phases as shown in Figure 2.

4.1. Fast start control strategy

Fast start control strategy is suitable to urgent torque demand conditions such as overtaking and the control method is described as follow.

Phase 1: HCU is awaiting the starting ICE command.
Phase 2: while starting ICE=1, EDC starts to fill oil, which process last for t1 seconds (here t1=0.2) to ensure the clearance between EDC can be eliminated, and the oil pressure finally comes to kisspoint pressure.
Phase 3: EDC begins to slip and transmit torque from EM to ICE, dragging the ICE to accelerate. During this phase, to ensure a constant torque outputting to axel, it’s necessary to increase the output torque of EM to compensate EDC’s friction torque.
Phase 4: when ICE speed is dragged to n1 (here n1=800r/min), HCU sends a command to ignite ICE, then ICE starts to work. In this way the ICE continues to accelerate via its own output torque as well as EDC’ drag torque. Besides compensate torque acting on EM is also a must.
Phase 5: once the speed ratio \((nu)\) of ICE and EM is more than \(a\) (here \(a=0.8\)), the control pressure of EDC increases dramatically to lock the clutch. Figure 3 shows the control pressure of EDC during fast start process.

\[\text{Start} \rightarrow \text{Phase 1: Awaiting} \rightarrow \text{StartICE}>0 \rightarrow \text{Yes} \rightarrow \text{StartingICE}=1 \rightarrow \text{Delta}_T_E=0 \rightarrow \text{Phase 2: Oil filling(C0)} \rightarrow \text{Yes} \rightarrow \Delta t>t_1 \rightarrow \text{Phase 3: Drag acceleration(ICE)} \rightarrow \text{Yes} \rightarrow N_{ICE}>n_1 \rightarrow \text{Phase 4: Ignition(ICE)} \rightarrow \text{Yes} \rightarrow nu>a \rightarrow \text{Phase 5: Synchnization&Lock(C0)} \rightarrow T_{ICE}=100\text{Nm} \rightarrow \text{End}\]

**Figure 2.** Engine-start control flow

4.2. Smooth start control strategy

When the vehicle is climbing on a slope or the SOC value is low, it’s applicable to start ICE. Since the torque demand is not emergent, so driving comfort is the priority to ensure, rather than start time.

![Figure 3. Fast start control pressure of EDC](image)

![Figure 4. Smooth start control pressure of EDC](image)

The control process is similar to fast control. First, \(t_1\) seconds (here \(t_1=0.3\)) is required to finish oil filling phase, then the clutch starts to slip and drag the ICE to accelerate. When the speed of ICE is more than \(n_1\) (here \(n_1=850\text{rpm}\)), ICE starts igniting and the control pressure of EDC drops to kissspoint
pressure as soon as possible to open the clutch. This process is very different from fast start control, because it’s critical to ensure the driving comfort by cutting off the vibration from ICE. Since EDC is open and not available to transmit torque, ICE then accelerates itself. When the speed ratio \((\nu)\) of ICE and EM is more than \(a\) (here \(a=0.85\)), EDC begins to lock.

Compared with fast start control, Figure 4 shows the control pressure of EDC during smooth start process.

5. Simulation results
The simulation results of fast start control and smooth start control are shown respectively as follow.

![Figure 5. Fast start control results](image5.png)

![Figure 6. Smooth start control results](image6.png)
5.1. Fast start control results
Figure 5 shows the simulation results of fast start control. The vehicle is assumed to be costing at 60 km/h in the 5th gear. ICE is turned off. Suddenly the driver pushes the accelerator to the maximum pedal position in 0.3 seconds. This is interpreted as an input torque request of 350 Nm, while the EM can generate only 260 Nm and only for a short time. So the ICE has to be started. To start the ICE as soon as possible, the control pressure of EDC maintains at a high level and the EDC keeps slipping to accelerate the ICE. ICE ignites at around 0.7s when the speed is over 800r/min. The whole start process last for only 0.46s, which can meet the sudden torque requirement form driver. On the other hand, this sharp increase of torque cause some vibration to the drivetrain, which is still acceptable.

5.2. Smooth start control results
Figure 6 shows the simulation results of smooth control results. During this situation, the vehicle is driven purely by the electric motor at 60 km/h in 5th gear with an input torque at 100Nm. However when there is a decreasing SOC (state of charge) of the battery, HCU will start the ICE without changing the input torque. Because this situation should not cause the attention from driver. To start the ICE smoothly, EDC opens when the ICE start igniting as mentioned in the smooth start control strategy. The whole process last for 0.8s, and the vibration is limited within 0.4m/s^2. When the start process finishes, the ICE maintains at the idle condition, and the car is still driven by the EM.

Compare the results above with each other, it’s proved that the control strategy can make different compromise between start speed and stability. During fast start process, only 0.46s is needed, which directly responds to the driver’s demand, twice as fast as smooth start. While the jerk on the other side is relatively obvious compared with smooth start. During smooth start, the driver doesn’t not send out any demand and he doesn’t have preparation for the coming jerk during engine start process, so any disturbance will cause discomfort. Therefore, in the smooth control strategy, stability is set as the first priority. From the results above, it’s found that the vibration during smooth start process is ignorable compared with fast start process, but at the expense of extending the start time. In a word, through the comparison, the effectiveness of control strategy is clearly proved.

6. Conclusions
This paper analysed the resistant torque during the engine start process, and establishes the physical model in MATLAB/Simulink. Considering the problem is a multi-objective optimization, different control laws were developed to suit various conditions. Both start time and driving comfort are considered during the engine start process and a compromised control strategy is established.

The simulation results shows that the control strategy is effective to balance the start time and the driving comfort under some typical condition.

As future work, a more detailed control strategy will be developed, other influence elements such as the SOC value and the start temperature will be included during the control, then, more driving conditions will be studied, and the fuel economy will be considered as well.

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