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Energy Management Strategy and Control Laws of An Inverse Differential Gear Hybrid Vehicle

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Abstract

This paper presents the Energy Management Strategy (EMS) and control laws of an inverse differential gear hybrid vehicle and also the simulation results for the dynamics response and performance of the system. In the system, an engine and a motor/generator are attached to the side gears individually and the power is transmitted through plenary gear to ECVT. By regulating the gear ratio of ECVT and the power outputs between engine and motor/generator, desired system dynamics can be achieved. The goal is to control the system dynamics such that the engine dynamics can be fixed at an optimal operation point while meeting the driver desire of vehicle speed in hybrid operation. While in pure engine or pure motor or brake regeneration modes, optimal gear ratio and engine operation or motor/generator operation to achieve fuel efficiency are the goal of the control laws. Simulation results show that the fuel consumption can be reduced to half of the original engine driven vehicle. Similar improvements can also be found in the performance of CO, HC, and NOx emission.

Keywords:Hybrid vehicle, Energy management strategy, Dynamics simulation

1 Introduction

Due to the reason of energy shortage and global warming, Electrical Vehicle (EV) has been a solution to solve the problem among international societies. Among the different types of electrical vehicles, Hybrid Electrical Vehicle (HEV) integrating motor and engine powers is the most successful one. This is because it can provide similar performance as the conventional Internal Combustion Engine (ICE) vehicle in terms of cruising range and power. Also, by an appropriate control strategy, the engine operation can be confined at a fuel efficient zone such that the fuel consumption and emission can be reduced [1].

The HEVs can be divided into two groups; serial HEV and parallel HEV. Configurations of these two groups of HEV are shown in Figure 1. For the serial HEV, the engine drives a generator to charge the battery and the vehicle is propelled by the motor. Examples of serial HEV are in [2]. On the other hand, there are three types of parallel HEV. For the first type, the motor and the engine share the same shaft. For the second type, the motor and engine are coupled by a coupler. Finally, for the third type, the front wheels and rear wheels are driven by motor and engine individually. Examples of early parallel hybrid vehicles include the BMW 518, Citroën XzaraDynactive and SaxoDynavolt, Daimler-Chrysler ESX 3, Fiat Multipla, and theFordMultiplia and P2000 Prodigy [3], Recently, more HEVs have be published, including Mercedes-Benz s400, Honda Insight [4], Toyota Prius [5], and many others. Among these HEVs, Toyota Prius is the most popular vehicle.

An important mechanism in Toyota Prius is a planetary gear set usually known as power-splitting devices (PSD). This PSD can integrate power from engine and motor. It also allows the motor or the engine to operate individually. A feature of this mechanism is that, in hybrid operation, the engine can be decoupled from the vehicle speed such that the engine can be controlled to operate at fuel efficient zone. In this research, a new type of PSD is adopted [6]. This device uses inverse differential gear to replace the planetary gear set.

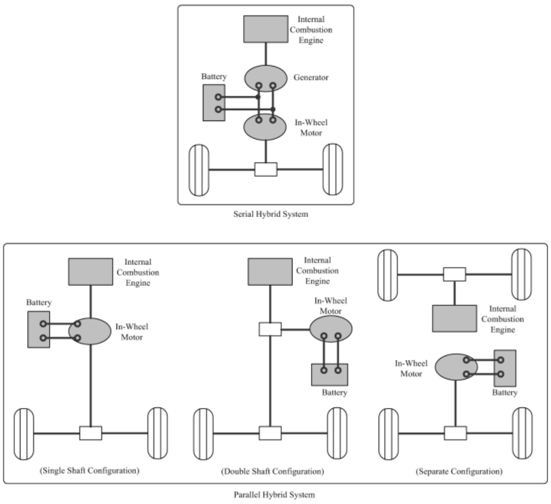

Figure 1 configurations of the HEVs

For the parallel HEV, energy management strategy is important, which manipulates the power flow such that the engine, motor, and generator operations can be efficient and battery State Of Charge (SOC) can maintain at a certain level while fulfill the power demand from the driver. For the development of energy management strategy, rule-base algorithm is one of the candidates [6]. An advanced type of algorithm is the fuzzy logic algorithm to improve the flexibility of the rule base algorithm [7]. Genetic algorithm is also developed such that the strategy can be adaptive [8]. Finally, genetic-fuzzy algorithm is developed such that by tuning the fuzzy logic rules, the algorithm can be adaptive [9]. These are only some of the examples, many energy management strategies have been developed using different control theories. Nevertheless, all of them are to seek for optimal use of the engine, motor, generator, and battery to obtain efficient energy usage. For this project, a rule base algorithm is adopted for its easiness to design.

2 System Configuration And Specification

System configuration of the inverse differential gear hybrid vehicle power train is shown in Figure 2. It is shown that an engine and a motor/generator are attached to the side gears individually and the power is transmitted through plenary gear to ECVT. By regulating the gear ratio of ECVT and the power outputs between engine and motor/generator, desired system dynamics can be achieved. The goal is to control the system dynamics such that the engine dynamics can be fixed at an optimal operation point while meeting the driver desire of vehicle speed in hybrid operation. While in pure engine or pure motor or brake regeneration modes, optimal gear ratio and engine operation or motor/generator operation to achieve fuel efficiency are desired while meeting the driver demand.

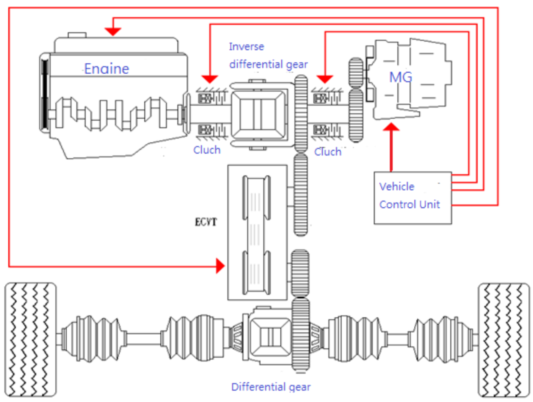

Figure 2: system configuration

3 Energy Management Strategy

Figure 3 shows the proposed EMS. In the EMS, there are seven operation modes, including a brake regeneration mode (mode 0), a low driver demand power mode (mode 1), a medium driver demand power hybrid mode (mode 2), a high driver demand power hybrid mode (mode 3), a low driver demand power charging mode (mode 4), a medium driver demand power charging mode (mode 5), and finally, a high driver demand power engine mode (mode 6). The driver demand power is calculated using the gas pedal depression angle or the brake pedal depression angle with linear conversion functions as shown in equation (1).

$$p_d = p_{\max}\frac{\theta_p}{\theta_{p\_\max}} \quad (1)$$

where p_d is the driver demand power, $p_{\max}$ is the system maximum power, θ_p is the pedal angle, and $\theta_{p\_\max}$ is the maximum depression angle. If gas pedal is detected, $p_{\max}$ is positive. On the other hand, if the brake pedal is detected, $p_{\max}$ is negative. Furthermore, for the design of EMS, two desired operation points in terms of fuel efficiency are located on engine brake specific fuel consumption (BSFC) map and the corresponding power magnitudes are denoted as p_{e1} and p_{e2} and $p_{e2} > p_{e1}$.

In EMS, if brake pedal is detected, mode 1 is excited. Desired brake force is than calculated and the generator is controlled to meet this demand. Furthermore, if the driver demand power is positive but smaller than a threshold, p_{e1}, mode 1 is excited, for which, vehicle is driven by motor only. Once the demand power gets higher than p_{e1}, mode 2 is excited, in which engine and motor are actuated simultaneously to drive the vehicle. Under this situation, two objectives must be reached; the first one is to reach driver demand power and the second one is to control the engine to operate at p_{e1}. These two objectives can be reached by regulating motor and ECVT. If the driver demand power continue to increase such that it is higher than p_{e2}, mode 3 is excited. Under this situation, the control objectives become driver demand power and p_{e2} for engine operation.

The above modes are excited when State Of Charge (SOC) of the on-board battery is above a threshold. Once the SOC gets lower than a threshold and the driver demand power is small, mode 4 is excited. In mode 4, engine and generator are actuated. The control objectives are driver demand power and p_{e1} as engine desired operation point. This can be achieved by regulating generator and ECVT. Similarly, if the driver demand power gets higher than p_{e1}, mode5 is excited and engine and generator continue to work simultaneously. Under this situation, control objectives are the driver demand power and p_{e2} as the engine desired operation point. Finally, if the driver demand power climb to a value higher than p_{e2}, generator is than shut down and engine works individually to meet the driver demand power.

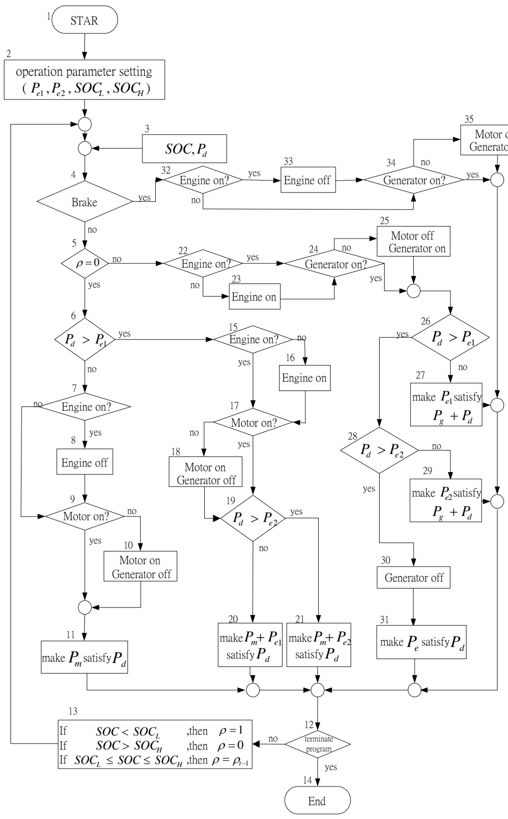

Figure 3: energy management strategy

4 Simulation Results

To evaluate the performance of the energy management strategy, simulations were conducted. For the simulation, Nissan March is chosen as the bench mark. The engine is a MitshbithiVeryca1.2 L engine. The motor/generator is developed by Industrial Technology Research Institute, Taiwan. Some of the specifications of the power train are listed in Table 1.

Table 1: specification of the power train

Parameters	Specifications
Engine	
Capacity	1.2 L
Engine type	SOHC 16V
Maximum power	50 kw
Maximum speed	6000 rpm
Motor/generator	
Maximum power	22 kw
Maximum torque	120 Nm
ECVT	
Range of gear ratio	0.1~2.4
Final gear	3.125

The engine BSFC map is shown in Figure 4, in which two engine desired operation points are allocated and are denoted as p_{e1} and p_{e2} depicted previously. These two points are 21.2KW@(2400rpm,84.23N-m) for p_{e1} and 30.15KW@(3204rpm,89.85N-m) for p_{e2}. The corresponding BSFC is 248.94 g/kw-h for p_{e1} and is 236.23 g/kw-h for p_{e2}.

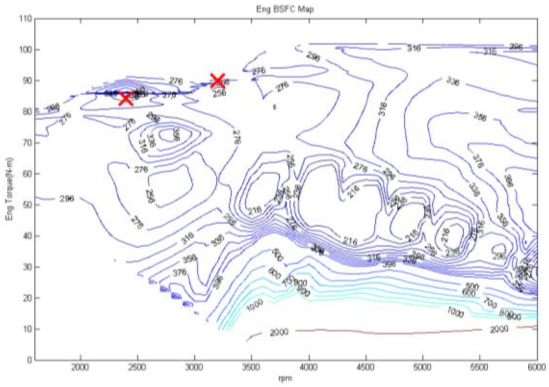

Figure 4: engine BSFC map

Figure 5 is the block diagram for system dynamics simulation. The simulation program is developed using Matlab/Simulink. As shown in Figure 5, a driver model is developed to control the pedals of the vehicle to follow the desired vehicle speed. In this project, NEDC 2000 is used as a desired speed pattern for simulation. The driver model is a PI controller for gas pedal control and a P controller for brake pedal control. The output of the driver model is acquired by the EMS to calculate driver demand power. The driver demand power, along with the battery SOC, is then used in the EMS to decide which mode to be excited. Once the appropriate mode is chosen, control laws in the EMS follows the work to calculate desired engine throttle angle, desired M/G output torque, and desired ECVT gear ratio such that the control objectives in each mode can be reached.

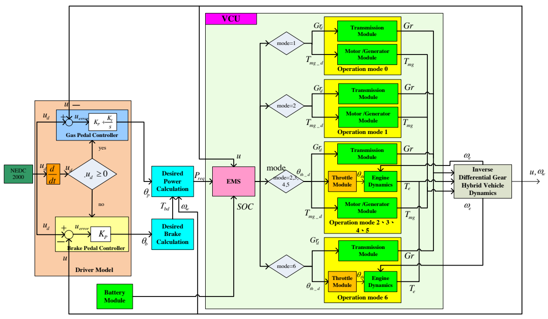

Figure 5:system dynamics simulation block diagram

Figure 6 shows the simulation results of a driver tracking NEDC 2000 speed pattern. It is shown that the speed tracking is precise by the driver. The tracking error is limited to a range of ±0.5 m/s. For the driver pedaling plot, positive value is gas pedaling and negative value is brake pedaling. In the acceleration stage, gas pedaling increase proportionally with the speed because more power is needed for the increase of road loading. While in the deceleration stage, brake pedaling increase as the speed slows down to maintain the deceleration since the road loading decreases. Finally, the driver required power calculated in EMS is linearly proportional to the pedaling, which is also shown in figure 6. Figure 7 shows the engine speed, the motor/generator speed, SOC, and operation mode. It is shown that the engine is successfully controlled at the optimal point while in hybrid modes (i.e. modes 4 and 5). The SOC decreases from an initial value of 70% in the beginning since enough SOC is identified by EMS and the motor mode is excited. It can be seen that the battery SOC drop to a bottom line of 40% and then increase again due to the excitation of engine-generator hybrid charging modes. The SOC rises to the initial value of 70% to meet the SAE testing regulation for hybrid vehicles. Finally, Table 2 shows the comparison of performance between hybrid type and engine type vehicles. Table 2 shows that the fuel consumption can be reduced to half of the original engine driven vehicle. Similar improvements can also be found in the performance of CO, HC, and NOx emission.

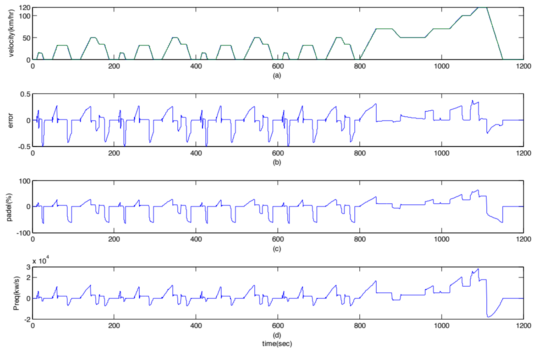

Figure 6: (a)speed tracking (b)tracking error (c)driver pedaling (d)driver requried power

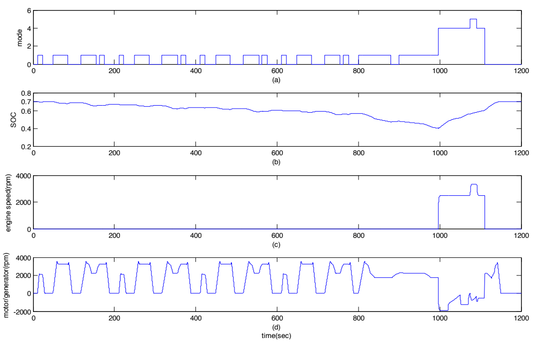

Figure 7: (a)operation mode (b)battery SOC (c)engine speed (d)motor/generator speed

Table 2: Fuel consumption, CO, NOx, HC emission

	Fuel(Km/L)	CO(g/Km)	NOx(g/Km)	HC(g/Km)
Hybrid Vehicle	42.02	0.11	0.0078	0.0011
Engine Vehicle	22.77	0.14	0.012	0.0028

5 Conclusion

This paper presents the Energy Management Strategy (EMS) and control laws of an inverse differential gear hybrid vehicle and also the simulation results for the dynamics response and performance of the system. Simulation results show that the fuel consumption can be reduced to half of the original engine driven vehicle with the hybrid configuration and the energy management strategy. Similar improvements can also be found in the performance of CO, HC, and NOx emission.

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