Intelligent Energy Management Strategy for a Separated-Axle Parallel Hybrid Electric Vehicle

Naser Fallahi[1] and Abolfazl Halvaei Niasar[2]

[1]Faculty of Electrical & Computer Engineering, University of Kashan, Kashan, Iran.
naserfallahi87@yahoo.com

[1,2]Faculty of Electrical & Computer Engineering, University of Kashan, Kashan, Iran.
halvaei@kashanu.ac.ir

Abstract:

Hybrid electric vehicles (HEV) in addition to provide the benefits of electric vehicles could satisfy consumers for some performances of conventional internal combustion engine (ICE) vehicles such as acceleration and long range. On this way, suitable energy optimization strategies should be employed to get desired efficiency, less fuel consumption and pollution. One of the favorite and simple configurations of HEVs is a parallel type. A student team at University of Kashan, IRAN have designed and manufactured Shaheb 2 hybrid electric vehicle. It is a separated-axle (or Through-to-Road (TTR)) parallel HEV type based on Pride platform. Employed energy management in Shaheb 2 is on/off strategy and three modes; motor, engine and hybrid have been implemented. This paper investigates the modeling of separated-axle (or TTR) parallel type of HEV in ADVISOR software and then evaluates two control strategies for Shaheb 2; on/off strategy and an intelligent control based on fuzzy logic. On this way, maximizing the engine is considered as an objective function. The simulation results indicate that the fuzzy strategy leads to less fuel consumption and lower pollution for given UDDS driving cycle rather than on/off strategy for Shaheb 2.

Keywords: Intelligent control, fuzzy, hybrid electric vehicle, separated-axle, on/off strategy, ADVISOR, Shaheb 2.

1. INTRODUCTION

The uncertainties of petroleum supply and concerns over global warming call for further advancement of green vehicles with higher energy efficiency and lower green house gas (GHG) emissions. Hybrid Electric Vehicle (HEV) technology plays an important role among various hybrid vehicle technologies, which utilize electric drives and innovative transmissions to improve overall energy efficiency, resulting lower fuel consumption than the conventional vehicles [1].
A hybrid electric vehicle can be classified as micro, mild, and full hybrid. Increase in hybridization generally allows better fuel efficiency improvement. There are different hybrid configurations currently proposed by vehicle manufacturers, which can be categorized into four types: series, parallel, series-parallel and combined hybrid [2]. Each type has got advantages and disadvantages. The use of advanced control strategies, along with advances in energy storage, may make more highly efficient and adaptive hybrids possibilities [3,4].
Among different hybrid types, two generally accepted classifications are series and parallel. While the series configuration is efficient for large energy demands, the parallel hybrid is more suitable satisfying high road power demands. Depending on the position and variety of the transmission system, there can be four parallel HEV architectures: pre-transmission, post-transmission, CVT, and separated-transmission (axle) hybrid [5].
The higher cost of HEVs rather than conventional ICEs, has limited their public uses. The total cost of HEV depends on the type of HEV. Complex types such as series-parallel HEV leads to high cost, whereas some architecture of parallel types such as separated-axle parallel are simpler and have lower cost. In a separated-axle parallel hybrid vehicle, the ICE and the electric motor can separately provide the propulsion force through the separated axles. Actually, each ICE vehicle can be converted to separated-axle HEV with some modifications [2,6]. Fig. 1 shows a block diagram for separated-axle parallel hybrid vehicle. Four-wheeling operation of them is one of the scarce characteristics of these vehicles.

[1] Submission date: 25 , 11. , 2012
Acceptance date: 05 , 11 , 2013
Corresponding author: Electrical Engineering Department- University of Kashan - Kashan - Iran

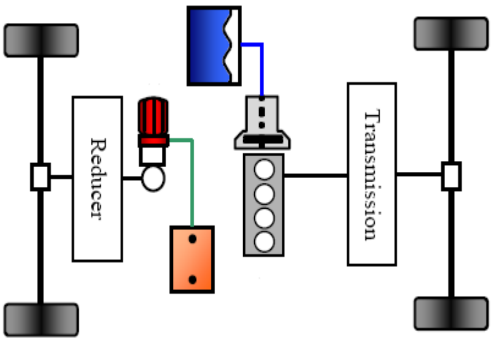

Fig. 1. Block diagram of a separated-axle parallel HEV

In order to decrease the energy consumption and emissions and increase the efficiency in HEV, energy management concepts must be implemented. Energy management strategies in HEVs have different types. On/off strategy, dynamic programming, fuzzy approach and neural networks are popular strategies that have been used in HEVs [3].
This paper, presents the design methodology for optimized energy management of Shaheb 2 vehicle manufactured at university of Kashan [7,8]. In section 2 a brief description of separated-axle of HEV and the specifications of Shaheb 2 is presented. The modeling of Shaheb 2 in ADVISOR is investigated in section 3. The energy management strategies of Shaheb 2 are presented in section 4 and finally in section 5, the simulation results in ADVISOR are given.

2. Illustration of Separated-Axle Parallel HEV

Separated-axle parallel HEV that named Through-the-Road (TTR) vehicle, similar to majority of configurations, uses two propulsion systems. Main difference between them is that the propulsion systems are acting separately. Electrical propulsion system is including battery, electric motor, voltage bus and electrical accessories and it is connected to rear axle. Mechanical propulsion system is divided to fuel converter, clutch and mechanical accessories and is linked to front axle. Because of linking electric Motor to rear axle, Transmitting of conventional vehicles to a TTR type is very simple.
The separated axle architecture offers some of the advantages of a conventional vehicle. It keeps the original engine and transmission unaltered and adds an electrical traction system on the other axle. It is also a four-wheel drive, which improves the traction on slippery roads and reduces the tractive effort on a single tire. The structure of this vehicle in lack of generator and some accessories is simple. Conventional vehicles can be converted to a HEV easily. However, electric machines and the eventual differential gear system occupy a lot of space and may reduce the available passenger space and luggage space. This problem may be solved if the transmission behind the electric motor is single-gear and the single electric motor is replaced by two small-sized electric motors that can be placed within the two in-wheel motors. Moreover, the batteries cannot be charged from the engine when the vehicle is at a standstill [9].
Fig. 2 shows the direction of power flow in this type of HEV. In the electric part, delivery power circulates from battery to electric motor and then to rear axle. In the mechanical part, power transmits from fuel converter to engine and engine delivers the power to front axle. Developed power of electrical and mechanical parts is controlled via hybrid control unit (HCU).
A student team of electrical and mechanical departments from University of Kashan have manufactured a separated-axle parallel HEV named Shaheb 2. Fig. 3 shows the vehicle and the student team.

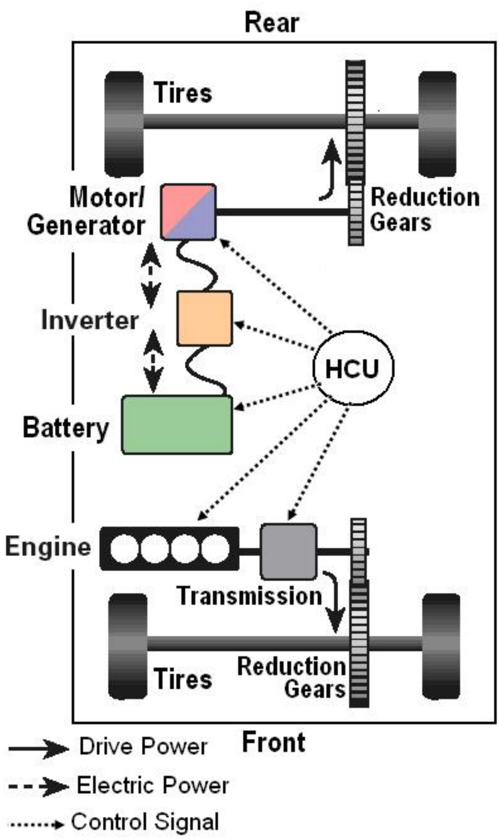

Fig. 2. Power flow in separated-axle HEV

Fig. 3. Shaheb 2 student team at university of Kashan

The employed conventional vehicle in this project is Pride 132 manufactured by Saipa Company in Kashan. Engine and its components are located on the front axle. Due to some technical and time limitations, few minor modifications have been carried out just in engine control unit (ECU); and ECU is in connection with HCU. One electric motor, inverter and battery pack are located on the rear axle as shown its schematic in Fig. 4. Some specifications of electrical and mechanical parts of Shaheb 2 are summarized in tables (1) and (2).

Table (1) Vehicle and engine technical data of Shaheb 2

Engine Technical Data	Value
Engine rated power	45 [kW]
Maximum speed in electrical mode	100 [Km/h]
Range in electrical mode	25 [Km]
Grade ability	%45
Acceleration (0-400 m)	18 [Sec]

Table (2) Electrical technical data of Shaheb 2

Component	Value
Electric motor power	22 [kW] @ 3000 [rpm]
Nominal voltage	144 [V]
DC-bus voltage	192 [V]
Maximum speed	6000 [rpm]
Rated torque	75 [N.M]
Efficiency	%95
Inverter power	45 [kVA]
Inverter hardware	DSP TMS320LF2407A
Control Scheme	Space phasor vector controlled
Battery type	Lithium-ion polymer
Battery cell voltage	14.8 [V]
Battery Nominal Cap.	10500 [mAh]

Fig. 4. The schematic of rear-axle in Shaheb 2

3. Modeling of Separated-Axle Parallel HEV in ADVISOR

In order to increase the efficiency and accuracy of automotive design, Computer Aided Engineering (CAE) has been playing an ever increasing role throughout the process of vehicle design. ADVISOR has been developed by the Argonne National Laboratory (ANL) in order to evaluate the energy efficiencies of the hybrid electric vehicle [10]. The model of Shaheb 2 vehicle has been developed in ADVISOR. The model of this vehicle is not in the library; however it can be possible to modify the model of parallel scheme. On this way, the torque coupler from parallel scheme is eliminated and a gearbox is added to electric path. Developed model of separated-axle HEVs ADVISOR is shown in Fig. 5.

4. Energy Management Strategy in Separated-Axle Parallel HEV

Some control strategies have been proposed and implemented to control parallel hybrid powertrain, such as: optimizing the battery SOC (Maximum Vehicle Range control) [2,3,11,12,13]. The ‘Thermostat’ or ‘On/Off’ or ‘Bang-Bang’ control is another control technique. It was developed initially for a series hybrid drivetrain and was later extended to the power flow control in a parallel HEV [10,14]. The engine load-leveling control algorithm is arguably the most popular power distribution algorithm to control parallel hybrid powertrains. The idea of load-leveling is to force the engine to act at or near its peak point of efficiency or its best fuel use at all times [10]. In this paper, traditional on /off control as well as fuzzy approaches have been applied for energy management of Shaheb 2 vehicle [3].

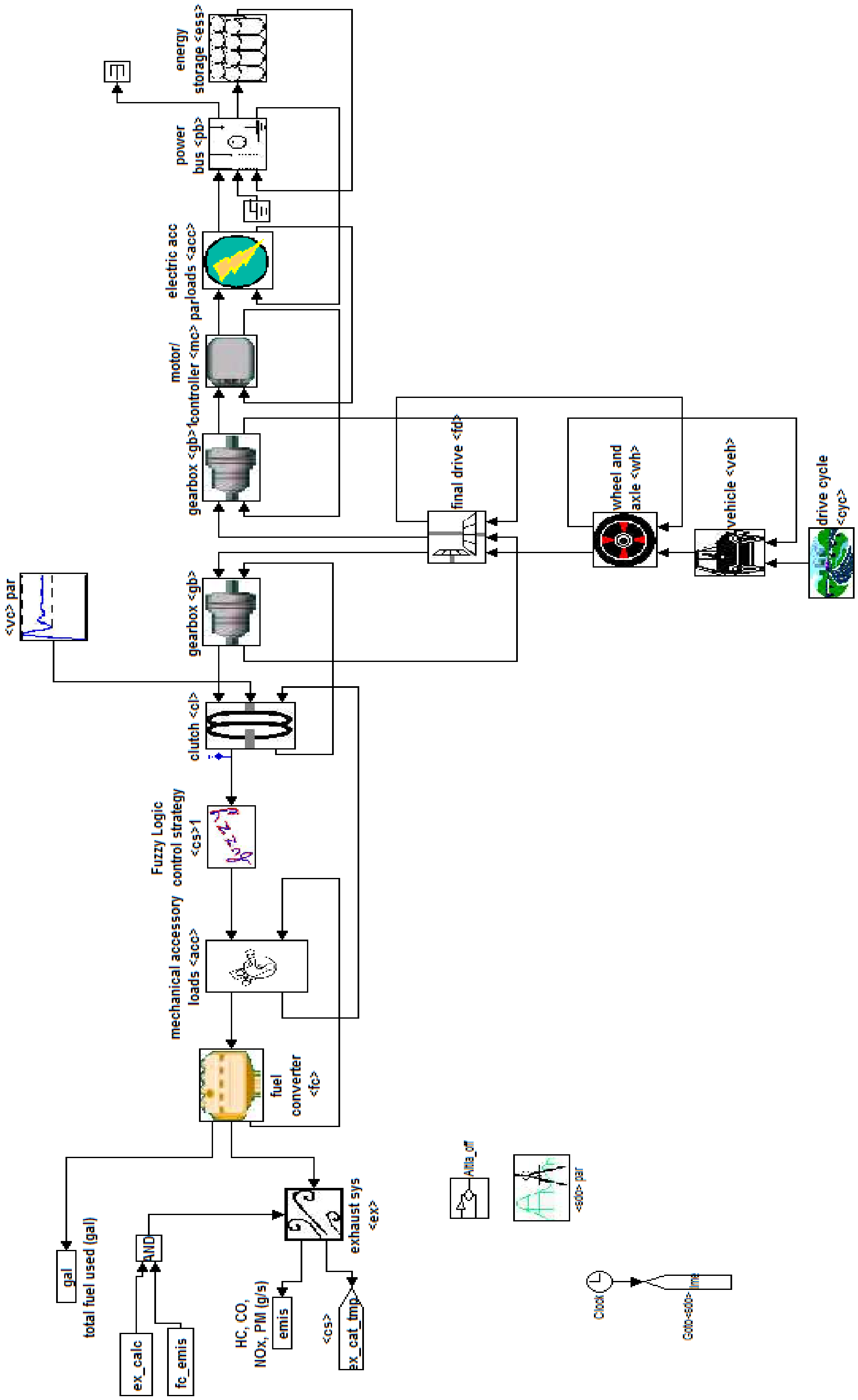

Fig. 5. The model of separated-axle parallel HEV in ADVISOR

In on/off control strategy, the below factors should be determined: launch speed, minimum torque of engine, the battery's state of charge (SOC) and maximum envelope torque of engine. The vehicle acts according to launch speed. If requested speed of vehicle be greater than launch speed, on/off strategy act in 3 modes as: "only engine", "only motor" and "hybrid mode". If requested speed was lower than launch speed, "only engine" or "only motor" modes are available. Fig. 6 and Fig. 7 show the operation modes in on/off strategy.

In Fig. 6, if requested torque be greater than maximum torque envelope the "hybrid mode" will be employed. The operation areas for engine and motor, depends on SOC rate as presented in the figure. In Fig. 7 the SOC of battery is too low to produce any torque for vehicle. So, the engine must provide requested torque and prepare battery to work in next cycles.

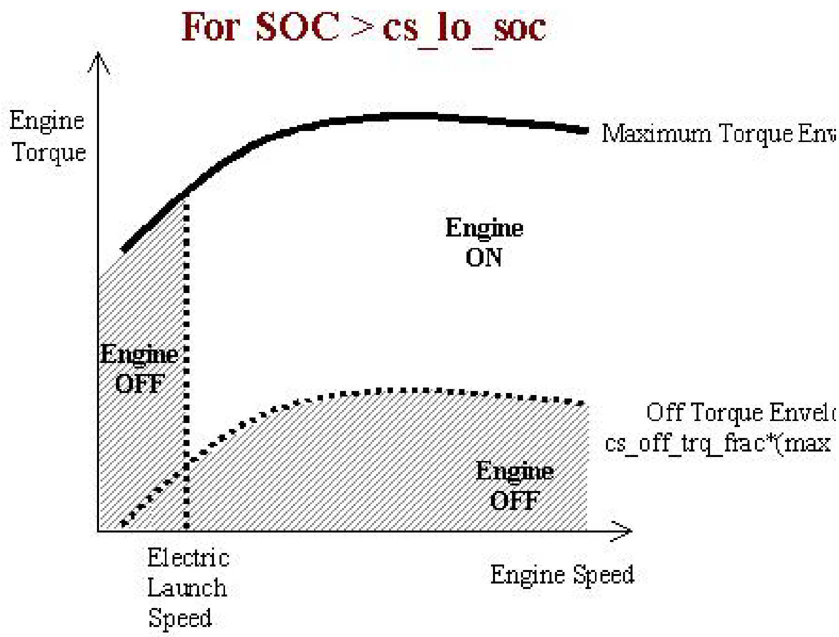

Fig. 6. Operation area for engine and motor in SOC>cs_lo_soc (control strategy_low_SOC)

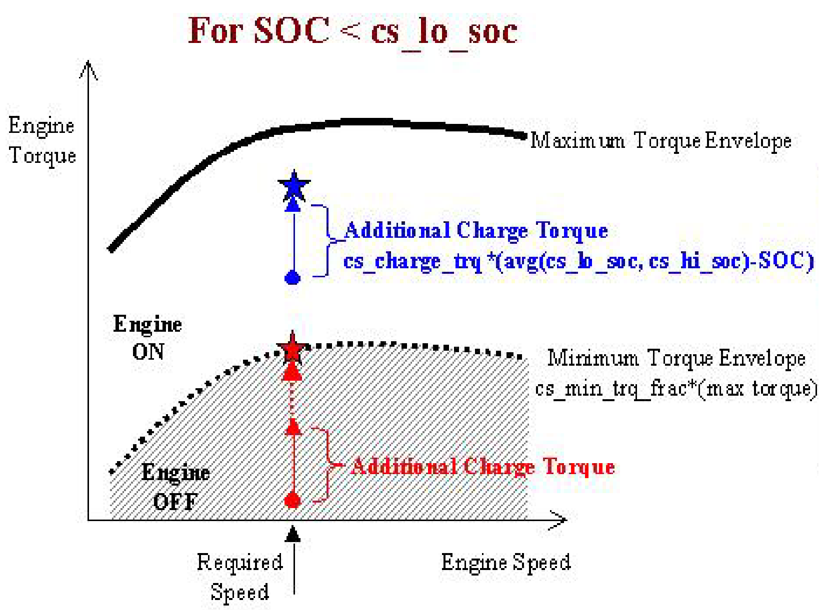

Fig. 7. Operation areas for engine and motor in SOC<cs_lo_soc

Hence, the requested torque is sum of requested torque for driving vehicle and additional torque to charging battery. If the torque be lower than minimum torque envelope, engine acts on minimum torque envelope.

In fuzzy approach, when engine is on, by considering to objective function, optimum points for engine will be determined and ADVISOR can simulate vehicle. Fuzzy approach in ADVISOR, according to their objective functions is divided to three modes:

- Maximum efficiency engine mode: in this mode, the objective is achieving to maximum efficiency for engine.
- Minimum fuel consumption: by marking operating points on torque-speed, it can reduce fuel consumption. Determination of optimum points to decrease fuel consumption is main objective in this mode.
- Minimum emissions: in this mode, the value for emission has to be specified and vehicle act according to this values.

5. Simulation Results

For simulation of Shaheb 2, on/off and fuzzy approaches are employed in ADVISOR. UDDS (Urban Dynamometer Driving Schedule) driving cycle that is known as city driving cycle is used in ADVISOR. In this simulation, fuzzy approach in engine efficiency mode as energy management strategy has been performed. The results of fuel consumption and emissions and SOC are studied. Fig. 8 shows UDDS driving cycle. In order to simulate the vehicle via fuzzy approach; UDDS driving cycle characteristics is presented in table 3.

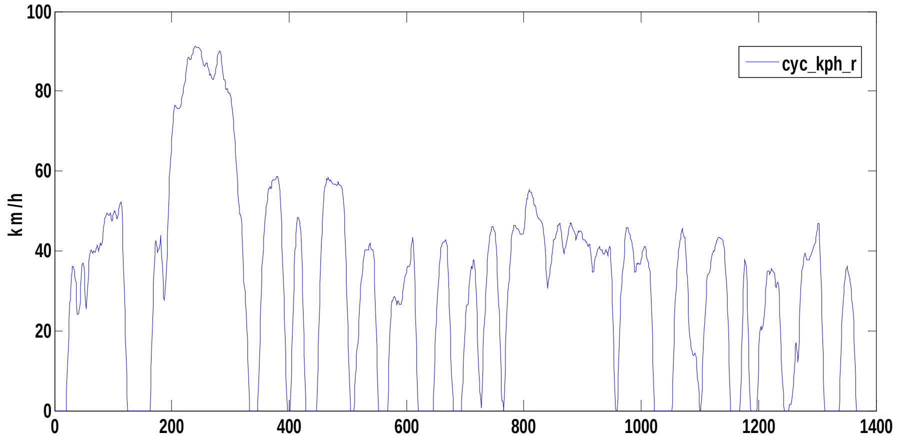

Fig. 8. UDDS driving cycle in ADVISOR

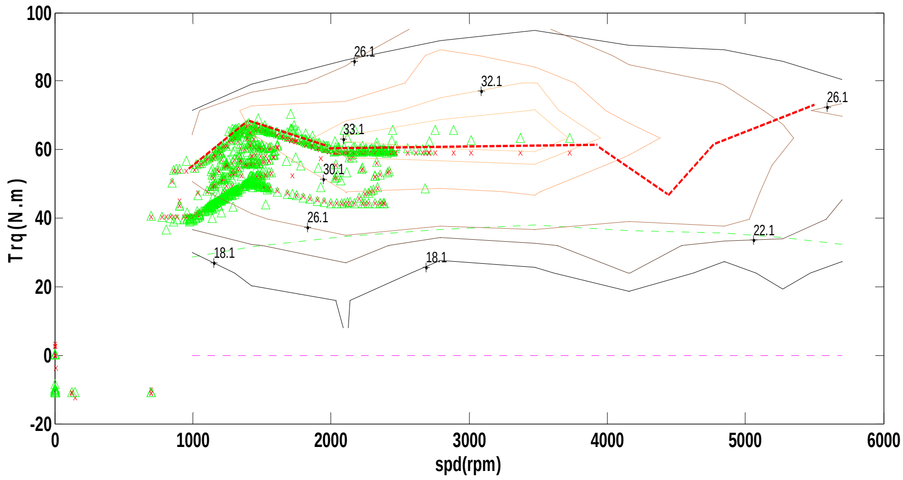

Fig. 9. Engine energy efficiency map

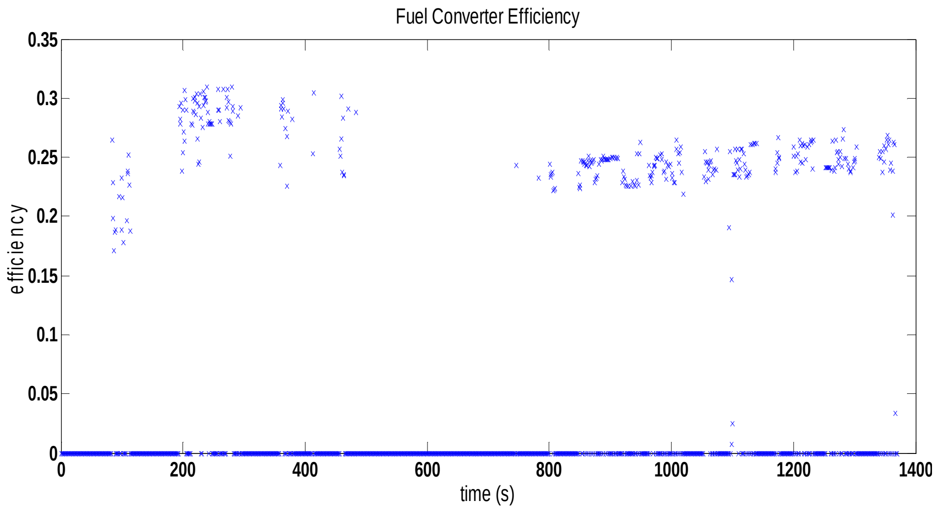

Fig. 10. Fuel converter efficiency via on/off strategy

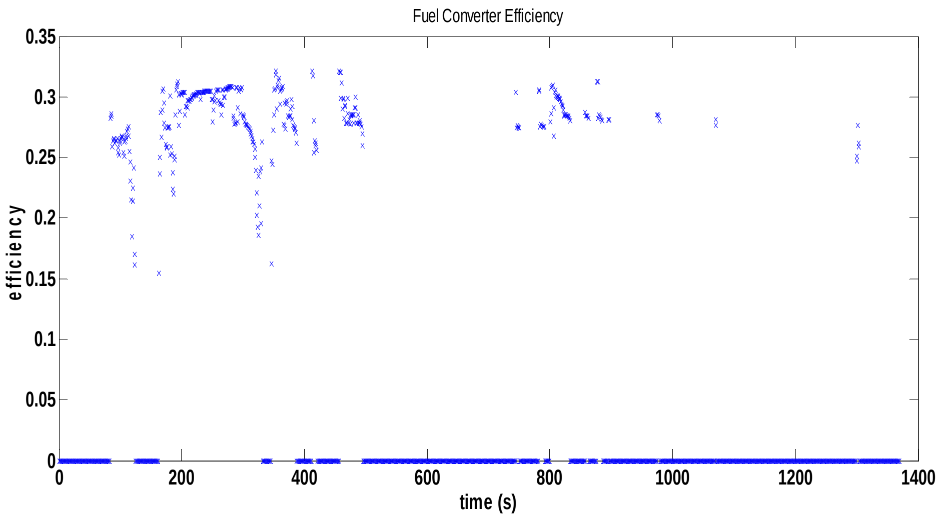

Fig. 11. Fuel converter efficiency via fuzzy approach

Table (3) Characteristics of UDDS cycle

UDDS characteristics	value
time	1369 [Sec]
distance	11.99 [km]
Max speed	91.25 [km/h]
Avg speed	31.51 [km/h]
Maximum acceleration	1.48 [m/Sec2]
Maximum Deceleration	-1.48 [m/Sec2]
Average acceleration	0.5 [m/Sec2]
Average deceleration	-0.58 [m/Sec2]
No. of stops	17

At first the optimized points on torque – speed characteristics of engine must be determined (shown in Fig. 9), Fuzzy control scheme forces the majority of operating points to be in vicinity of the highest point of efficiency.

Fuel converter efficiency for both two strategies has been presented in Fig. 10 and Fig. 11. It should be noted that the efficiency of fuel converter in fuzzy approach is more than on/off strategy and its average is about %27.

The battery's state of charge (SOC) in fuzzy approach and on/off strategy has been shown in Fig. 12 and Fig. 13. Via fuzzy approach, SOC is between 0.78 and 0.28. However via on/off control strategy, SOC vanishes to 0.2.

At the end of cycle, the vehicle consumes about 0.5 liter per cycle. In Fig. 15, the value of fuel consumption increases continuously. At the end of cycle, the fuel consumption is about 0.45 liter per cycle and the rate of consumption in fig15 is constant approximately.

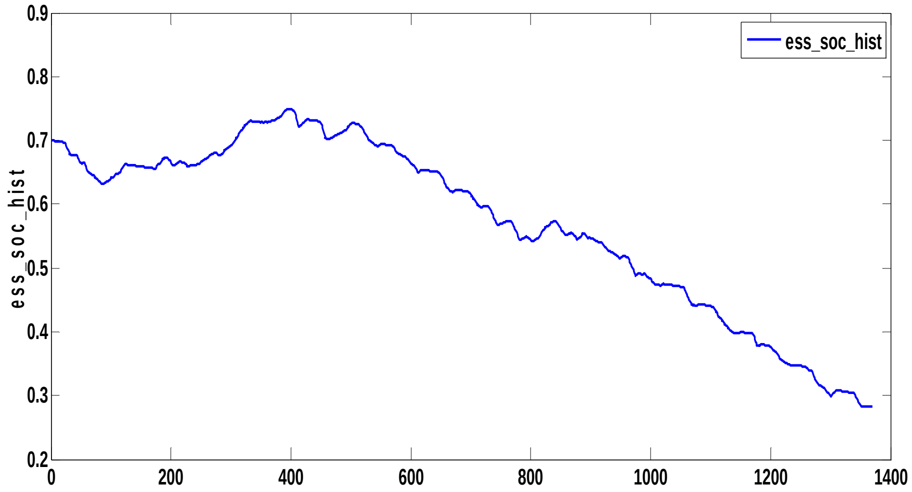

Fig. 12. SOC of battery via fuzzy approach control
(Energy storage system_SOC_histogram)

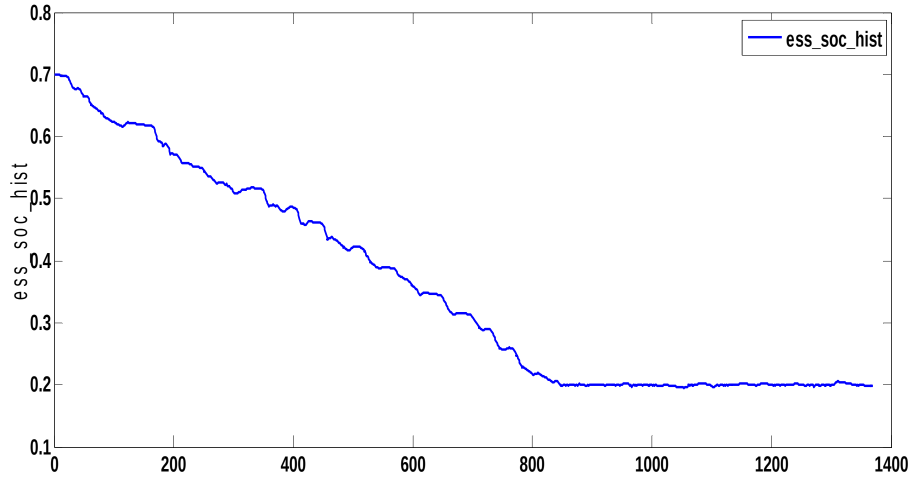

Fig.13. SOC of battery via on/off strategy

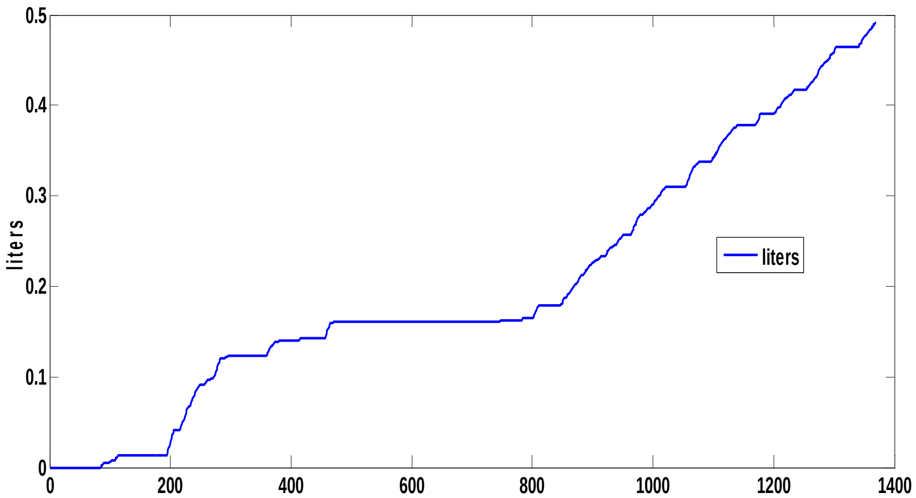

Fig. 14. Fuel consumption in UDDS cycle via on/off strategy

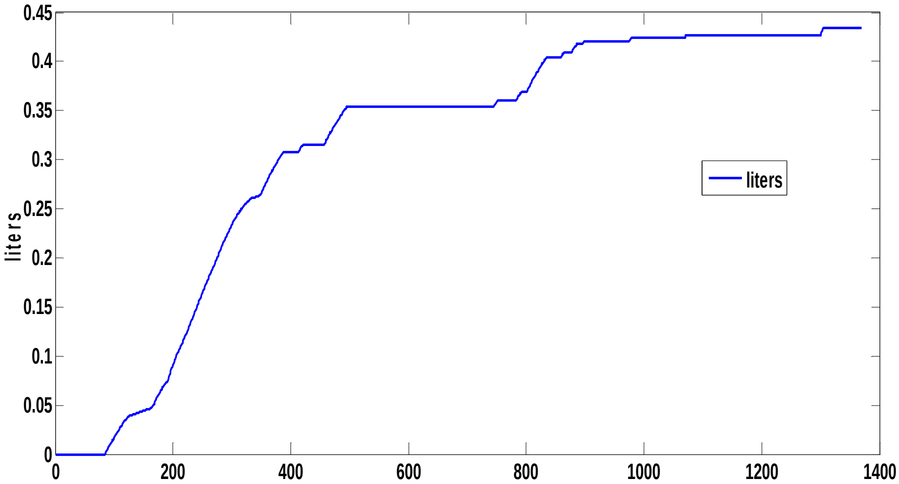

Fig. 15. Fuel consumption in UDDS cycle via fuzzy approach

Fig. 16 shows the torque of the motor via on/off strategy. It’s noted that in Fig. 16 after 800 sec, the motor is employed in negative torque more than last times. The reason is more requirements charging after 800 sec. The motor acts as a generator to charge the batteries.

Fig. 17 and Fig. 18 show the emissions of CO and HC via on/off and fuzzy strategies. The emissions depend on two factors: requested torque of engine and quality of engine operation. It is expected that the emissions via fuzzy approach to be lower than on/off strategy. The overall values have been presented in table (4). For given driving cycle with higher requested torque, the results of fuzzy approach is more suitable and engine provides the requested power and it can operate in optimized points.

From table (4), the fuel consumption in on/off strategy is about 4.1 liters/Km and this value for fuzzy approach is about 3.6. Table (5) compares the performance characteristics of Shaheb 2 in fuzzy approach and on/off strategy. In this simulation, launch speed via every two approaches is considered as 12.5 m/s or 45 Km/h.

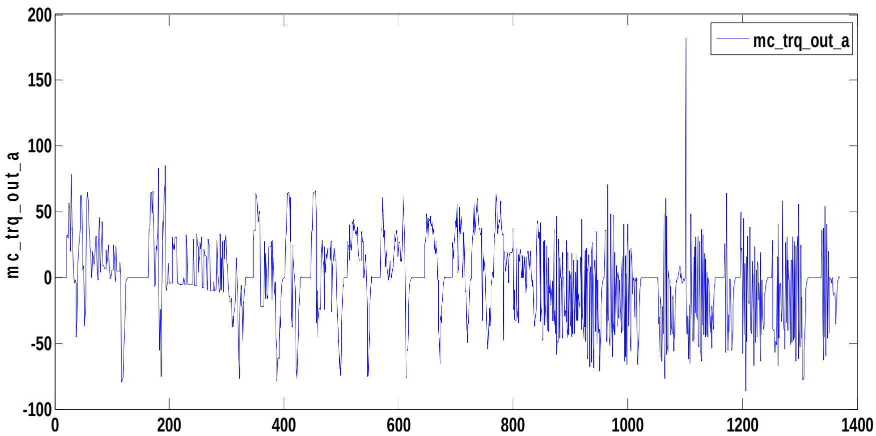

Fig.16. Torque of the motor via on/off strategy

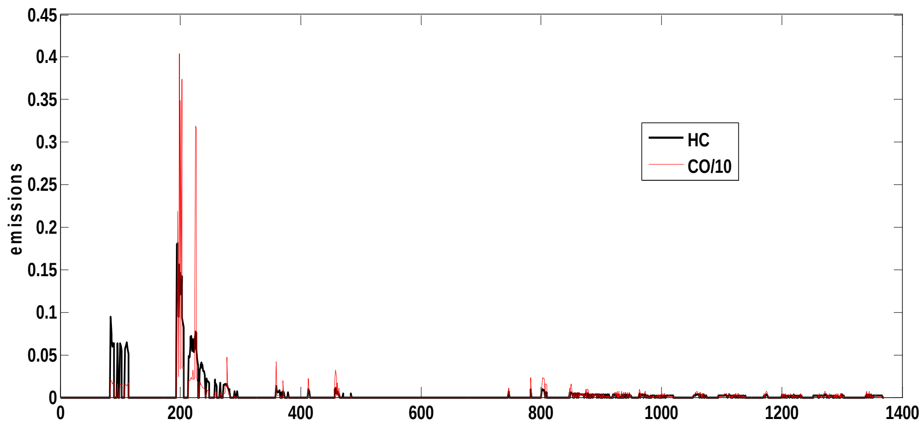

Fig. 17. Emissions in UDDS cycle via on/off strategy

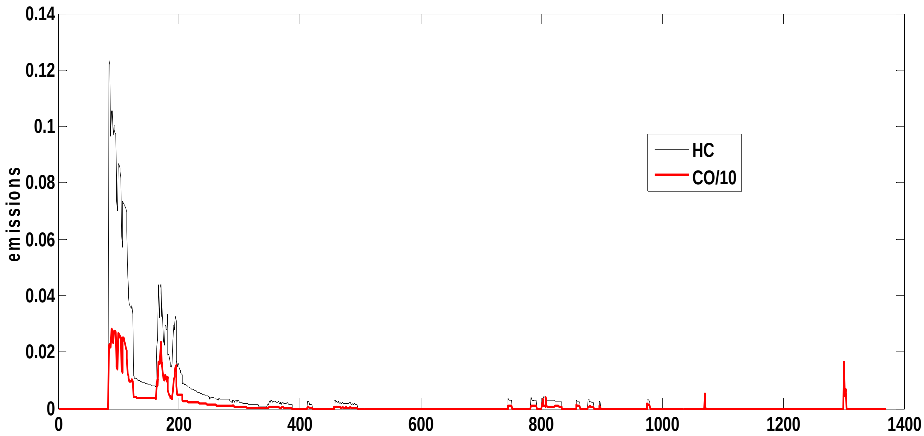

Fig. 18. Emissions in UDDS cycle via fuzzy approach

Table (4) Emissions and fuel consumption results

Control strategy	Fuel Economy (L/100km)	CO Emission (g/km)	HC Emission (g/km)	NOx Emission (g/km)
On/off	4.1	3.954	0.426	0.372
Fuzzy	3.6	1.397	0.448	0.364

Table (5) Performance characteristics results

Control strategy	Time 0-100 km	Distance in 5s	Time in 400m	Max speed (kmph)
On/off	10	50.6	17.2	179.7
Fuzzy	11.1	51.1	17.7	169

Experimental results in on/off strategy shows that time elapsed distance in 400 meter is 18 sec. and maximum speed is 175 Km per hours which indicates on simulation accuracies.

6. Conclusions

In this paper the comparison results of two energy management methods; on/off strategy and fuzzy approach for TTR parallel HEV Shaheb 2 has been presented. Fuzzy controller optimizes the energy flow, and performance of engine. The engine can operate in its optimum points and the emission in this strategy is lower than on/off. For given driving cycle, when the engine is on, the delivered torque corresponding to optimized points, is higher than the requested torque from driver and it is an opportunity for battery to be charged. So, the engine operates in optimum points; fuel consumption has been improved 12.1% than on/off strategy; the emission is low at the end of cycle; and SOC of battery has been reserved 16.1% rather than other techniques. In on/off strategy engine can't act in its optimum points. So, the emission is higher than fuzzy approach. Because of high launch speed in this scheme, the SOC depletion has been performed immediately and it's not any chance for engine to work at optimized points. Due to more freedom operation of engine in on/off strategy, the results of performance characteristics especially in acceleration for on/off strategy is more desirable than fuzzy approach. In fuzzy approach the engine is enforced to operate in vicinity of optimum points and max speed and other requirements in this approach is lower than on/off strategy's value. For future works, for implementing the fuzzy strategy, instead of engine efficiency cost function, multi-objective cost function such as engine efficiency/ minimum fuel consumption can be considered.

Acknowledgment
The authors are grateful to University of Kashan for supporting this work by Grant No. 52971.

References

[1] M. Ehsani, Y. Gao; A. Emadi; "Modern Electric,Hybrid Electric,and Fuel cells Vehicle fundamental, theory, and design", CRC, 2003, second edition.
[2] F. Salmasi, "Designing control strategies for hybrid electric vehicles," IASTED International Conference on Applied Simulation and Modeling, June 2005.
[3] X. Zhang, C. Mi, "Vehicle power management modeling, control and optimization", SPRINGER, 2010.
[4] A. Hajizadeh, "Intelligent Control Strategy of Fuel Cell Hybrid Vehicles," Intelligent Systems in Electrical Engineering Journal, Vol. 2, No. 2, pp.55-66, 2011, (in Persian).
[5] A. Halvaei Niasar, H. Moghbelli, A. Vahedi; "Design Methodology of Drive Train for a Series-Parallel Hybrid Electric Vehicle (SP-HEV) and its Power Flow Control Strategy", IEEE International Electric Machines and Drives Conference (IEMDC), Texas, USA, 2005, pp. 1549-1554.
[6] J. C. Mathews, K. J. Walp, G.M. Molen, "Development and Implementation of a Control System for a Parallel Hybrid Powertrain," IEEE Vehicle Power and Propulsion Conference, VPPC '06, pp. 1-6, 2006.
[7] S. Golabi, A. Halvaei Niasar; "Design and Manufacturing of Hybrid Electric Vehicle Pride at University of Kashan, Part 1: Mechanical sub-system", EVSD1390, Tehran, Iran (in Persian).
[8] A. Halvaei Niasar, S. Golabi; "Design and Manufacturing of Hybrid Electric Vehicle Pride at University of Kashan, Part 2: Electrical sub-system", EVSD1390, Tehran, (in Persian).
[9] www.nrel.gov/transportation/analysis
[10] M. Ehsani, Y. Gao, S. E. Gay, and A. Emadi, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design, Washington D.C.: CRC Press, 2004.
[11] B. M. Baumann, G. Washington, B. C. Glenn, and G. Rizzoni, "Mechatronic design and control of hybrid electric vehicles," IEEE/ASME Trans. Mechatronics, Vol. 5, No. 1, pp. 58-72, March 2000.
[12] H. Wallentowitz, R. Ludes, "System control application for hybrid vehicles," Proc. 3rd IEEE Conference Control Applications, Vol. 1, No. 2, pp. 639-650, August 1994.
[13] C. Liang, W. Qingnian, L. Youde, M. Zhimin, Z. Ziliang, and L. Di, "Study of the electronic control strategy for the power train of hybrid electric vehicle," Proc. of IEEE International Vehicle Electronics Conference, Vol. 1, No. 4, pp. 383-386, September 1999.
[14] Z. Rahman, K. L. Butler, and M. Ehsani, "A comparison study between two parallel hybrid control concepts," SAE 2000 World Congress, SAE Paper No. 2000-01-0994.

Abbreviations
cs_lo_soc: control strategy_low_SOC
cs_off_trq_frac:control strategy_off_torque_fraction
cs_min_trq_frac: control strategy_minimum_torque_fraction
cyc_kph_r: driving cycle_ kilometer per hour_requested
ess_Soc_hist: Energy storage system_SOC_histogram
mc_trq_out_a:motor/controller_torque_out_achieved