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Analyse of Clutch-brake System Control Based on Experimental Tests and Applied in Hybrid Power Train

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Abstract

Clutch-brake system is important element in advanced Compact Hybrid Planetary Transmission Drive (CHPTD). The proper designed clutch/brake system equipped with planetary transmission and additional gears could save energy and improve performance of hybrid powertrain, especially during frequent vehicle starting and regenerative braking. This paper dedicate to design of clutch engaging control strategy in ICE starting procedure. The control of each element in CHPTD during ICE starting is described. Different clutch engaging control strategies are proposed and validated on laboratory stand for various conditions. Optimized control strategy for clutch engaging is selected by analysing the simulation and experimental test results.

Keywords: control system, modelling, planetary gear

1 Introduction

The original Compact Hybrid Planetary Transmission Drive (CHPTD) is a complex hybrid power train architecture which was originally invented and developed by Prof. Szumanowski [1]. Figure 1 shows solution of newly improved CHPTD with an additional gearbox.

The improved CHPTD is a low cost solution for it uses only one set of planetary gears and one electric motor for all operating modes. A small internal combustion engine is employed as an alternative power source. As a power summing unit, the planetary gearbox combines two power sources and the output shaft. The improved CHPTD could achieve higher efficiency than other existing hybrid powertrain because of its efficient power distribution via planetary transmission [2-6]. Several sets of clutch-brake system are used together with mechanical transmission for changing operating modes of the powertrain and adjusting gear ratio. It provides the possibility and flexibility for advanced control strategies of the improved CHPTD.

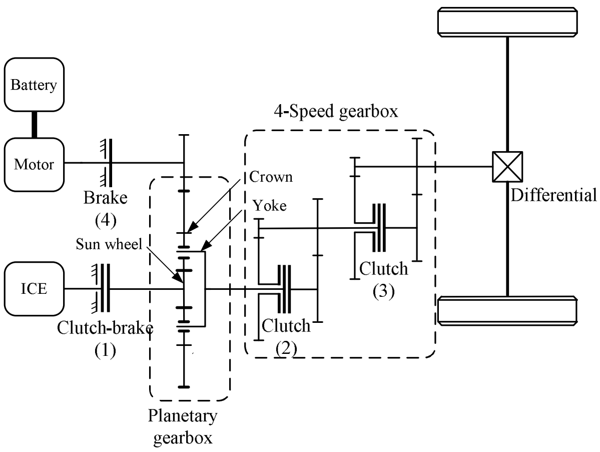

Figure1: Configurations of the improved CHPTD with gearbox

The clutch-brake system operation is directly connected with control of powertrain. The relation between control signal of clutch-brake system and operating modes of power train is shown in Table 1.

Table1: Control signal of clutch-brake systems for different operating modes of plug-in hybrid power train

Operating mode of plug-in hybrid power train	**Control signal of clutch-brake systems**	
	Clutch-brake (1)*	**Brake (4)****
Pure electric and regenerative braking mode	off	off
Pure engine mode	on	on
Hybrid mode	on	off
Engine charge battery (when vehicle stop)	off	off

* 'On': clutch engaged and brake disable; 'off': clutch disengaged and brake enable.
** 'On': brake enable; 'off': brake disable.

The design of this innovative zero steady-states electrical energy consumption clutch-brake system was introduced in authors' previous paper [XX].

1.1 Introduction of laboratory stand of hybrid power train with planetary gear and clutch-brake unit

The configuration of hybrid power train laboratory stand was build according to CHPTD (see Figure 2). The main parameters of hybrid power train laboratory stand are shown in Table 2.

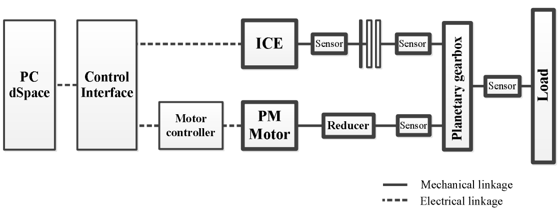

Figure 2: Configuration of hybrid power train laboratory stand according to CHPTD

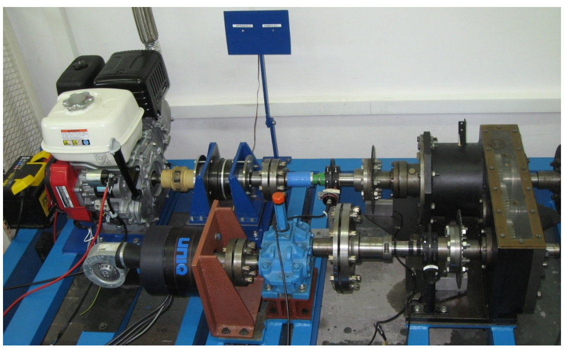

Figure 3: Laboratory stand of CHPTD

Table 2: The main parameters of hybrid power train laboratory stand

Basic ratio of planetary gearbox	2.96
Gear ratio of reducer for electric motor	3.7
Gear ratio of additional reducer for electric motor	0.949
Moment of inertia of ICE	0.13 kg•m^2
Moment of inertia of PM motor	0.07 kg•m^2
Moment of inertia of load	4.41 kg•m^2
Torque capacity of electromagnetic clutch	50Nm
Internal combustion engine (Honda iGX 440)	
Net power	9.5kW @ 3600rpm
Constant rate power	7.5kW @3000rpm 8.0kW @3600rpm
Max. net torque	29.8Nm @2500rpm
PM motor	
Peak power	40kW
Continuous power	19.8kW
Maximal rotary speed	7500rpm

2 Simulation based on laboratory stand of hybrid power train

To investigate the behaviours of laboratory stand and influence of control parameters and control strategies, a simulation model based on laboratory stand of hybrid power train is built in MATLAB/SIMULINK environment.

2.1 Simulation model

The simulation model of hybrid power train is established in Matlab/Simulink environment based on existing laboratory stand (see Figure 4). The parameters of elements in this simulation model are chosen the same as the real condition.

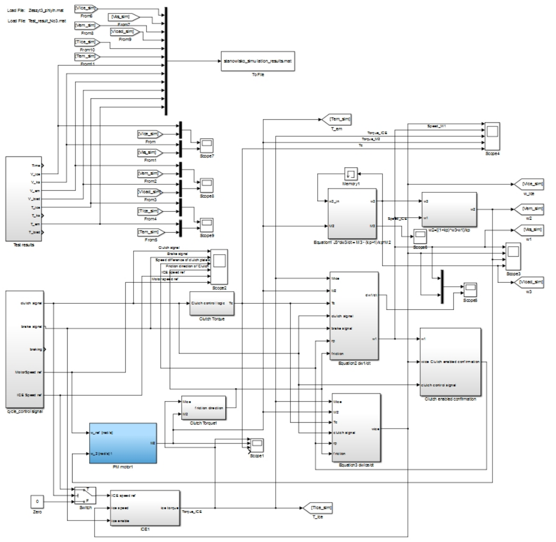

Figure 4: Simulation model of hybrid power train based on laboratory stand in MATLAB/SIMULINK environment

2.1.1 Simulation model of power sources

The power sources in the hybrid power train laboratory stand includes internal combustion engine and permanent magnet motor. Simplified models of ICE and PM motor are employed to simulate the behaviors of power sources.

Internal combustion engine

The simulation model of internal combustion engine is shown in Figure 5. The external characteristic of Honda IGX440 engine is shown in Figure 6.

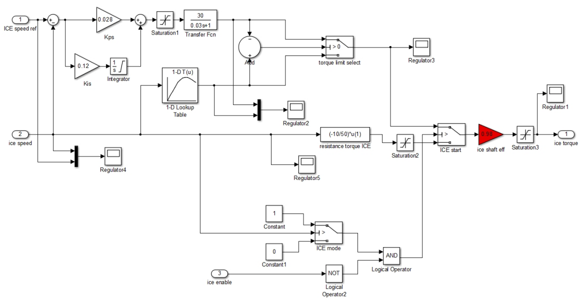

Figure 5: Simulation model of internal combustion engine

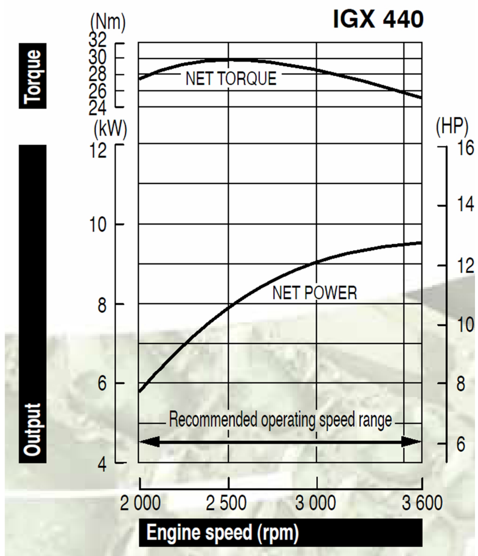

Figure 6: The external characteristic of Honda IGX440 engine

A step response test of internal combustion engine is made to find proper parameters of PI controller (see Figure 7). The procedures of test for determining PI parameters are as below.

1. Set the ICE to idle speed and give step signal of reference speed to ICE.
2. Record the speed response of ICE.
3. Give the same step signal of reference speed to ICE simulation mode.
4. Adjust the parameters of PI controller and make the simulation result to match the test result.

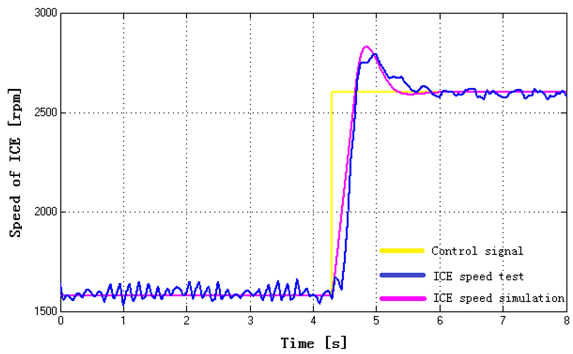

Figure 7: Step response of internal combustion engine

PM motor

The parameters of PM motor are listed in Table 3. For lack of detail parameters, the simulation model of PM motor is based on simple brushless PM motor and PI controller. PI regulator is included in PM motor to simulate the motor controller. The additional bench test is made to find the parameters of PI regulator. The procedures of such test are similar as those for ICE.

Table 3: The parameters of PM motor

Rated power [kW]	18.6
Rated speed [rpm]	7500
Nominal voltage [V]	75
Nominal current [A]	256
Calculated number of the pole pairs	1
Back EMF constant [V/s]	0.096
Torque constant [Nm/A]	0.093
Rotor inertia [kg m^2]	0.009
Fixed resistance motor torque [Nm]	0.3
Coefficient of mechanical losses dependents on motor speed [s/Nm]	0.00184
Coefficient of iron losses dependents on motor speed [s/Nm]	0.0001
Inverter efficiency [-]	0.95

2.1.2 Simulation model of clutch-brake unit

In simulation model, the clutch/brake control signal is generated by control logic. This block can generate control signal by analysing the reference speed of motor which is connected with driving cycle.

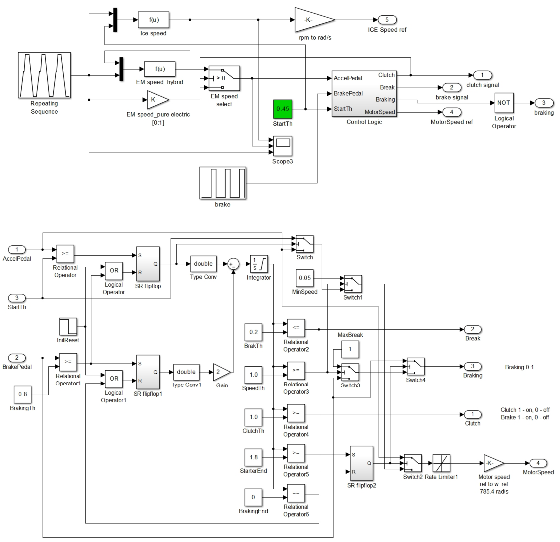

Figure 9: Driving cycle and control logic block

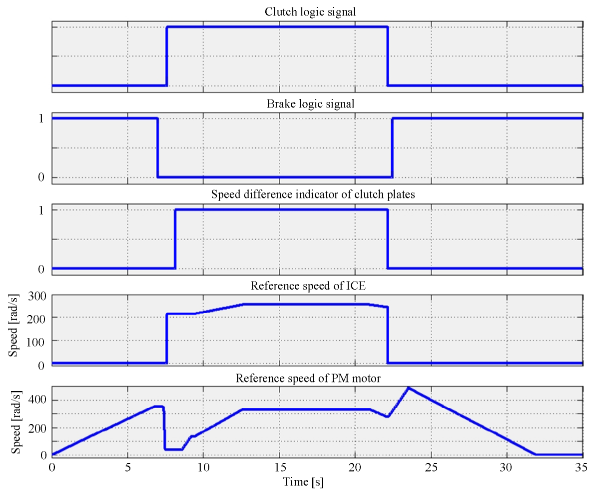

Figure 10: Control signal generated by control logic block

In simulation model, the up mentioned logic signal controls the calculation of torque on sun wheel shaft (see Equation 1).

$$\begin{cases} (J_1 + cr_p J_{ice})\dfrac{dw_1}{dt} = cr_p M_{ice} - \dfrac{1}{k_p} M_2 - cf(1-r_p)M_c + b(1-r_1)M_b + br_1 \dfrac{1}{k_p} M_2 \\ (cr_p J_1 + J_{ice})\dfrac{dw_{ice}}{dt} = M_{ice} - cr_p \dfrac{1}{k_p} M_2 + cf(1-r_p)M_c \end{cases} \quad (1)$$

Where:

J1 - the moment of inertia on sun wheel shaft;

Jice - the moment of inertia on ICE shaft;

ω1 - angular velocities of sun wheel shaft;

ωice - angular velocities of ICE shaft;

Mice, M2 - moment acting on ICE and ring shaft;

Mc - torque transmitted through the clutch friction plates;

c - logic signal of clutch (0 - clutch off, 1- clutch on);.

b - logic signal of brake (0 - brake off, 1 - brake on);

rp - speed difference indicator (0 - ωice≠ω1, 1 - ωice=ω1);

r1 - direction indicator of sun wheel shaft (0 - ω1>0, 1 - ω1⩽0);

f - relative friction direction of clutch plates (-1 - ωice<ω1, 1 - ωice>ω1).

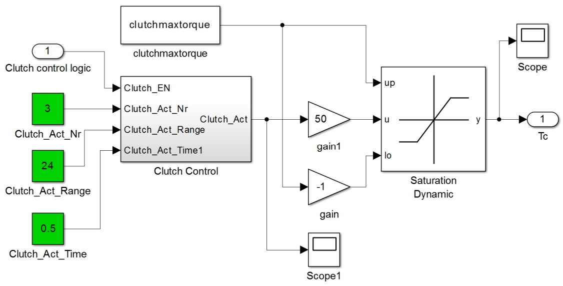

Figure 11: Simulation model of clutch current control unit

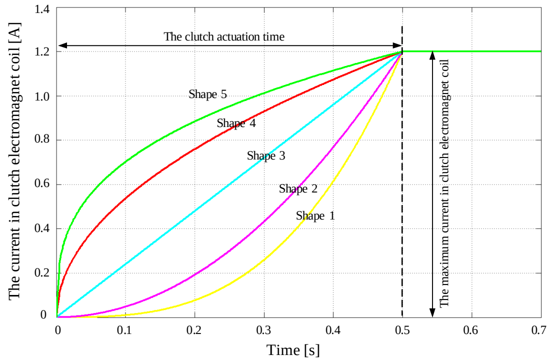

Figure 12: The control of current in clutch electromagnet coil

2.2 Speed control of power sources in power train

The power sources in power trains include internal combustion engine and PM motor. The speed of load in power train depends on the speed distribution of each power source. The calculation of reference speed of power sources is based on different operation mode and some assumptions.

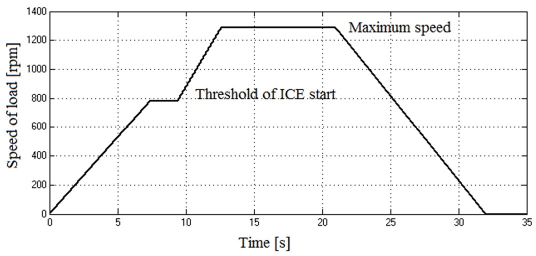

Figure 13: An exemplary driving cycle

Pure electric start

For pure electric start, the internal combustion engine is disconnected from power train and the sun shaft of planetary gear is blocked. In this case, the load of power train is drove by PM motor only.

$$w_{em} = \frac{1+k_p}{k_p} i_{reducer} w_{load} \tag{2}$$

Where:

w_{em} -reference speed of PM motor;

w_{load} -reference speed of load from driving cycle;

k_p -basic ratio of planetary gear;

$i_{reducer}$ -ratio of reducer between planetary gearbox and PM motor.

Hybrid drive

The speed distribution of power sources for hybrid drive depends on driving cycle and some assumption. The hybrid mode of power train starts when speed of load is over the threshold. For hybrid mode, the speed of ICE is limited in range $[w_{ice\_min}, w_{ice\_max}]$ to improve the fuel efficiency. Thus, the control function of ICE is as below.

$$w_{ice} = a w_{load} + b \tag{3}$$

When,

$$\begin{cases} w_{ice} = w_{ice\_min} \\ w_{load} = w_{load\_Th} \end{cases} and \begin{cases} w_{ice} = w_{ice\_max} \\ w_{load} = w_{load\_max} \end{cases}$$

So,

$$w_{ice} = \frac{w_{ice\_max} - w_{ice\_min}}{w_{load\_max} - w_{load\_Th}} w_{load}$$

$$+ (w_{ice\_max} - \frac{w_{ice\_max} - w_{ice\_min}}{w_{load\_max} - w_{load\_Th}} w_{load\_max})$$

Where:

w_{ice} -reference speed of ICE;

w_{ice_min}, w_{ice_max} -minimum and maximum speed of ICE in hybrid mode;

w_{load_Th} -threshold speed of load for starting hybrid mode;

w_{load_max} -maximum speed of load in driving cycle.

For the power train is equipped with planetary gearbox, the relation of w_{ice}, w_{em} and w_{load} is following Equation 7. Then, the reference speed of PM motor is calculated as below.

$$w_{em} = \frac{(1+k_p)w_{load} - w_{ice}}{k_p} i_{reducer} \qquad (4)$$

2.3 Simulation results

The objectives of simulation are as below.

1. Observe the behaviors of each element in hybrid power train.
2. Analyze the starting procedure of ICE.
3. Analyze the influence of timing of control logic for clutch engagement and ICE start.
4. Analyze the influence of clutch engagement control for ICE start.

Table 4: The parameters of control signals in simulation*

No.	Timing of control logic					Start_Th	Clutch control	
	Brake_Th [s]	Speed_Th [s]	Clutch_Th [s]	Starter_ End [s]	Braking_Th [s]		Clutch_Act_Time [s]	Clutch_Act_Nr [s]
1	0.2	0.5	0.8	1.8	0.8	0.45	0.5	3
2	0.2	0.6	0.8	1.8	0.8	0.45	0.5	3
3	0.2	0.7	0.8	1.8	0.8	0.45	0.5	3
4	0.2	0.5	0.5	1.8	0.8	0.45	0.5	3
5	0.2	0.5	0.6	1.8	0.8	0.45	0.5	3
6	0.2	0.5	0.7	1.8	0.8	0.45	0.5	3
7	0.2	0.4	0.7	1.8	0.8	0.45	0.5	3
8	0.2	0.4	0.8	1.8	0.8	0.45	0.5	3
9	0.2	0.3	0.7	1.8	0.8	0.45	0.5	3
10	0.2	0.5	0.7	1.2	0.8	0.45	0.5	3
11	0.2	0.5	0.7	1.2	0.8	0.45	0.8	3
12	0.2	0.5	0.7	1.2	0.8	0.45	0.2	3
13	0.2	0.5	0.7	1.2	0.8	0.45	0.5	1
14	0.2	0.5	0.7	1.2	0.8	0.45	0.5	2
15	0.2	0.5	0.7	1.2	0.8	0.45	0.5	4
16	0.2	0.5	0.7	1.2	0.8	0.45	0.5	5

*The parameters of control signals in this table influence the timing of engine start and clutch engaging procedure (see Figure 12 and 14).

The parameters of control signals in simulation are shown in Table 4. The simulation includes three parts.

- **No.1-No.9** Different timing of electric motor braking (Speed_Th) and clutch engaging (Clutch_Th)
- **No.10-No.12** Different clutch actuation time (Clutch_Act_Time)
- **No.6 and No.13-No.16** Different shapes of increasing current in clutch electromagnet coil.

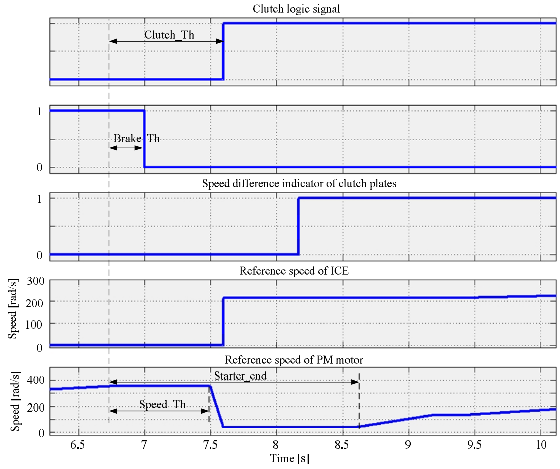

Figure 14: Indication of control signals in simulation

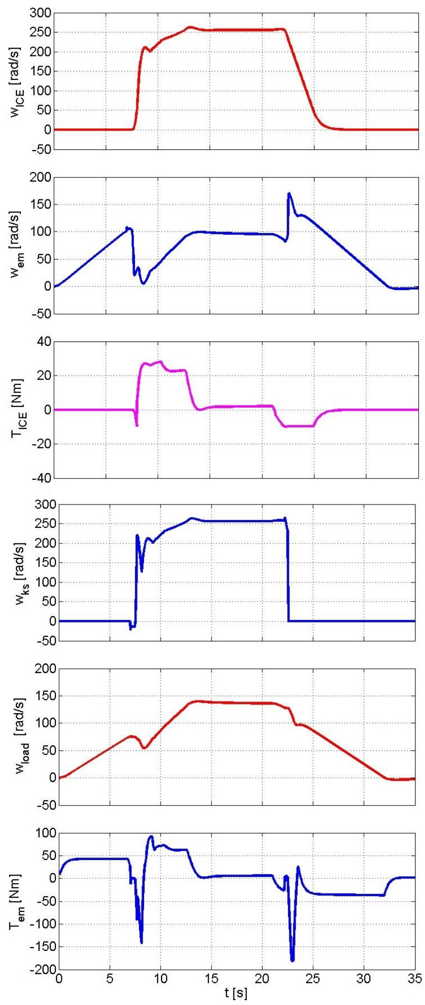

Figure 15: Simulation results for one set of parameters (No3 in Table 4)

Figure 16 presents the behaviours of power train during ICE starting. The ICE starting procedure is depicted as below.

- Point A: Brake of sun shaft is released. The sun shaft could run freely.
- Point B: The negative torque is generated on ring of planetary by braking the PM motor. With this negtive torque, the sun shaft is accelarating posetivly.
- Point C: The clutch on sun shaft is engaging with ICE shaft. Then the ICE shaft speed increases.
- Point C' to D: ICE shaft keeps accelerating while ICE has resistance torque.
- Point D: When ICE speed is over the threshold of starting, ICE starts and generats posetive torque.
- Point E: Speed of sun shaft is synchronized to the ICE shaft, which means the clutch is fully engaged.

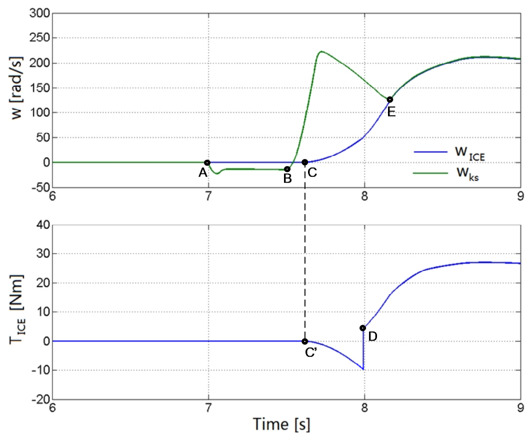

Figure 16: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No3 in Table 4)

2.3.1 Influence of different timing of electric motor braking and clutch engaging

Figure 16-20 present the simulation results of CHPTD simulation model with different timing of electric motor braking and clutch engaging. The detail behaviours of internal combustion engine and sun shaft, which are both connected to clutch, are presented as well.

According to simulation results, the internal combustion engine can start normally when the timing difference of electric motor braking and clutch engaging is below 0.4 seconds. If the timing difference of electric motor braking and clutch engaging is too big (see Figure 45), the speed of ICE cannot reach the threshold for starting, which means ICE start failure.

When the timing difference of electric motor braking and clutch engaging is zero (see Figure 37 and 38), the clutch engages before sun shaft is accelerated. In this case, the clutch engages without speed difference of its two plates and the abrasion of the clutch plates is minimized. However, the ICE torque undulation is quite big during engine start and the fuel consumption could increase significantly.

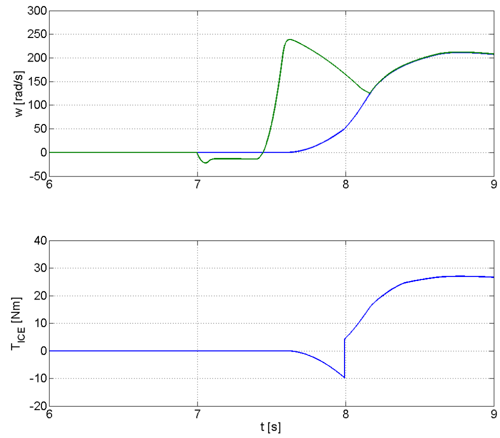

Figure 17: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No2 in Table 4)

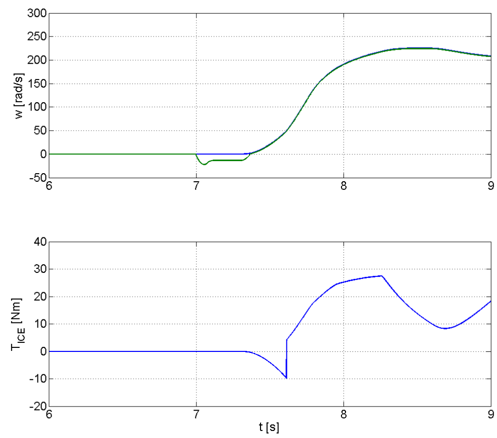

Figure 18: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No4 in Table 4)

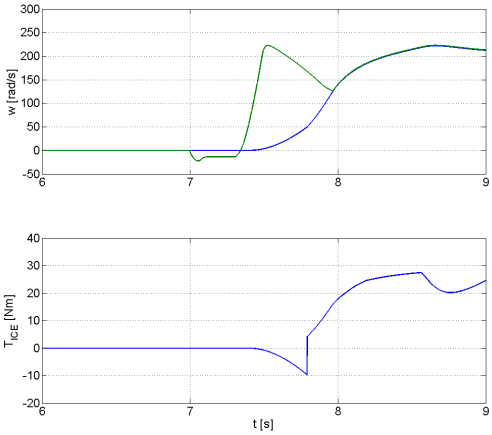

Figure 19: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No5 in Table 4)

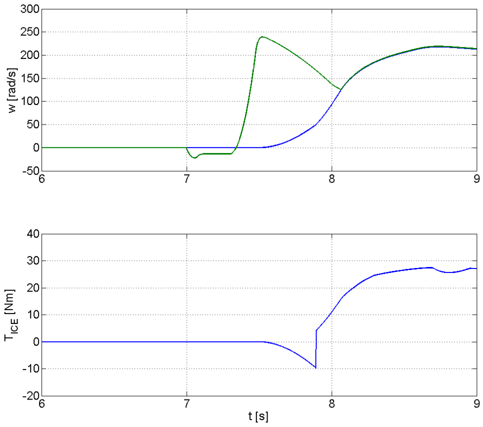

Figure 20: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No6 in Table 4)

The conclusions of simulation results for different timing of electric motor braking and clutch engaging are as below.

- The timing of electric motor braking and clutch engaging can strongly influence the clutch engaging behavior.
- The timing difference of electric motor braking and clutch engaging should be in proper range. Too big timing difference may cause the engine start failure. Too small timing may cause big undulation of engine torque which may increase the fuel consumption.

2.3.2 Influence of Different clutch actuation time

The clutch actuation time means the time duration of current in electromagnet coil increasing from zero to maximum value (see Figure 12). The clutch actuation time strongly influences the behaviours of power train.

The clutch actuation time should cooperate with control of all elements in power train, especially the timing of PM motor giving negative torque during ICE start.

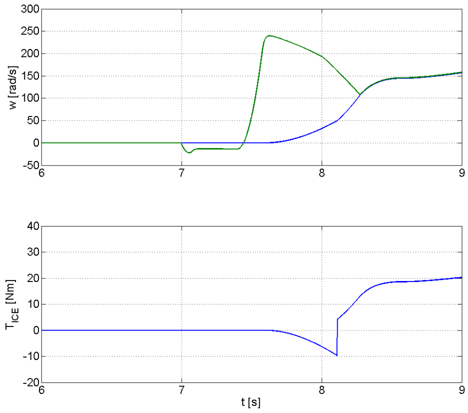

Figure 21: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No10 in Table 4)

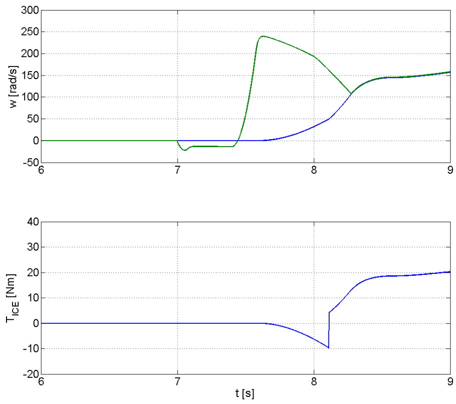

Figure 22: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No11 in Table 4)

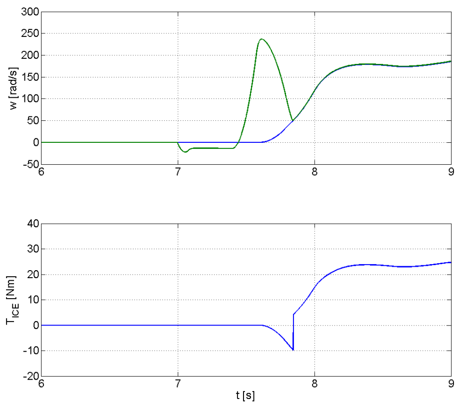

Figure 23: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No12 in Table 4)

By analysing the simulation results, the conclusions on performance for different clutch actuation time are as below.

For too big clutch actuation time, the torque of sun shaft cannot transfer to ICE shaft efficiently. Then ICE cannot start for its speed is below the starting threshold during PM motor giving negative torque.

For too small clutch actuation time, ICE starts when PM motor is still in braking mode. In this case, ICE is forced to output very big torque which means the fuel consumption during ICE start may increase obviously. At the same time, the negative torque of PM motor is also increasing which is forced by ICE. The value of negative torque of PM indicates the current in armature. Too big current in armature may damage the PM motor. So, although the ICE starts quickly when clutch actuation time is small, it is not good for power train.

According to analysing of simulation results, the proper value of clutch actuation time is 0.4-0.5sec.

2.3.3 Influence of Different shapes of increasing current in clutch electromagnet coil

During clutch engaging, torque transfers from sun shaft to ICE shaft. The current in the clutch electromagnet coil creates attraction force between clutch plates, which influence the maximum torque transferred by clutch. Figure 24-26 show the different behaviours of clutch engagement for different current shapes in clutch electromagnet coil according to Figure 12.

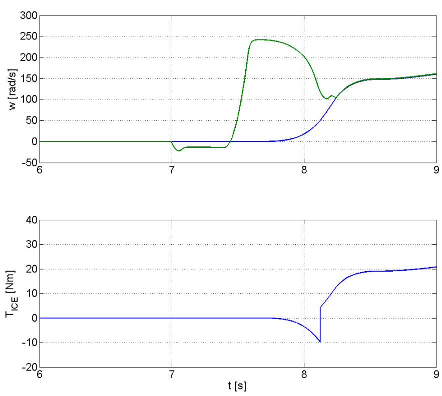

Figure 24: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No13 in Table 4)

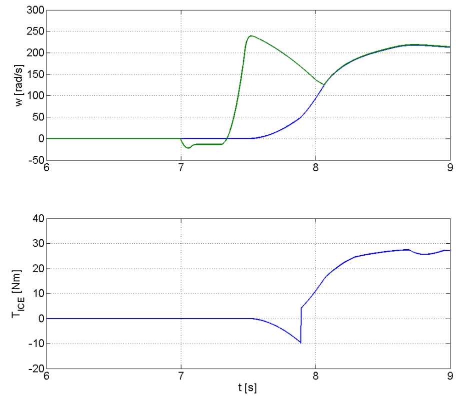

Figure 25: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No6 in Table 4)

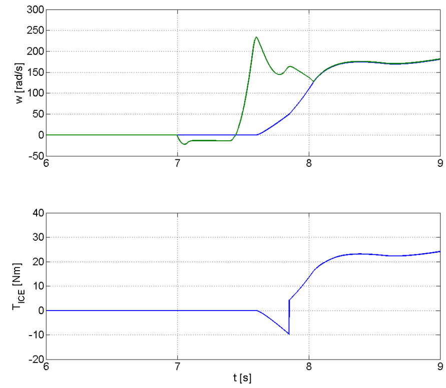

Figure 26: Simulation results of ICE speed, sun shaft speed and ICE torque during ICE starting (No16 in Table 4)

Based on calculation, clutch engagement has smaller energy losses as well as smaller engaging time with current shape No.5 in electromagnet coil (see Figure 26).

3 Bench test on laboratory stand of hybrid power train

The objectives of bench test on laboratory stand of hybrid power train are as below.

1. To verify if the simulation results can follow the behavior of test results.
2. To analyze the difference between simulation and test results.

The bench tests on laboratory stand were made with the same setting of parameters in Table 4.

Figure 27-29 are the exemplary comparison of simulation result and test result.

- Figure 27 zone A:

During ICE start and acceleration, the speed difference between simulation result and test result may cause by following reasons.

1. The function of ICE controller is unknown. It is assumed that ICE has PI regulator. Although additional tests were made to determine the parameters of ICE speed regulator, there may be some errors or even the assumption was not correct.
2. There should be additional resistance torques applied on all the shafts in power train for there are frictions and mechanical connectors.

- Figure 27 zone B:

Between the brake of sun shaft release and PM motor start braking, the sun shaft could run freely. The torque applied on sun shaft through planetary gearbox is very small. So, theoretically, the speed of sun shaft should be negative, which presents in simulation result. However, on laboratory stand, the additional friction torque on sun shaft balanced the torque from planetary gearbox. That is why the sun shaft hasn't negative speed.

- Figure 27 zone C:

In test result, the speed of sun shaft does not drop to zero. The remote speed sensor used on this shaft stops transfer signal when the rotary speed is low than some threshold.

- Figure 29 zone A:

Test result of TICE has longer time than simulation result when the value is negative. This should be caused by time constant of clutch control system. In simulation, the time constant of clutch control system is almost zero. But in real condition, time constant exists in clutch controller and even the inductance of clutch electromagnet coil.

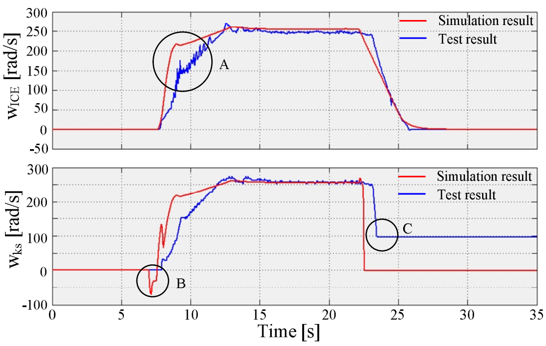

Figure 27: Simulation result and test result comparison of ICE speed and sun shaft speed (No3 in Table 4)

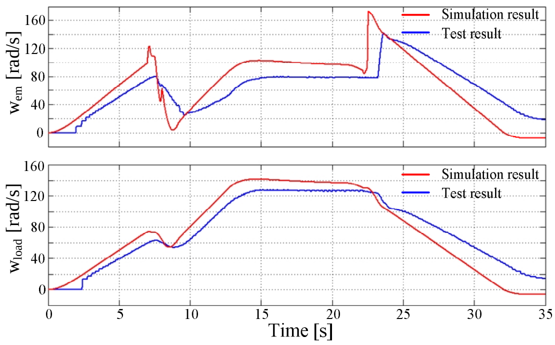

Figure 28: Simulation result and test result comparison of PM motor speed and load speed (No3 in Table 4)

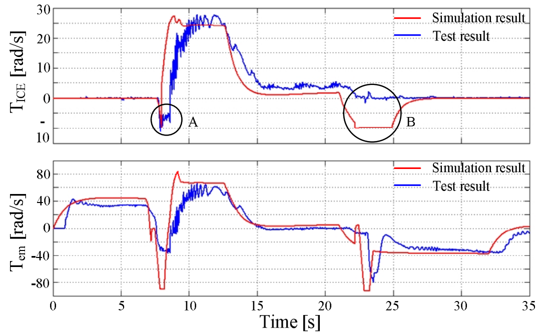

Figure 29: Simulation result and test result comparison of ICE torque and PM motor torque (No3 in Table 4)

Generally, the simulation and test results can match each other. However, there are some differences between them. Because there are more elements and additional conditions in real laboratory stand rather than simulation model. Only main factors are considered in simulation model.

4 Conclusions

According to simulation results, both different timing of electric motor braking and clutch engaging and current in clutch electromagnet coil could strongly influence the engine start performance. By applying Artemis driving cycle to simulation model, it is verified that the simulation model could operate correctly in different conditions.

By comparing the simulation and bench test results with the same setting of parameters and control strategy, it is verified that the simulation model could simulate the behaviours of laboratory stand correctly. However, there are some differences between simulation and bench test results. The possible reasons are explained.

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