NEDC Based Compensated Forward Simulation Approach with Energy Management for Parallel Hybrid Electric Vehicles

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Abstract

This paper presents the power management strategy for a parallel hybrid electric vehicle (PHEV). The vehicle is powered by dual energy sources consisting of internal combustion engine (IC engine) as the peak power source and the electric battery as the secondary energy source. The operational principle of the power management strategy and the possible power flow patterns are described. Based on the power flow and energy availability of the energy sources, the decision making and the relevant switching function are designed to facilitate the effective power sharing between the two sources. The standard New European Driving Cycle (NEDC) velocity profile has been utilized via a suitable compensator that feed the data into the forward mathematical model. The obtained results indicated the strengths of such a hybrid topology.

Nomenclature and abbreviations

$V(t)$	-Velocity of the vehicle (m/s)
$F(t)$	-Load force (N)
M	-Weight of the vehicle (kg)
R	-Radius of the wheel (m)
$\omega(t)$	-Angular velocity of the wheel (rad/s)
g	-Gravity (m/s^2)
$u(t)$	-Ground wind velocity (m/s)
$\alpha(t)$	-Angle of inclination
$\beta(t)$	-the heading angle of the vehicle related to Ground wind
ρ	-Density of the air (kg/m^3)
A_f	-frontal projected area of the vehicle (m^2)
C_d	-Aerodynamic drag coefficient of the vehicle
f_r	-Tire friction
SoC_n	- Nominal State of charge of the battery
$P_L(t)$	- Load power of the vehicle (W)
$P_{EM}(t)$	- Output power of the electric motor (W)
$P_{ICE}(t)$	- Output power of the IC engine (W)

I. Introduction

The field of automotive engineering is undergoing the largest globalization ever in the history. It addresses the necessity of the transportation to the mankind. Since the availability of the energy resources are limited to fulfill the future requirement and also it is producing more unwanted materials to the environment, there is a huge demand for the energy management techniques in automobiles. With the intention of providing the feasible solution to the above, many researches are proceeding to investigate the key causes which are highly influence the power train performance in automobile. Moreover few of them are mainly focusing to identify the alternative energy resources, which can be used in automobile.

The mentioned cause's results to evolve the next generation technology called hybrid electric technology in the automotive industry to enhance fuel economy compared with the conventional IC engine. Moreover the study of hybrid electric vehicle (HEV) is under research since 1970 and many researchers have been engaged to increase the performance of the system [1]. However, the technology is not matured and still in the growing stage, there are potential areas to explore to improve the performance of the system.

Mainly hybrid vehicles are powered by multiple energy sources, the power and energy management techniques are playing the major role in hybrid vehicles [3].

The energy management in hybrid vehicles can be used to store the energy generated at one operating condition and then supplement the accumulated energy at a different operating condition [8]. While the vehicle is accelerating, it requires more power to create the inertia and when it navigates with a constant velocity it requires the power, which is equal to overcome the external resistance. So as the common strategy to improve the fuel efficiency in hybrid vehicle is to downsize the peak power rating of the primary energy sources. The instantaneously increasing load power demand would be supplemented by the secondary power resource. Similarly when the vehicle is decelerating the created kinetic and potential energy of the vehicle would be converted and stored as the chemical energy in the battery for the future usage.

Even though the concept is appearing promising and easy to implement, the challenging part of the hybridisation is the integration of the independent power sources to supply the demand power according to the circumstances. So far there are several methodologies have been investigated to optimize the power train architecture such as fuzzy logic and rule based power management strategy [2], neural networks [4], dynamic programming [3], etc. Rather than dealing the power management problem with the specific control methodology, here the effective switching approach for the parallel hybrid power train architecture has been investigated.

Moreover the work here, discuss the possible power flow pattern of the dual energy sources based (IC engine and electric battery) parallel hybrid electric vehicle and the effective power and energy management strategy, which can be employed to increase the efficiency of the system. It has been assumed that the system behaves ideally, so that the operational efficiency losses and the time taken to activate and deactivate the independent system are negligible. In section II & III the mathematical equation of the vehicle and the general power flow pattern are given. The power train architecture and the switching strategy of the vehicle are presented in the section IV. In section V & VI the obtained simulation results and the conclusion has been presented, which address the benefit of the proposed strategy.

II. Mathematical Modeling

This section describes the general mathematical equation of the vehicle dynamics.

When the vehicle navigates in an unknown terrain the force required to propel the vehicle can be given by the following equation.

$$F(t) = M.R.\frac{d\omega(t)}{dt} + \{A.\sin\alpha(t) + .. \quad (1)$$

$$.. + B.(R.\omega(t) + u(t).\cos\beta(t))^2 + C.\cos\alpha(t)\}$$

Hence the load power required to overcome the resistance is

$$P_L(t) \square F(t).V(t) = [M.R.\frac{d\omega(t)}{dt} + \{A.\sin\alpha(t) + ..$$

$$.. + B.(R.\omega(t) + u(t).\cos\beta(t))^2 + C.\cos\alpha(t)\}].V(t)$$

(2)

Also,

$$A - Mg$$

$$B - \frac{1}{2}\rho.A_f.C_d$$

$$C - Mg.f_r$$

$$V(t) - R.\omega(t)$$

III. The power train architecture and the switching strategy

Fig. 1 shows the generic power train architecture of the parallel hybrid electric vehicle, which includes all the possible power switching strategy. The individual power flow pattern has been briefly described in the following sections. Moreover the decision making and the operating principle of the switching strategy is addressed in the table-1. In order to analyze the system and to generate the relevant logic, It is hypothesized that the P_{ICE_t} (power capacity of the IC engine) is grater than the P_{EM_t} (power capacity of the electric motor).

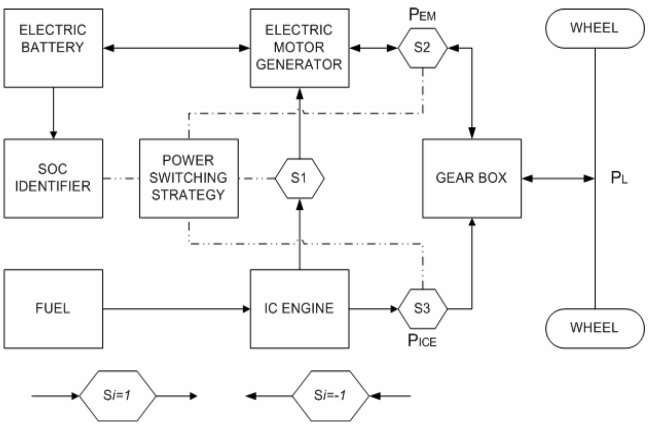


Fig. 1 Generic power flow diagram of the parallel hybrid vehicle, which includes all possible power flow directions.

CONDITION	$P_L(t)$	$P_{EM}(t)$	$P_{ICE}(t)$	SoC_n	S1	S2	S3
1	<0			<1	0	-1	0
2	>0	$> P_L(t)$		> 0	0	1	0
3	>0	$> P_L(t)$		< 0	1	0	1
4	>0	$< P_L(t)$	$> P_L(t)$	<1	1	1	0
5	>0		$< P_L(t)$	>0	0	1	1

Table-1 SoC_n and the switching strategy

Here the allowable lower bound of the SoC_n is considered as 0 and the allowable upper bound is considered as 1(SoC_n <0 means, where the SoC_n of the battery is bellow the allowable lower bound)

In general $SoC_n \in [0,1]$
The detail description of the Table-1 is as follows,

Condition 1:- if the $P_L(t)$ is negative and the SoC_n <1 then the motor generator would convert the kinetic energy of the vehicle as electrical energy to recharge the battery (regeneration process). Suppose the SoC_n of the battery is in saturation level then the kinetic energy would be dissipated as heat in the break and tire.

Condition 2:- if the $P_L(t)$ is positive and the $P_{EM}(t)$ is grater than the $P_L(t)$ then the E-motor would be use to propel the vehicle till the SoC_n reach its allowable lower limit.

Condition 3:- if the $P_L(t)$ is positive and the $P_{EM}(t)$ is grater than the $P_L(t)$, but the availability of the SoC_n is not sufficient, then the IC- engine would be used to propel the vehicle while the redundant power of the IC engine would be converted as electric power to recharge the battery.

Condition 4:- if the $P_L(t)$ is positive and $P_{EM}(t) < P_L(t)$, but $P_{ICE}(t)$ > $P_L(t)$ and also the SoC_n in the battery is bellow the saturation level, then the IC- engine would propel the vehicle while the redundant power of the IC engine would be converted as electric power to recharge the battery (similar operation as condition 3, but the power demand is varying in both cases).

Condition 5:- if the $P_L(t)$ is positive and the $P_{ICE}(t)$ < $P_L(t)$ but the addition of $P_{ICE}(t)$ and $P_{EM}(t)$ is grater than the $P_L(t)$ and also the SoC_n is within the allowable limit, then both IC- engine and E-motor would be used to propel the vehicle.

However the practical limitations such as the time required to operate the independent power sources, effective interval of the IC engine's switching period, the energy required to switch on the IC engine, etc, the described logic cannot be integrated with the real system. It result in to determine that it would be effective to activate the IC engine in a constant time interval and let the IC engine to supply the power for at least a certain predetermined period. Moreover the switching interval of the IC engine can be obtained from the available energy in the battery and the load power demand.

To increase the fuel economy of the IC engine, it is highly desirable to maintain the IC engine's operating condition on its optimum efficiency region, which also leads to reduce the emission and to increase the lifetime of the IC engine. Similarly, the limitation of the chemical properties of the battery requires maintaining its SoC_n in-between the effective boundary.

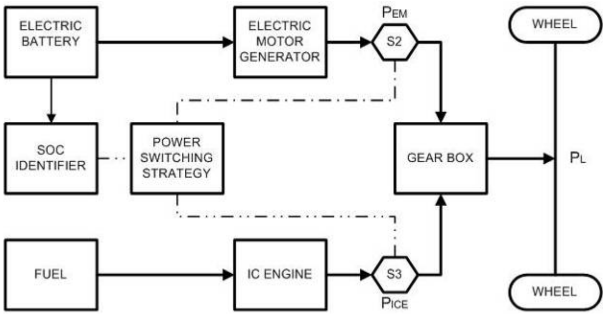
IV. General Power flow patterns

This section describes the variation of the load power demand by the vehicle and the appropriate power flow from the duel energy resources to supplement the power requirement. The power flow pattern has been analyzed based on the energy availability of the individual energy sources by incorporating the issues, which are discussed in the section III. Moreover the triggered condition and the relevant power flow diagram, which bellow the each condition is giving more explanation about the system.

1- If the load power requirement is more than the summation of the independent power which can be supplied by the dual energy sources, then the maneuver is not realistic.

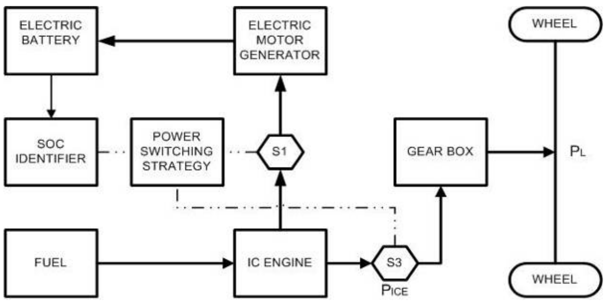
2- On the other hand if the battery has sufficient energy and the load power requirement is less than or equal to the summation of the independent power sources, then both of the sources would supply the power to over come the load power requirement.

$$P_{ICE}(t) + P_{EM}(t) \rightarrow P_L(t)$$



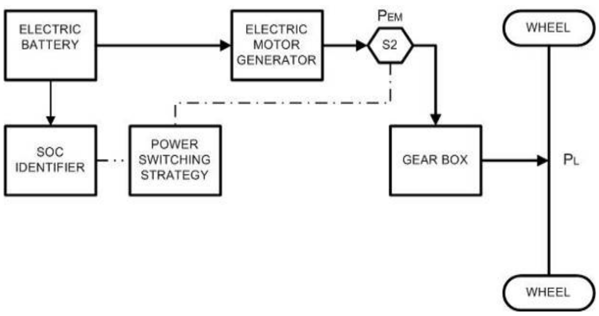
3- If the load power requirement is less than the power supplied by the IC engine, and the battery can be given more energy to accumulate, then the excess amount of power can be converted as electrical power to charge the battery. In this case the electric motor would act as generator. The power flow pattern would be as bellow.

$$P_{ICE}(t) \rightarrow P_L(t) + P_{EM}(t)$$



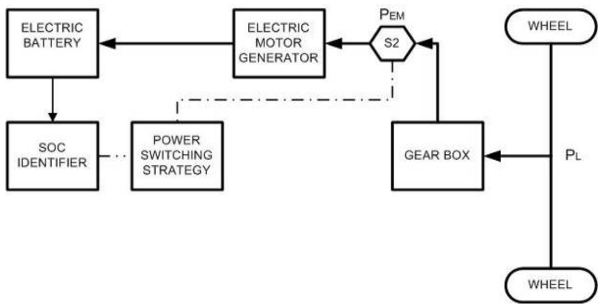
4- If the battery has the sufficient energy and if the motor is power enough to overcome the load power requirement then the electric motor alone would propel the vehicle. In this case the power flow would be from electric motor to the vehicle

$$P_{EM}(t) \rightarrow P_L(t)$$



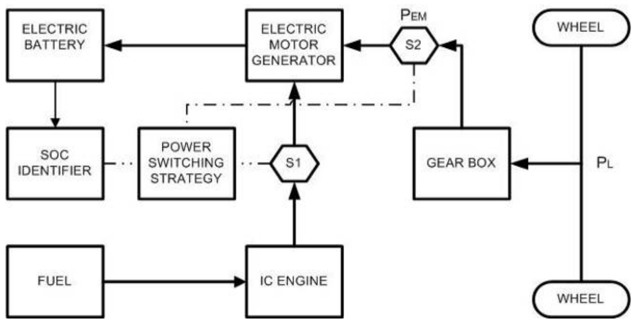
5- If the vehicle is propelled by external forces such as gravity, wind, etc or when the driver insist to break the vehicle, then the electric motor would act as a generator to capture the energy and which would effectively charge the battery. In this case the power flow would be from vehicle to the electric motor.

$$P_L(t) \rightarrow P_{EM}(t)$$



6- When the charge of the battery is less than the allowable limit, then the IC engine will be activated to propel the vehicle, so as the redundant power of the IC engine will be converted as electric energy to charge the battery. But in some circumstances the vehicle can be propelled by the external forces such as wind, gravity, etc, and in this occasion the generator would effectively capture the power generated by the IC engine and the external force. The power flow pattern for this condition is as bellow

$$P_L(t) + P_{ICE}(t) \rightarrow P_{EM}(t)$$



V. Simulation approach and results.

The model has been simulated with the standard NEDC (New European Driving Cycle) velocity profile to understand the behavior of the proposed strategy. Moreover the essential initial condition such as terrain condition, wind velocity, weight of the vehicle, etc has been given to the model and then it is simulated in the simulink environment. With the intention of realize the hybridization and the effectiveness of the energy conservation, it has been assumed that the battery has zero charge at the beginning and the transmission losses are negligible. Further, according to the load power demand and the individual capability of the power sources, the switching strategy would place in operation.

Fig. 2 shows the block diagram of the data converter which has been used to feeds the expected data into the vehicle forward model. The output results obtained from this model is analyzed to understand the behavior of the methodology.

In Fig. 3 the standard NEDC velocity profile is attached and it explains that effectively 75% of the time the vehicle is realizing the motion and the remaining 25% is idling. Since the frequent switching is not efficient in the conventior vehicle, the fuel used by the IC engine within the 25% of t idling time is considered as redundant. But the propos strategy shows that it can be effectively utilized employing an appropriate methodology in hybrid vehicles.

Fig.4 (a) shows the energy requirement by the vehicle for t entire maneuver and the Fig.4 (b) shows the energy suppli by the IC engine. According to the proposed decision maki strategy, when the IC engine is operating the excess amou of the power, which produced by the IC engine is convert as electrical power and it is accumulated in the battery and has been clearly reflected in Fig. 4 (c). Further more it sho that when the IC engine is switched off then the batte started to loose its accumulated energy and it is converted motor power, which is used to propels the vehicle. In additi to that the switching strategy monitoring the SoC_n of t... battery and it maintain the SoC_n in its effective region. It is highly desirable to increase the life of the battery with excellent efficiency.

Fig. 5(a) shows the load power variation of the vehicle an Fig. 5(b) shows the effective switching period of the IC engine. According the created strategy when the load powe demand increased above the certain limit then the electri motor and the IC engine would propel the vehicle and i shown in the period between 950sec to 1150 sec. the Fig. 5(c shows the power variation of the electric motor. As notatior it has been considered positive when the motor is acting a the generator and negative when the motoring action i present.

Moreover it has been investigated that only 36% of the tim period the IC engine has been triggered to its operating mod and 50% of the time period the vehicle powered by th electric motor. Further 58% of the accumulative time perio the motor act as generator to charge the battery.

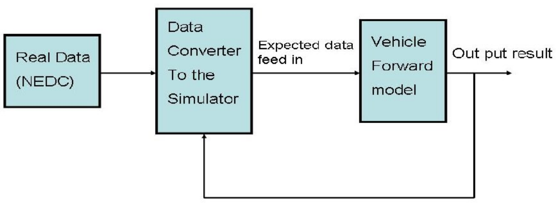


Fig. 2 the block diagram of the data converter, which feed the standard NEDC velocity data into the vehicle forwar model

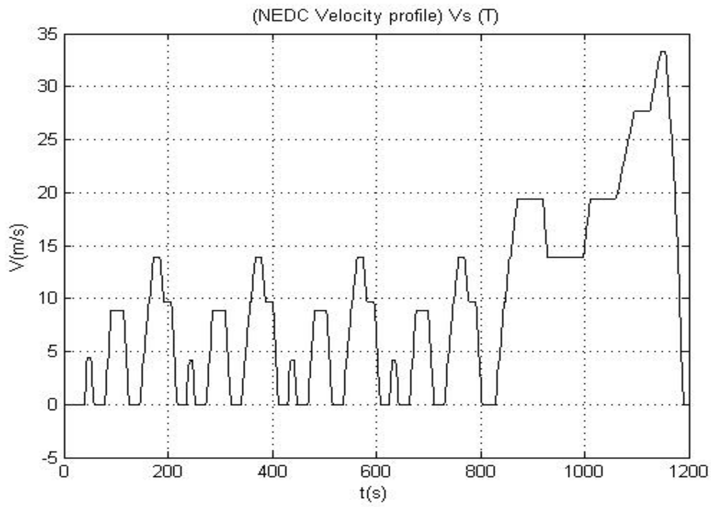


Fig. 3. the standard New European Driving Cycle (NEDC) velocity profile.

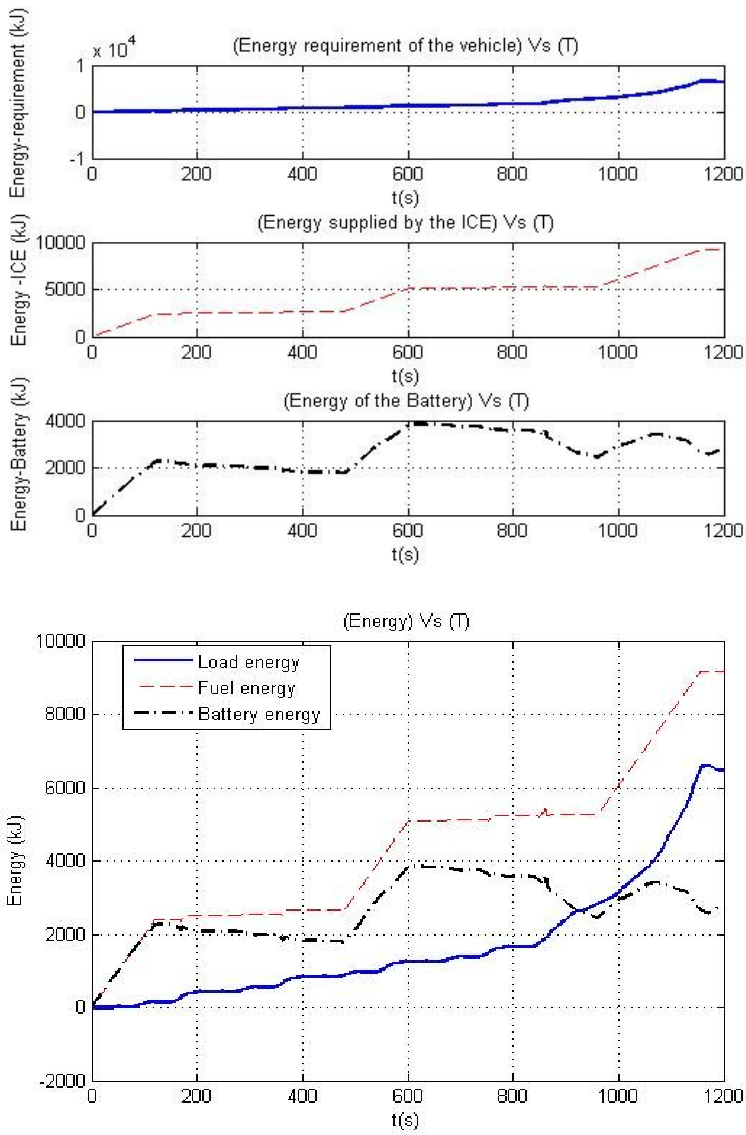


Fig. 4 simulation result shows the energy fluctuation in the dual energy sources according to the energy consumption of the vehicle.

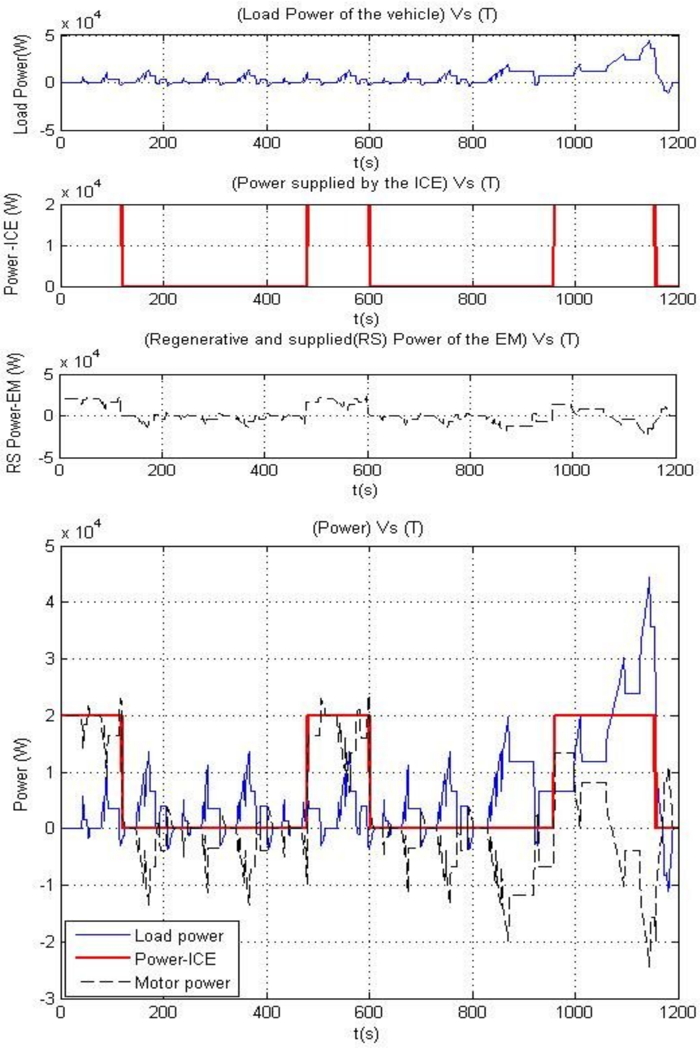


Fig. 5. Simulation results show the power demand of the vehicle and the contribution of the individual sources to supply the demand.

Based on the simulation results it can be conclude that the proposed methodology is effectively contributing to obtain the excellent energy conservation among the dual energy sources.

VI. Conclusions

The proposed concept provides effective and efficient energy conservation among the dual energy sources. The energy management and the power management are differentiated by the formulated strategy. It has been justified that the ability of making the appropriate decision on appropriate time would result in to significant energy saving without scarifying the driver's objective. Moreover the obtained simulation figures regarding the energy consumptions leads us to conceive the energy wastages in the conventional way of operating, which can be easily avoid by incorporating appropriate hybrid technology.

References

[1] B.K.Powell, K.E.Bailey. "Dynamic modeling and control of hybrid electric vehicle power train systems" IEEE, Vol 98, pages 0272-1708, October 1998.

[2] H. Hannoun, D. Diallo, C. Marchand Kheir."Energy management strategies for parallel hybrid vehicles using fuzzy logic" Control Engineering Practice. Vol 11, pages 171-177, 2003.

[3] R.Beck, A.Bollig and D.Abel,"Comparison of two Real-Time Predictive Strategies for the Optimal Energy Management of a Hybrid Electric Vehicle" Oil&Gas Science and Technology-Rev.IFP,Vol.62(2007), No.4, pp. 635-643

[4] Hasan Mehrjerdi, Jamel Ghouili. "Mechatronic design and control of hybrid electric vehicle" IEEE/ASME Transactions on Mechatronics, Vol. 5, No. 1, March 2000

[5] Reza Langari, Jong-Seob Won, "Intelligent energy management agent for a parallel hybrid vehicle- part I: system Architecture and Design of the Driving Situation Identification Process" IEEE Transactions on vehicular technology, Vol 54, no.3, May 2005

[6] Xiaolai He, Micheal Parten. "energy management strategies for a hybrid electric vehicle" Proceeding of IEEE, Vol 5, 2005.

[7] K.David Huang, Sheng-Chung Tzeng. "Intelligent mechanism for parallel hybrid vehicle system". Applied Energy, vol. 82, pages 133-147, 2005.

[8] Jih-Sheng (Jason) Lai, Dogulas J. Nelson,"Energy Management Power Converters in Hybrid Electric and Fuel Cell Vehicle". Proceedings of the IEEE, Vol.95, No.4, April 2007.