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MODELING AND CONTROL OF POWER-SPLIT HYBRID ELECTRIC VEHICLE USING FUZZY LOGIC METHOD

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Abstract

Nowadays, automotive manufactures increasingly have lead to development of hybrid vehicles due to energy consumption growing and increased emissions. the power-split hybrids due to the simultaneous using of speed and torque couplings has integrated advantage of series and parallel hybrid systems and minimize their disadvantages , however the power-split hybrids control strategy is far more complex than other types. Generally the control strategy tries to use the optimize operating point of HEV components such as ICE, TM, MG, batteries and etc. in this research the using of fuzzy logic control method is considered to increase optimize the power-split Hybrid components operation. The power-split HEVs model have been built with ADVISOR-Matlab/Simulink Software for an C class car based on TOYOTA Prius Model, and the simulation results showed significant improvements in fuel consumption and performance and as well as emissions.

Keywords: internal combustion engine (ICE), traction motor(TM), hybrid electric vehicle (HEV), power-split device, motor/generator (MG)

1. Introduction

In previous research some models for simulation of power-split hybrids by fuzzy logic method is presented, but there is no more study concerning fuzzy logic controller based on this Software, In this study, a model based on ADVISOR Software is presented. Energy management in hybrid electric vehicle is an important issue because it can significantly influence the performance and component sizing of the vehicles. Especially, energy control strategy is one of the most important in HEVs. Good control strategy means to reduce fuel consumption, decrease emissions, and improve driving performance. In addition, the intelligent energy management methods can observe and learn driver behaviors in different vehicle conditions. These methods were appropriately applied for controlling HEVs.

Toyota Prius was the first successfully commercialized HEV. Its control strategy has been widely studied since it was put in the market in 1997. ADVISOR, as a powerfully and widely used computer simulation tool for HEVs, has a built-in model of Toyota Prius which includes the component data in ADVISOR library [5].

The purpose of this research was to implement the intelligent control strategy to improve the driving performance and reduce fuel consumption and emissions. The model was built with Simulink/Matlab and base on Fuzzy logic toolbox and added to ADVISOR model instead to classic controller. In this model, fuzzy logic controllers were designed, that by demanded torque and speed and state of battery charge, the controller defined the required engine torque and speed to optimize engine operating region. Finally, the simulation of HEVs with ADVISOR fuzzy logic controller implemented and the results are compared with the ADVISOR classic controller. The benefits of fuzzy control strategy can be summarized as:

The remaining sections cover the following subjects:

Section 2 discusses the simulation models with the details of hybrid key components. Section 3 describes the control strategy. Section 4 presents the results of the model simulation. And, finally the conclusions are made in section 5.

2. System Model

The target vehicle (base on Toyota Prius) utilizes a power-split hybrid power train system that merges the series and parallel HEV to maximize the benefits of both systems. A planetary gear system is a tow degree freedom system that enables the engine to connect the driver wheels directly when desired and disconnected from the wheels so as to charge the battery only [1]. The vehicle specifications are listed in Table1.

Table 1. Vehicle specifications

Item	Quantity
Vehicle Mass	1300
Vehicle Drag Coefficient	0.32
Vehicle Frontal Aria	1.8 m^2
Wheel Base	2.345m
Center Of Gravity Height	0.6m
Rolling Resistance Coefficient	0.013
Wheel Radius	0.287m
Final Drive Ratio	3.93
Power and Torque of ICE	46kW/124Nm@4000rpm
Power and Torque of TM	30kW/305Nm
Power and Torque of MG	15kW/55Nm
Battery Energy	1.872kWh/288V
Ring Gear No.	78
Sun Gear No.	30
Air Density	1.2 kg/m^3

2.1. Planetary Gear System

The rotational speeds of the ring gear (ω_r), sun gear (ω_s) and carrier gear (ω_c) satisfy the following relationship[3].

$$\omega_s R_s + \omega_r R_r = \omega_c (R_s + R_r) \qquad (1)$$

Where R_r and R_s are the radius of the ring gear and sun gear, respectively. In the Toyota Prius, the generator, motor and internal combustion engine (ICE) are directly connected to the sun gear, the ring gear, and carrier gear, respectively. The wheels are connected to ring gear through the differential gear. With the differential gear ratio (r_{final}) and the ratio (i) between the ring gear and the sun gear, Eq. (1) can be rewritten as:

$$\frac{i}{r_{final}} \omega_w + \omega_{MG} = \omega_{ICE} (1 + i) \qquad (2)$$

Where ω_w , ω_{MG} , and ω_{ICE} are speed of wheel, motor-generator, and engine, respectively

According to Eq. (2), the relation between the engine speed and the wheel speed is determined not only by a gear ratio, but also by the generator speed.

Traction motor speed and wheel speed are proportional.

$$\omega_{TM} = \frac{1}{r_{final}} \omega_w \qquad (3)$$

Generator speed is defined as below.

$$\omega_{MG} = (1 + i)\omega_{ICE} - \frac{i}{r_{final}} i \qquad (4)$$

The drive shaft is connected to the ring gear through a final reduction gear with gear ratio (r_{final}). Hence the total drive torque at the wheels is:

$$T_d - \frac{1}{r_{final}}(T_r + T_{TM}) - \frac{1}{r_{final}}(T_{TN} + \frac{i}{i+1} T_{ICE}) \qquad (5)$$

Where T_d, T_r, T_{TM}, and T_{ICE} are the wheel tractive torque, ring gear torque, generator torque, and engine torque, respectively.

Engine Fuel Consumption:

The fuel consumption rate of the engine can be modeled as an algebraic function of the engine torque and engine angular speed.

$$\dot{m}_f = f(T_{ICE}, \omega_{ICE}) \qquad (6)$$

In this study, the fuel consumption, efficiency, Co emission map, Nox emission map and HC emission map of Related Engine, as shown in Figs. (1-a, 1-b, 1-c, 1-d 1-e) respectively

Similarly, the motor and generator were modeled with efficient maps. A 2-D lookup table was chosen to represent the efficient map of motor or generator.

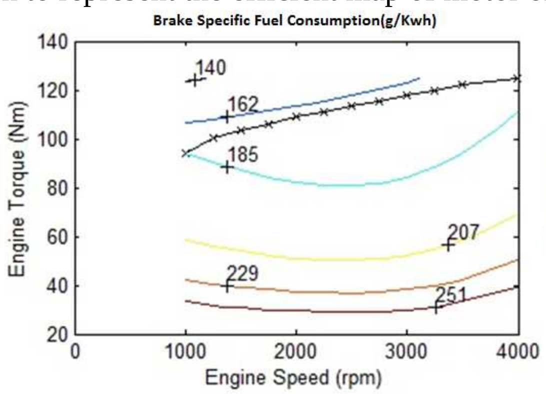

Figure 1-a. Fuel consumption of ICE

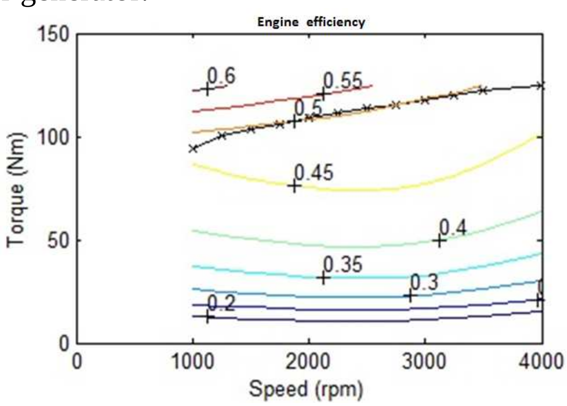

Figure 1-b. Efficiency of ICE

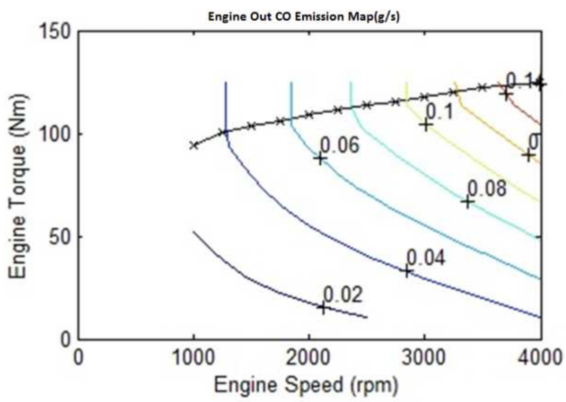

Figure 1-c. Co Emission Map of ICE

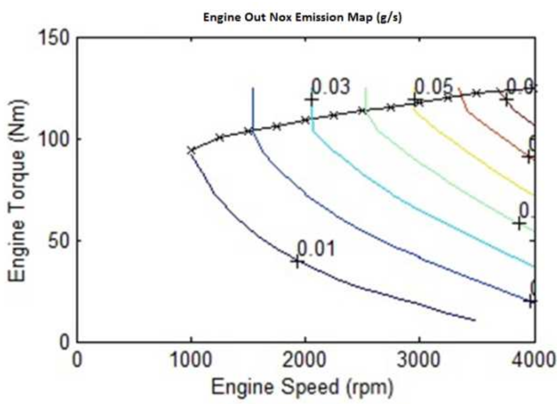

Figure 1-d. NOX Emission Map of ICE

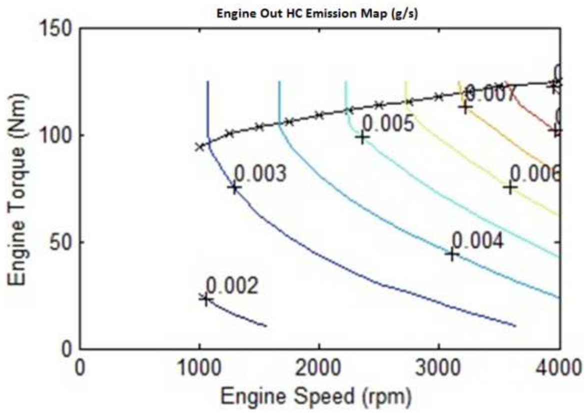

Figure 1-e. HC Emission Map of ICE

2.2. Vehicle Dynamics

The longitudinal vehicle dynamics can be represented by

$$m\dot{V}_x - F_x - C_a V_x^2 - R_x - mg\sin(\theta) \quad (7)$$

Where M , g , V_x, C_a, R_x, F_x and θ are mass of vehicle, acceleration of gravity, vehicle velocity, aerodynamic drag parameter, longitudinal force due to rolling resistance, longitudinal tire force, and road gradient angle, respectively.

Wheel Dynamics:
The dynamics of vehicle wheels, which were lumped into one virtual wheel, were given by:

$$I_w\dot{\omega}_w = T_d - T_{fbrake} - r_w F_x \quad (8)$$

WhereI_w, T_{fbrake} and r_w are inertia moment of wheels, demanded braking torque of front axle, and wheel radius, respectively.

Battery State of Charge *(SOC):*
Power discharge from the battery, and charge to the battery are given by

$$P_{batt} = \eta^k T_{MG}\omega_{MG} + \eta^k T_{TM}\omega_{TM} + P_{acc} \quad (9)$$

Where η is the electrical-mechanical conversion efficiency, P_{acc} was power of electric accessory, and $K = -1$ during discharging and $K = 1$ during charging.

3. Control Strategy

3.1. Traction Torque Controller

This section shows the control strategy to optimize the vehicle fuel consumption, emissions and performance along with sustaining the SOC, engine torque and engine speed at an optimal level. The control strategy must be able to follow the driver's command.

The design criteria for this controller were set optimal ranges of the ICE, battery charge-discharge, traction motor (TM) efficient map and motor-generator (MG) efficient map. An optimal area of ICE was at speed range of 1500-3500 rpm and output torque of 70 to 110 Nm. Similarly, the TM should be controlled to operate at torque below 150Nm, the MG should be controlled to operate at torque below 150Nm, Charging and discharging the battery was most efficient at medium SOC level, 0.55 to 0.65 [4].

The traction controller has designed according to the following strategies[6]:

The first case, the SOC is considered low. If demanded torque was low, the ICE should be controlled to operate at optimal area. If demanded torque was medium or high, the ICE should be controlled to generate a higher output torque to meet both the demanded torque and the battery charging requirement.

The second case, the SOC is considered medium. If demanded torque was low, the ICE should be turned off. If demanded torque is medium, the ICE should be controlled to operate at optimal area. Similarly, if demanded torque was high, the ICE should be controlled to generate an optimal output torque. The remained torque was supplied by the traction motor.

For the last case, the SOC is considered high. If demanded torque was low or medium, the ICE should be turned off. The vehicle operated as pure electric vehicle. If demanded torque was high, the ICE should be controlled to generate an optimal output torque. The remained torque was supplied by the motor.

From the above analysis, it preferred three inputs of fuzzy logic controller including demanded torque, SOC, and demanded vehicle speed. The definitions of these inputs were listed as follow

3.2. Traction demanded torque input

it represented the required torque from the driver. The input included three membership functions as in Fig. 2.

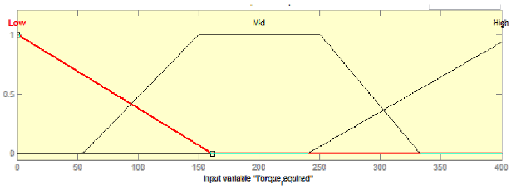

Figure 2. The demanded driving torque

Member functions of demanded driving torque are as follow:

$$\mu(T-Low)=\begin{cases}1-\dfrac{x}{160} & 0\le x\le 160\end{cases}$$

$$\mu(T-Mid)=\begin{cases}\dfrac{x-55}{95} & 55\le x<150\\ 1 & 150\le x\le 250\\ \dfrac{250-x}{85}+1 & 250<x\le 335\end{cases}$$

$$\mu(T-High)=\begin{cases}\dfrac{x-240}{160} & 240\le x\le 400\end{cases}$$

3.3. SOC input

They preferred the concourse of SOC at [0.45, 0.75], and the universe of discourse was [0, 0.45] and [0.75, 1]. The membership functions can be seen in Fig. 3.

The new Fuzzy logic controller which replaced with conventional controller in ADVISOR is presented in Fig. 7.

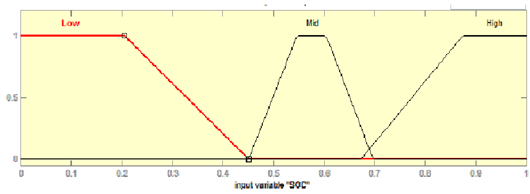

Figure 3. The SOC input

Member functions of SOC are as follow:

$$\mu(SOC-Low)=\begin{cases}1 & 0\le x\le 0.2\\ 1-\dfrac{x}{0.45} & 0.2<x\le 0.45\end{cases}$$

$$\mu(SOC-Mid)=\begin{cases}\dfrac{x-55}{95} & 0.45<x<0.55\\ 1 & 55\le x\le 0.6\\ \dfrac{250-x}{85}+1 & 0.6<x\le 0.7\end{cases}$$

$$\mu(SOC-High)\begin{cases}\dfrac{x-0.68}{0.19} & 0.68\le x<0.87\\ 1 & 0.87\le x\le 1\end{cases}$$

3.4. Vehicle speed input

it had three membership functions as shown in Fig. 4.

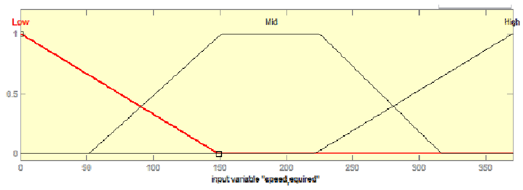

Figure 4. The vehicle speed input

Member functions of demanded driving speed are as follow:

$$\mu(S-Low)=\left\{1-\frac{x}{150}\right. \qquad 0\le x\le 150$$

$$\mu(S-Mid)=\begin{cases}\dfrac{x-50}{100} & 50\le x<150\\ 1 & 150\le x\le 220\\ \dfrac{220-x}{96}+1 & 220<x\le 316\end{cases}$$

$$\mu(S-High)=\left\{\frac{x-220}{150}\right. \qquad 220\le x\le 370$$

Two outputs of fuzzy controller were the ICE torque and speed. The outputs were used to choose the optimal operated engine area, Figs. (5-6).

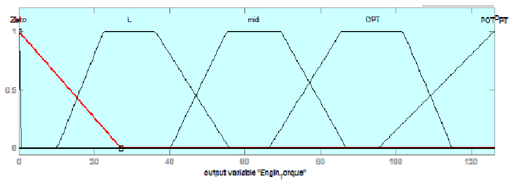

Figure 5. The ICE torque output

Member functions of ICE torque are as follow:

$$\mu(ET-Zero)=\{0 \qquad x=0$$

$$\mu(ET-LL)=\left\{1-\frac{x}{27} \qquad 0\le x\le 27\right.$$

$$\mu(ET-L)=\begin{cases}\frac{x-10}{12} & 10\le x<22\\ 1 & 22\le x\le 37\\ \frac{37-x}{18}+1 & 37<x\le 55\end{cases}$$

$$\mu(ET-Mid)=\begin{cases}\frac{x-40}{15} & 40\le x<55\\ 1 & 55\le x\le 70\\ \frac{70-x}{17}+1 & 70<x\le 87\end{cases}$$

$$\mu(ET-OPT)=\begin{cases}\frac{x-67}{20} & 67\le x<87\\ 1 & 87\le x\le 100\\ \frac{100-x}{15}+1 & 100<x\le 115\end{cases}$$

$$\mu(ET-OPTOPT)=\left\{\frac{x-95}{31} \qquad 95\le x\le 126\right.$$

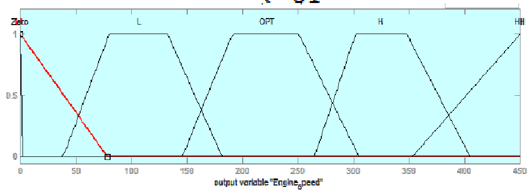

Figure 6. The ICE speed output

Member functions of ICE speed are as follow:

$$\mu(ES-Zero)=\{0 \qquad x=0$$

$$\mu(ES-LL)=\left\{1-\frac{x}{79} \qquad 0\le x\le 79\right.$$

$$\mu(ES-L)=\begin{cases}\frac{x-40}{39} & 40\le x<79\\ 1 & 79\le x\le 130\\ \frac{130-x}{50}+1 & 130<x\le 180\end{cases}$$

$$\mu(ES-OPT)=\begin{cases}\frac{x-148}{36} & 148\le x<184\\ 1 & 184\le x\le 250\\ \frac{250-x}{55}+1 & 250<x\le 305\end{cases}$$

$$\mu(ES-H)=\begin{cases}\frac{x-268}{32} & 268\le x<300\\ 1 & 300\le x\le 345\\ \frac{345-x}{60}+1 & 345<x\le 405\end{cases}$$

$$\mu(ES-HH)=\left\{\frac{x-352}{98} \qquad 352\le x\le 450\right.$$

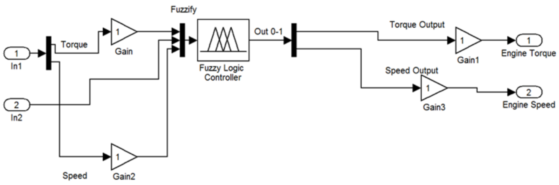

Figure 7. Fuzzy logic controller

4. Fuzzy rules

The rules of fuzzy logic controllers are as Figure 8.a , Figure 8-b and figure 8-c

SOC=LOW							
		vehicle demanded torque					
		LOW		MID		HIGH	
vehicle demanded Speed	LOW	L	L	MID	LOW	OPT	OPT
	MID	MID	OPT	OPT	OPT	OPT˙OPT	OPT
	HIGH	OPT	OPT	OPT˙OPT	OPT	OPT˙OPT	HH
		Engine Torque	Engine Speed	Engine Torque	Engine Speed	Engine Torque	Engine Speed

Figure 8-a. Fuzzy rules as a function of vehicle demanded torque and speed at low SOC

SOC=MID							
		vehicle demanded torque					
		LOW		MID		HIGH	
vehicle demanded Speed	LOW	ZERO	ZERO	L	L	OPT	L
	MID	L	L	MID	L	OPT	OPT
	HIGH	OPT	OPT	OPT	H	OPT˙OPT	H
		Engine Torque	Engine Speed	Engine Torque	Engine Speed	Engine Torque	Engine Speed

Figure 8-b. Fuzzy rules as a function of vehicle demanded torque and speed at middle SOC

SOC=HIGH							
		vehicle demanded torque					
		LOW		MID		HIGH	
vehicle demanded Speed	LOW	ZERO	ZERO	ZERO	ZERO	MID	L
	MID	L	L	MID	L	MID	OPT
	HIGH	MID	OPT	OPT	H	OPT`OPT	OPT
		Engine Torque	Engine Speed	Engine Torque	Engine Speed	Engine Torque	Engine Speed

Figure 8-c. Fuzzy rules as a function of vehicle demanded torque and speed at high SOC

5. Simulation and results

The traction torque and braking torque controller have been implemented and simulated in ADVISOR(MATLAB Simulink) using specified driving cycles, , NEDC. Fig.9 shows the simulated vehicle velocity following the desired driving cycle. The velocity of vehicle was closed to the desired driving speed. Fig.10 shows the engine speed and torque when engine switched on and off. Figs.(11-a, 11-b) represented the operating points within the efficiency map of ICE. The operating points mostly located in the optimal region. Similarly, Fig.12 indicates operating points within the efficiency map of traction motor. Traction Motor also operated in high efficiency areas. Fig.13 depicts the state of charge of battery when the vehicle followed three NEDC driving cycles. The SOC at the beginning and end was the same at 0.7, the battery operated in optimal range through the driving cycles. Fig.14 represent rate of emissions during simulation in NEDC duty cycle. To evaluate the implemented controllers, the simulation was compared with the simulation using non-fuzzy control of ADVISOR, GT-SUIT software simulation result, Honda Insight result. Table 2 shows the results of fuzzy logic control (FLC) model Compared with the other mentioned models in specific driving cycles.

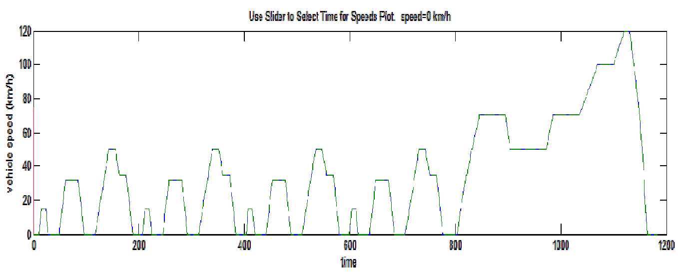

Figure 9. Simulated and desired vehicle velocity in NEDC

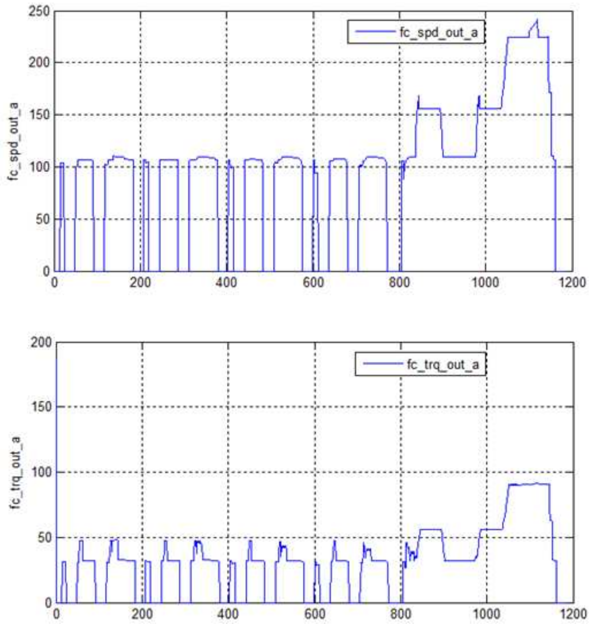

Figure 10. The ICE speed and torque

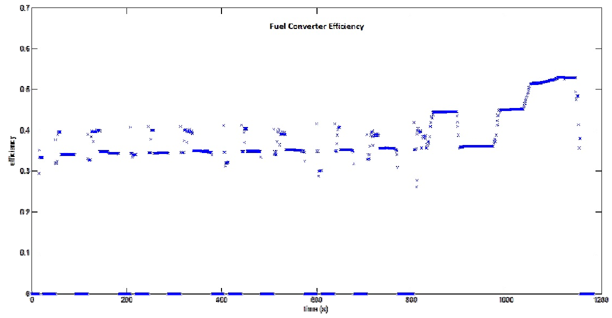

Figure 11-a. Operating points of ICE

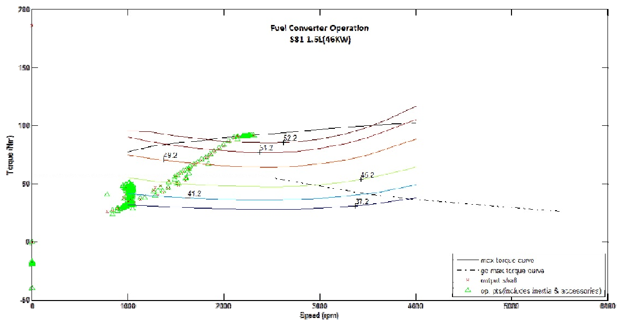

Figure 11-b. Operating points of ICE

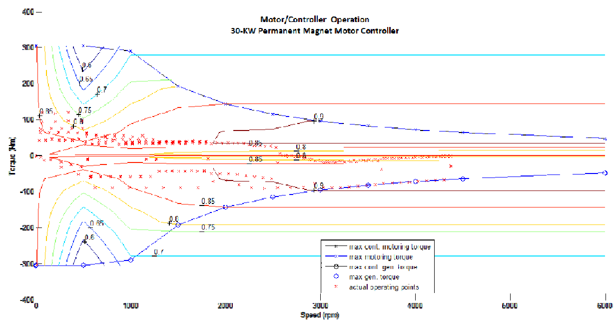

Figure 12. Operating points of TM

Table 2. fuel economy, performance and emissions

		Advisor conventional controller	Fuzzy logic controller	GT-SUIT Model	HONDA Insight
Fuel consumption(L/100 Km)		5.1	4.1	5.5	4
Emissions(grams/Km)	CO	0.772	0.969	0.801	0.895
	HC	0.784	0.108	0.752	0.791
	NOX	0.108	0.058	0.15	0.088
0-96.6 acceleration time(S)		15.3	14.5	17	13.3
64.4-96.6 acceleration time(S)		7	6.5	8	6.5
0-137 acceleration time(S)		30.4	50.5	39	27.5
Max. Acceleration(m/s^2)		3.4	4.8	4	4.1
Max. Speed(Km/hr)		163.4	137.2	155	180

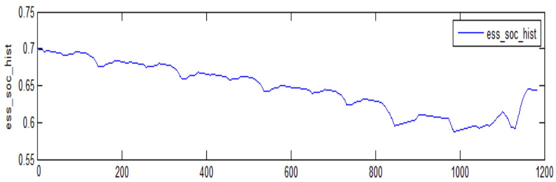

Figure 13. Battery SOC

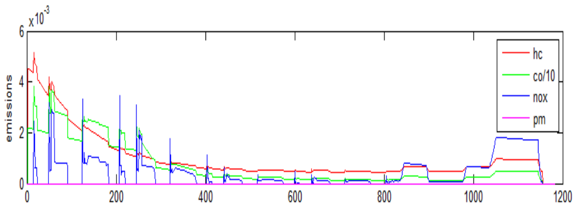

Figure 14. Emissions rate during simulation

model with the new control strategy(fuzzy logic) achieved a better efficiency during the urban driving simulation. All of main components, ICE, TM, MG, and battery, were operated in the optimal regions of the efficiency maps, Not only, the fuel economy improved from 5.1 to 4.1 lit/100Km, but also, the acceleration performance was improved from 15.3 to 14.5 second at 0 to 96 km/h acceleration. In the case of emissions, HC reduced from 0.784 to 0.108 g/Km, Nox reduced from 0.108 to 0.058 g/Km and CO increased from 0.772 to 0.969, Therefore, proposed control strategy which controller was designed from the efficiency maps (ICE, TM, MG and battery) successfully improved the control system for the power split HEV.

Conclusion

The fuzzy logic controller, traction controller, for power split hybrid electric vehicle have been implemented and proven. The traction controller optimized the power flow between the main components of power split HEV when vehicle was in traction.
The implemented power controller ensured to consistently satisfy driver inputs (accelerator pedal), the sufficient battery for operating, and the optimization of fuel economy for power split HEV and also optimize the vehicle emissions.

Acknowledgments

I offer my thanks to my dear master Dr. Khajavi and all those who helped me in this study

Notations

ω_s The rotational speeds of the sun gear
ω_r The rotational speeds of the ring gear
ω_c The rotational speeds of the carrier
ω_W The rotational speeds of the wheels
ω_{MG} The rotational speeds of the motor-genrator
ω_{ICE} The rotational speeds of the internal combustion engine
ω_{TM} The rotational speeds of the traction motor
R_s Radius of the sun gear
R_r Radius of the ring gear
r_{final} Differential gear ratio
i Ratio between the ring gear and the sun gear
T_d Wheel tractive torque
T_{ICE} Internal combustion engine tractive torque
$\dot{m}_f$ The fuel consumption rate of the engine
η Electrical-mechanical conversion efficiency
T_{MG} Motor generator tractive torque
T_{TM} Traction motor tractive torque
P_{batt} power of electric accessory
P_{acc} Power discharge from the battery, and charge to the battery
m Vehicle mass
$\dot{V}_x$ Vehicle acceleration
F_x Longitudinal tire force
C_a Aerodynamic drag coefficient
V_x Vehicle velocity
R_x Longitudinal force due to rolling resistance
g Acceleration of gravity
θ Road gradient angle
r_w Wheel radius
$T_{f\,brake}$ Demanded braking torque of front axle
I_w Inertia moment of wheels
$\dot{\omega}_w$ Angular acceleration of wheel

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