Design of a Multi Objective Fuzzy- Proportional Compensator for a Power-split Hybrid Electric Vehicle

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Abstract
In this research the model of the Toyota Prius vehicle as a power-split Hybrid Electric Vehicle is chosen from ADVISOR and the information required about a vehicle and drive cycle are extracted from it. In order to have better energy management, a fuzzy compensator is used beside the planetary gear set, which is responsible for sharing power between energy sources. This compensator helps the planetary gear set on supplying the requested speed and torque from final drive and better sharing power between energy sources considering how the requested power instantaneous changes are. Also to provide the requested speed and torque in a better way a P controller is used. At the end, the results of implementation of this controller are compared to those of the primary model. The results show that the designed fuzzy rule based compensator is able to decrease the driving costs.

Keywords
hybrid electric vehicle, energy management, fuzzy compensator, internal combustion engine, electric motor

1. INTRODUCTION
Nowadays, Environmental pollutants exist in big cities and about 30 to 40 percent of these pollution are due to consumption of fossil fuels, hence Reduction of such pollutants is focused in the urban.

Since a large percent of fossil fuel is consumed by vehicles in big cities, many big automotive companies made great strides to deal with this problem, in which design and production of Hybrid Electric Vehicles can be referred. Hybrid Electric Vehicles use two or more sources of energy to drive the vehicle (at least combustion and an Electrical motor) and as a result gain the benefits of each source of energy during driving.

How the power is shared between sources of energy (namely Electric and internal combustion motors) while the vehicle is operating is called energy management strategy or control strategy of Hybrid Electric Vehicle. With appropriate energy management at each moment, maximum instantaneous efficiency can be achieved for the vehicle.

The power management controller determines the operation mode of both the electric motor and the ICE and the required torque from each driving system. The power management controller depends greatly on the state of charge (SOC) of the battery. The controller notice the battery SOC instantaneously to make sure that the battery has sufficient energy to run the electric motor. SOC estimation for batteries is discussed in many literatures (Singh et. al., 2004; Hamada et. al., 2011).

According to the hybrid configuration properties that involve nonlinear and time variant structure, it seems that fuzzy logic is the best choice among many present methods for solving the problem. In fact, fuzzy logic decision property in real time operations and power sharing between Electric and combustion motors can be used instead of using certain laws. In the other words, fuzzy logic controller is a modification of a normal regular controller. One of the main advantages of regular fuzzy methods is their robustness against imprecise measurements, component changes and also an adaptation of fuzzy law against variation of conditions.

In (Poursamad and Montazeri, 2008), a fuzzy compensator is designed and proposed for controlling the performance of combustion motor and the genetic algorithm is used to optimally tune the fuzzy controller. The results obtained from the mentioned research show that the fuel consumption and pollution production are decreased during drive cycle and the performance parameters are improved as possible.

In (Kheir et. al., 2004), the design of a fuzzy controller is dealt with in order to make a compromise between the simultaneous decrease in fuel consumption and NO_x pollutant in parallel Hybrid Electric Vehicles (HEVs). In (Schouten et. al., 2002), in order to have better power sharing between combustion and electrical sources in a parallel Hybrid Vehicle a fuzzy controller is designed for improving the performance of each component. In (Brahma et. al., 1999), a fuzzy control strategy is used with the aim to maximize the fuel efficiency in a Hybrid Electric Vehicle in which a regular fuzzy controller is applied to improve the energy management.

One of the best researchers performed in the field of fuzzy control on Hybrid Electric Vehicle is presented in (Won and Langari, 2002). The proposed fuzzy energy management is based on the concept of "environmental driving awareness". In fact, the rules data base of the proposed fuzzy distributor of the moment is to show technical information based on relation properties between the road trip, driving situation and the energy flow in the drive chain of Hybrid Electric Vehicle. In order to identify the road type, driver driving style, driving path, driving situation and different parameters of driving pattern characteristic must be extracted from the drive cycle. The main problem involved with this method is that it does not consider the efficiency of the drive chain components.

Totally, it can be deduced from the studies that the designed compensator must satisfy the following conditions:

1. Satisfy driver's moment and speed demand as possible.
2. Use from laws correspondent with the Hybrid Vehicles that lead to the minimization of vehicle environmental and economic costs.

Thus, in the present paper, not only the driver's present requested speed and moment are considered but also the instantaneous changes style of these two factors is considered which leads to take larger steps in order to minimize the driving cost.

The paper is organized as follows: in section 2 power-split Hybrid Vehicle is introduced. Then in section 3 Advisor simulator is briefly described. In section 4 fuzzy compensator is designed. In section 5 simulations are presented to verify the performance of the designed compensator. Finally, in section6 the conclusion is defined.

2. HYBRID ELECTRIC VEHICLES (HEV)

In Hybrid Electric Vehicles, series, parallel and power-split configurations are more common.

2.1 Power-split hybrid electric vehicles

Power-split configuration is connected through both moment and speed between these two motors and gains all benefits of two mentioned configurations.

In different conditions, this configuration can be applied in hybrid series or parallel structure such that at low speed it is purely electric with no pollution while in high speed it is dependently combustion or a combination of these two systems (Martel et. al., 2011).

Since power-split configuration is newer and also more complex, it can be investigated from different aspects of view and can be improved in term of performance.

There are three sources of energy in the power-split configuration: internal combustion motor, electric motor and generator. The required power for driving the wheels is shared between these sources through a power split device that is called a planetary gear set. The electric motor can be driven as a generator and charges the battery (Martel et. al., 2011).

3. ADVISOR SIMULATOR AND TOYOTA PRIUS MODEL

Advisor simulator is a tool for simulating a vehicle. This simulator is proposed in (ADVISOR, version 2003) and enables one to rapidly analysis the efficiency and fuel cost in ordinary, Electric and Hybrid Vehicles based on measured input-output relations of motive system components. The followings are some

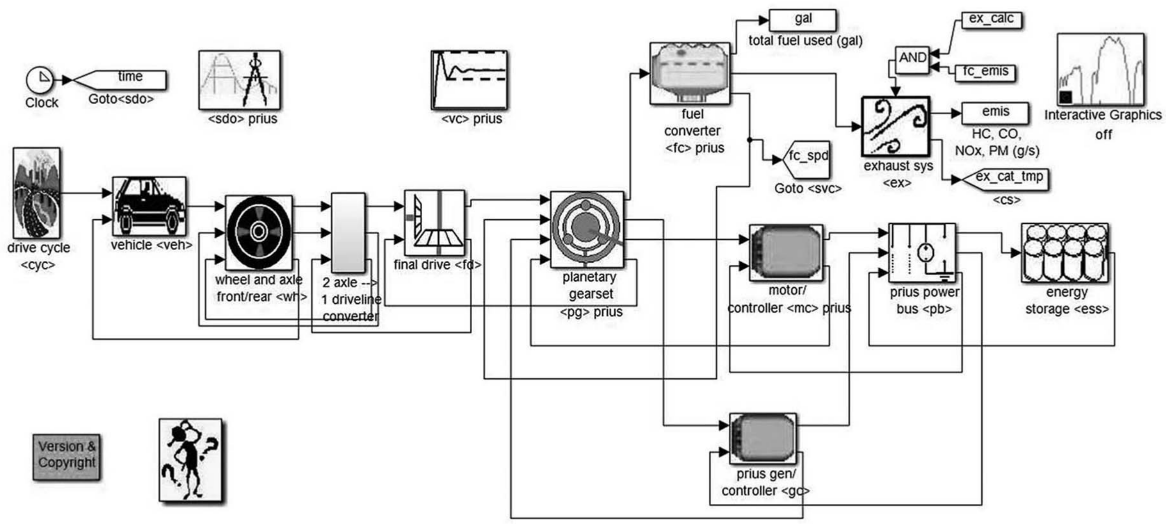

Fig. 1 Power-split hybrid electric vehicle model (ADVISOR, version 2003)

applications of Advisor simulator (Ozden, 2013):

1. Obtaining information about energy consumption and dissipation.
2. Evaluating energy management strategy in Hybrid Vehicle.
3. Investigating the approximate rate of pollutant dispersion in different conditions.
4. Evaluating the approximate amount of energy for traveling a path.

The model of power-split Hybrid Electric Vehicle in Advisor simulator is illustrated in Figure 1.
In this simulated environment, different tuning of vehicle such as type of vehicle that is used (ordinary, Electric, Series or Parallel or power-split Hybrid), drive cycle, test conditions and etc. can be performed. In the present study, power-split vehicle is tested.

3.1 Drive cycle

Drive cycle is a speed curve in term of time that is applied to demonstrate the driving pattern of a special vehicle and is used in a desired driving environment.

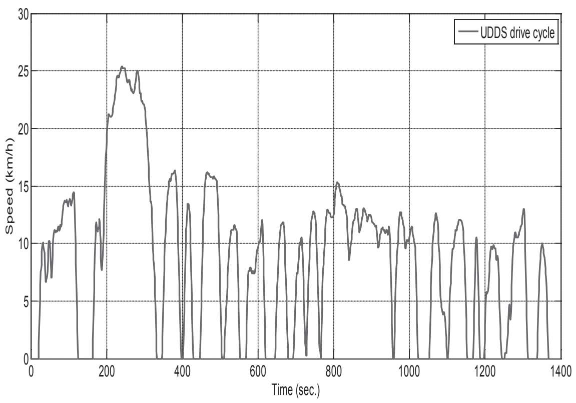

Fig. 2 Urban dynamometer driving schedule (UDDS) (ADVISOR, version 2003)

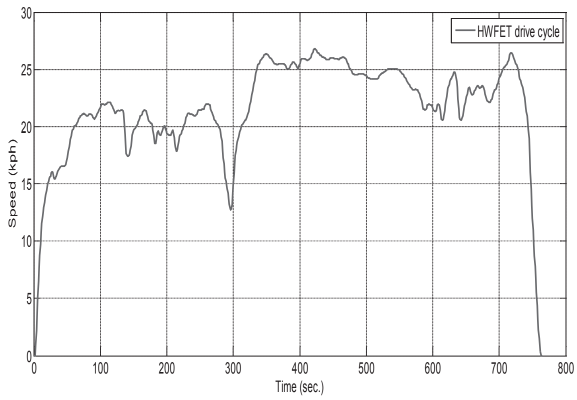

Fig. 3 Highway fuel economy test (HWFET) (ADVISOR, version 2003)

Table 1 Information of UDDS (ADVISOR, version 2003)

Time (s)	1369
Distance (km)	11.99
Maximum speed (km/h)	91.25
Medium speed (km/h)	31.51
Maximum acceleration (m/s2)	1.48
Minimum deceleration (m/s2)	-1.48
Mean acceleration (m/s2)	0.5
Mean deceleration (m/s2)	-0.58
Idle time (s)	259
Number of stops	17

Table 2 Information about HWFET (ADVISOR, version 2003)

Time (s)	765
Distance (km)	16.51
Maximum speed (km/h)	96.4
Medium speed (km/h)	77.58
Maximum acceleration (m/s2)	1.48
Minimum deceleration (m/s2)	-1.48
Mean acceleration (m/s2)	0.5
Mean deceleration (m/s2)	-0.58
Idle time (s)	6
Number of stops	1

The main goal of development of vehicles driving cycle is evaluation of fuel consumption and vehicle's pollutant using chassis dynamometer tests or simulations. Driving cycles used in this paper are UDDS (Urban Dynamometer Driving Schedule) and HWFET (Highway Fuel Economy Test) that are depicted in Figure 2 and Figure 3 respectively. The information about these cycles is presented in Table 1 and Table 2 respectively.

4. DESIGN OF FUZZY COMPENSATOR

In power-split Hybrid Electric Vehicles, a planetary gear set is used instead of a gear wheel system. This system provides the relation between sources of energy. The planetary gear set makes infinite gear relation possibilities. This system is composed of one solar-gear, some planetary gear and one annular gear. Rotation of solar and annular gears leads to rotation of planetary gears which are located between them. The planetary gear set shares the requested power of driver between sources of energy proportional with the relation of solar and annular gear teeth. Maximum efficiency of internal combustion motor, electric motor and generator is 39, 91 and 84 percent respectively.

According to the performance procedure of Hybrid Electric Vehicle and in order to better share the power between electric motor and internal combustion engine and with the aim of better braking energy recovery, a fuzzy compensator is used beside planetary gear set.

The driver requested braking force is proportional with driving safety. The value of the braking force denotes the proposed compensator input, present and previous moment requested speed and moment of differential from planetary gear set, and the instantaneous battery SOC.

Also, its outputs are the required change in the requested moment and speed of each source of energy involving internal combustion motor, eclectic motor and generator. At each moment, the compensator tunes the value of required speed and moment of each source of energy, according to the change trend of each requested speed and moment inputs and by considering the battery charge situation.

The value of braking force indicates the braking distance and the time in which the driver wants to stop the vehicle. The large requested braking force of driver denotes stopping a vehicle in a short time and distance. In this condition, it is needed to increase the generative force that is achieved from wheels. When the demand braking force of the driver is medium, it is required to fewer increase the generative force that is achieved from wheels and when the driver demand braking force is low, the generator must receive fewer force from wheels since the force loss value in wheels is low.

In the design of the compensator, Mamdani implication is used and for stating the membership function a Gaussian function is used. The vehicle speed has a main role in guaranteeing the braking safety and its effect must be considered in braking force.

When the vehicle is driven with low speed, the braking force must be low to provide vehicle safety. When the vehicle speed is medium, the braking force can be increased to some extent and when the vehicle speed is high, the braking force can be increased to a large value. In case where the vehicle speed is very high, force must be achieved from the wheels as possible. The membership function defined for speed is depicted in Figure 4. It is known that in Hybrid Electric Vehicle, at the starting up moment of the vehicle and when the speed is low, the electric motor drives the vehicle. In medium and high speed, internal combustion motor is used to steer the vehicle and at high speeds, both two motors play role in steering the vehicle.

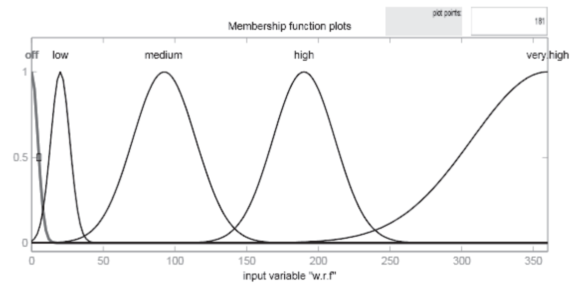

Fig. 4 Membership function defined for speed

When the SOC is very low, the battery is in critical point and only internal combustion motor must be used. In this case, eclectic motor by changing to the generator and the generator itself receive the force achieved from combustion motor and save it on battery. When the SOC is low, the above action is performed with less intensity. In this situation there is no need that the motor change to the generator and the required battery energy is provided by internal combustion motor through the generator. When the SOC is medium and the driving situation is normal, the battery does not need the force of internal combustion motor and only in case of demand braking force, battery is charged from the force achieved from the wheels. When the SOC is high, the energy saved in battery is also used for driving vehicles. Thus, in this paper, four cases of very low, low, medium and high are used to describe the battery charge situation.

In this control strategy, the different situations of driving are determined and the system performance is described for each of them. For example, in braking, this compensator helps the generator to receive more power from the wheels and save it on battery. The main condition for system is to provide the driver demand, according to present limitations. Thus, according to the driver demand different situations of HEV performance can be occurred that may be optimal or not.

At each level, according to the present demand for speed and the moment and the varied styles of speed and moment with respect to the previous case, the required change at demand speed and moment of each source of energy is determined.

5. SIMULATION

In this section, simulation of Toyota Prius vehicle is performed on the Advisor simulator to verify the performance of proposed compensator at each desired factor. Simulation results involve a comparison between the fuel consumption, SOC and the dispersion rate of each pollutant before and after applying the proposed compensators. As it was stated before, for studying the performance of proposed compensators, UDDS driving cycle, which is correspondent with the urban standard driving schedule and HWFET that is correspondent with highway standard driving cycle are used.

5.1 Costs in UDDS driving cycle

5.1.1 Vehicle fuel consumption

Now in this section, the role of the designed proportional-fuzzy compensator is investigated. The total fuel consumption of the system before and after applying the compensator is depicted in Figure 5. By calculating the surface under the curve of these two diagrams and by subtracting them, the real improved value of the fuel consumption can be achieved.

It can be seen that the proportional-fuzzy compensator reduces the fuel consumption to about 57.67 percent with respect to the case without compensator.

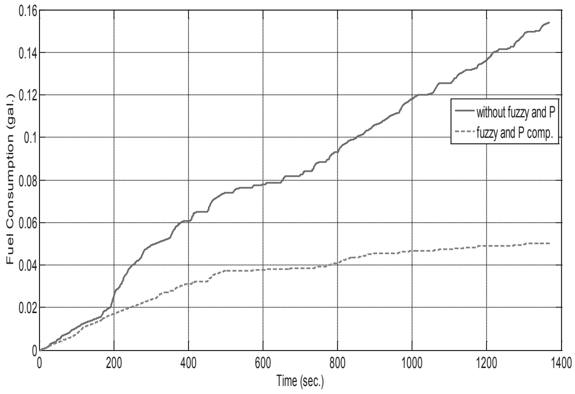

Fig. 5 Fuel consumption curve in the presence and absence of these two compensators

5.1.2 Battery state of charge

The variation of the battery charge situation is depicted in Figure 6. In this case the remained SOC of the vehicle at the end of the path has improved to about 25.04 percent.

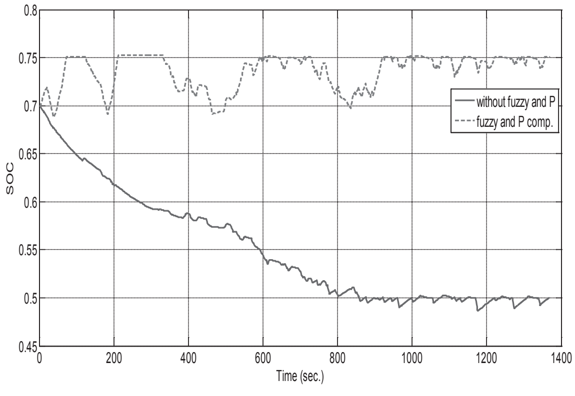

Fig. 6 Battery SOC curves in the presence and absence of the two compensators

5.1.3 Pollutant dispersion rate

It can be demonstrated that the dispersion values of HC, CO and NO_x pollutants in the presence of compensator have been decreased to about 17.22, 27.97 and 73.15 percent respectively.

5.2 Cost investigation in HWFET driving cycle

In this section, performance of proposed compensator is investigated in HWFET driving cycle. This is a standard driving cycle in highways.

5.2.1 Fuel consumption

The total fuel consumption of the system before and after applying the compensator is depicted in Figure 7. The upper and lower curves are corresponding with the fuel consumption in the absence and presence of compensator respectively. The decrease in the fuel consumption in the last moments can be clearly seen.

It can be seen that the fuel consumption can be reduced to about 59.05 percent using fuzzy and proportional compensators in comparison with the case without using these compensators.

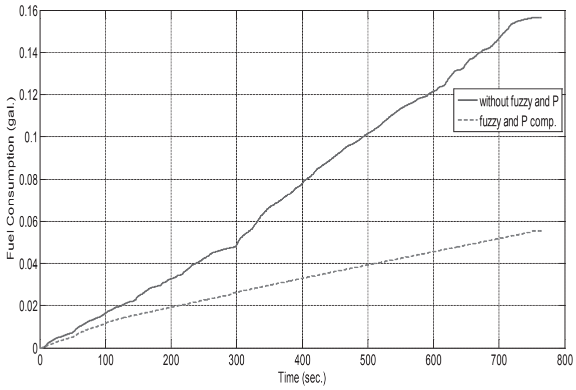

Fig. 7 Fuel consumption curve in the presence and absence of the two controllers

5.2.2 Battery charge situation

Figure 8 shows the variation trend of the battery charge situation. It is clear that by involving this compensator, SOC is in higher level in comparison with the previous case. The rest of the SOC is improved to the 18.44 percent at the end of the path.

5.2.3 Pollutant dispersion rate

It can be demonstrated that the dispersion values of HC, CO and NOx pollutants in the presence of compensator have been decreased to about 0.22, 22.14 and 72.97 percent respectively.

Table 3 deals with a comparison between the results

Table 3 Comparison between previous and present researches (improvement percentage)

	(Lee and sul, 1998)	(Poursamad and Montazeri, 2008)	Kheir et al., 2004)	(Schouten et al., 2002)	(Baumann et al., 2000)	(Syed et al., 2008)	(Zhou et al., 2013)	Presented research
Fuel consumption	-	1.75	14.9	6.8	12.4	3.5	56.16	57.67
SOC	-	-	-	50	-	-	-	33.73
HC pollutant	-	8.52	-	-	-	-	56.16	17.22
CO pollutant	-	-16.42	-	-	-	-	-	27.97
NO_X pollutant	20	30.76	28	-	-	-	-	73.15

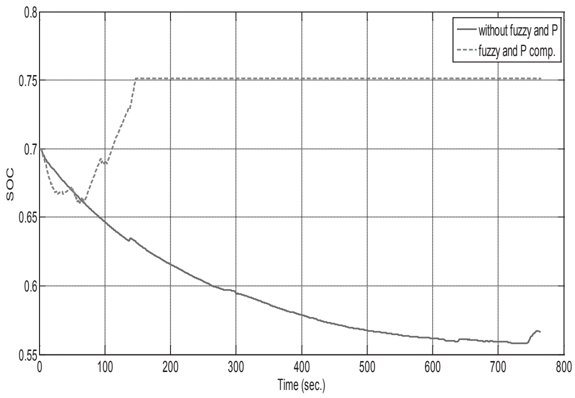

Fig. 8 SOC curves in the presence and absence of the two compensators

achieved from the present research with those obtained from previous researches. The presented results verify significant improvement of the proposed method.

7. CONCLUSION

In this paper, first a fuzzy compensator is designed for a power-split Hybrid Electric Vehicle. This compensator is used for better energy management. Then a proportional compensator applies to driver demand. The results obtained in the presence of compensator are compared with those obtained in the absence of these designed compensators. The goal of applying these compensators is to decrease the vehicle environmental and economic costs, namely the compensator rate of consumption, improvement of the battery charge situation and decrease of pollutant dispersion and as a result the presented results are achieved. The results show that applying decision property of fuzzy compensator leads to a reduction in the system cost and achievement of desired goals.

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