Fuel Efficient Control Strategy, Based on Battery-Ultracapacitor Energy Storage System, in Parallel Hybrid Electric Vehicles

Amir Hossein Eghbali, Student Member, IEEE, Behzad Asaei, Member, IEEE, and Peyman Nader, Member, IEEE
University of Tehran, Electric and Computer School, Islamic Azad University, Iran, Borujerd Branch
amir.eghbali@gmail.com, b.asaei@ut.ac.ir, naderi@ee.kntu.ac.ir

Abstract- **Different control strategies have been released to solve the problems and improve the performance of hybrid electric vehicles. Energy storage power management is one of the most important parameters which affects on control strategy and other parts of a hybrid vehicle. In this paper a battery-ultracapacitor energy storage system and its control strategy based on minimizing the fuel consumption and operating the engine in efficient region has been developed. The simulation results prove this fact that ultracapacitors can be trustable secondary energy storage and increase the overall performance of system.**

I. Introduction

Improvement in Hybrid Electric Vehicles (HEVs) Technology is the fastest solution for reducing the conventional IC engine vehicles problems. Hybrid Electric Vehicles (HEVs) have improved their performance and made suitable for commercial and domestic use during the last decade. But still there is a long way to reach the abilities of conventional vehicles. Energy storage system (ESS) is the most important and vital part of HEV and the batteries are main types of electric ESS which have own advantages and disadvantages. Researches during these years confirm the fact that, according to the different power request in various driving cycles and also the natural specification and behavior of batteries, existence of secondary electric ESS could be an appropriate choice for supplying the requested energy in defined situations. Moreover it can reduce the pressure on the primary ESS (Batteries) for instant delivering high instantaneous power, which is needed in acceleration times, from battery could have damaged effects in long time and reduces the battery life cycle and efficiency, hence using a secondary ESS seems to be necessary [4],[8].

Ultracapacitors, regarding their physical specifications, are the types of energy storage systems which have ability to deliver the high power and currents. Fast charging, long life cycles, and resistance from high current delivering and capturing, make them desired secondary ESS. Table 1, shows the specifications of ultracapacitors in comparison with batteries [3], [5]. As it can be seen in table 1, in terms of energy and power density, ultracapacitors are positioned between battery technology and electrolytic capacitor technology. Moreover, because they are capable of cycling millions of times, they can be virtually maintenance-free over the life of any product in which they are used.

Defining the hybrid structure with using two types of energy storage systems and proposing its control strategy for different states are presented in this paper. One of the biggest Advantage of HEVs is to ability the regenerate the power in braking times. Using ultracapacitors for regeneration also shows acceptable results in compare with batteries. Regenerative braking efficiency is one of the key points which in battery based on its limitations and charging conditions have encountered some problems; ultracapacitors can be an ideal element for improving the regeneration efficiency.

Table 1, Different ESSs specifications [3], [5].

	Lead Acid Battery	Ultra-capacitor	Conventional Capacitor
Charge time	1 to 5 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Discharge Time	0.3 to 3 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Energy (wh/kg)	10 to 100	1 to 10	< 0.1
Cycle Life	1000	> 500,000	> 500,000
Specific power (w/kg)	<1000	< 10,000	< 100,000
Charge/discharge efficiency	0.7 to 0.85	0.85 to 0.98	> 0.95

In next section the proposed hybrid system configuration with using ultracapacitors are presented, after that conditions and control strategies of applying battery and ultracapacitor in HEVs has been written in section 3. Simulation results in various driving cycles, efficiency and fuel consumption are presented in sections 4 and 5 respectively.

II. System Configuration

A parallel hybrid configuration with torque coupling method has been considered in this paper. The energy flowing directions (delivering and receiving) are shown in Fig. 1, in acceleration times energy flows from battery or ultracapacitor toward the electric motor and in braking modes motor acts like a generator and give back the energy to the ESSs [2],[4].

As it can be seen in Fig. 1, the main controller unit receives all the data from inputs and situations to produce proper commands for other parts to fulfill the driving requests. The most important commands are sharing of each ESS which should be determined through the control strategy. By push the pedals from driver the system receives the input commands, indication variables obtain from sensors which are installed on both primary and secondary ESS. In table 2, all the input, indications, and outputs variables has been categorized.

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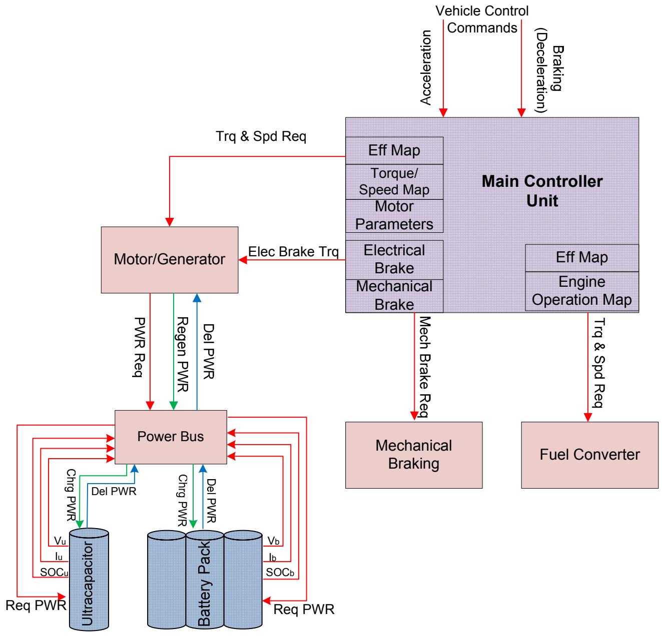

Fig. 1, Energy flowing strategy and controller unit

For each element such as engine, electric motor, battery, ultracapacitor, and etc some look up tables has defined; for example engine has efficiency, torque, speed, fuel consumption, emission, and maximum torque maps. The main controller unit applies these maps to process the situations based on the input requests. The method of how controller works and the algorithm of data process have mentioned in the following section.

Table 2, Control variables

Variable	Type	Unit	Comment
trq_req (T*)	Input	Nm	Request Torque
Spd_req	Input	m/s	Request Speed
bt_soc	Indication		Battery State of Charge
bt_crrnt	Indication	A	Battery Current
bt_voltage	Indication	V	
uc_soc	Indication		Ultracapacitor SOC
uc_crrnt	Indication	A	Ultracapacitor Current
uc_voltage	Indication	V	
trq_del	Output	Nm	Delivered Torque
Spd_del	Output	m/s	Delivered Speed
trq_regen	Output	Nm	Regenerative Torque

III. EFFICIENT CONTROL STRATEGY

One of the most important parameters for reducing the fuel consumption is, holding the engine operating point near the efficient field. In proposed strategy the system tries to force engine to work in efficient mode. When system works with two ESSs, control strategy will be more complicated in comparison with one ESS because monitoring the indications of both energy storage systems simultaneously and making the proper choices for delivering the required energy and many other parameters need a complete and intelligent control strategy. Three main conditions have been checked when received a request signal.

- Battery SOC, which should be in 0.45<BT-SOC<0.7
- Ultracapacitor SOC, 0.7<UC-SOC<1
- Max torque which electric motor can deliver

Four main states during a drive cycle can happen which are described below.

a. 0.7 < UC-SOC < 1 & 0.45 < BT-SOC < 0.7

In this state the SOC of battery and ultracapacitor are in the safe range and both of them deliver energy. The requested torque has been checked by the maximum available electric motor torque, related flowchart has been shown in Fig. 2.

b. 0.7 < UC-SOC < 1 & BT-SOC < 0.45

Because the hysteresis model has used for keeps the SOC level in defined values if one of the energy storages is out of the determined range, it should be charged by means of another ESS or engine. If the battery was out of range and needs to charge, the requested torque will compare with engine optimum operating points. Fig. 3 shows the detail mentioned algorithm.

c. UC-SOC < 0.7 & 0.45 < BT-SOC < 0.7

In this situation battery as primary ESS, supports the requested power and also the power for charging the ultracapacitor. Supplying the requested torque for power train is just like the part a, which has mentioned before.

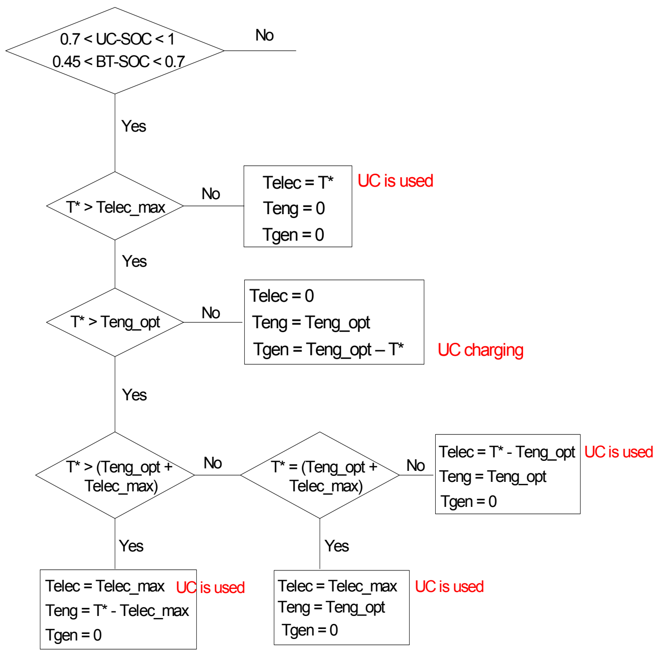

Fig. 2, control strategy in 0.7 < UC-SOC < 1 & 0.45<BT-SOC<0.7

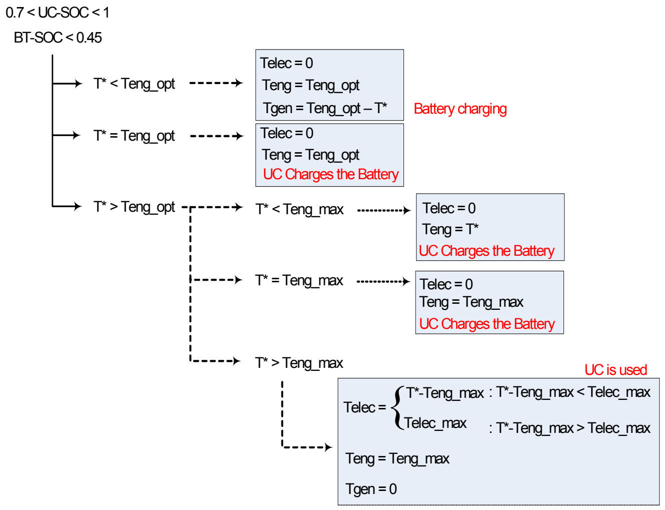

Fig. 3, torque and power sharing algorithm

d. UC-SOC < 0.7 & BT-SOC < 0.45

When both energy storages are in out of range and need to be charged; only engine should run and supplies the request torque for drive train, battery and ultracapacitor charging. Fig. 4 shows the power and torque sharing in these conditions.

Ultracapacitors based on their SOC level also used in 3 different conditions, acceleration, battery current limiting, and regenerative braking [4]. As stated before high currents are needed for accelerating using the ultracapacitor in these times can reduce the pressure of battery pack and increase its lifecycle.

IV. Simulation Results

Many parameters have been inspected during simulations; some of them are more important and have crucial effects on overall system operation and efficiency such as battery and ultracapacitor SOC and current, delivered power from electric motor and engine, and regenerative braking maximum torque available. Proposed vehicle specifications are listed in table 3 and 4, the system operating voltage is 310 V.

Table 3, Vehicle design parameters.

Description	Max Power	Peak Efficiency	Comment
FC Engine	41kw	34%	55hp
Elec Motor	30kw	91%	
Transmission		0.93	Man(5spd)
Battery			8Ah

Table 4, Ultracapacitor specifications [9].

Description	Cap (F)	ESR,DC (mΩ)	Isc (A)	Emax (wh/kg)	Pmax (w/kg)
Ultracapacitor	110	9.5	4300	2.91	6200

Making simulations on different drive cycles leads to have better results about the proposed theory, FTP and highway drive cycles have been checked in simulation tests. As it can be seen in fig. 5, both SOC of battery and ultracapacitor maintain between the determined level simultaneously, for avoiding the battery from delivering high currents, a max level for battery current has been determined.

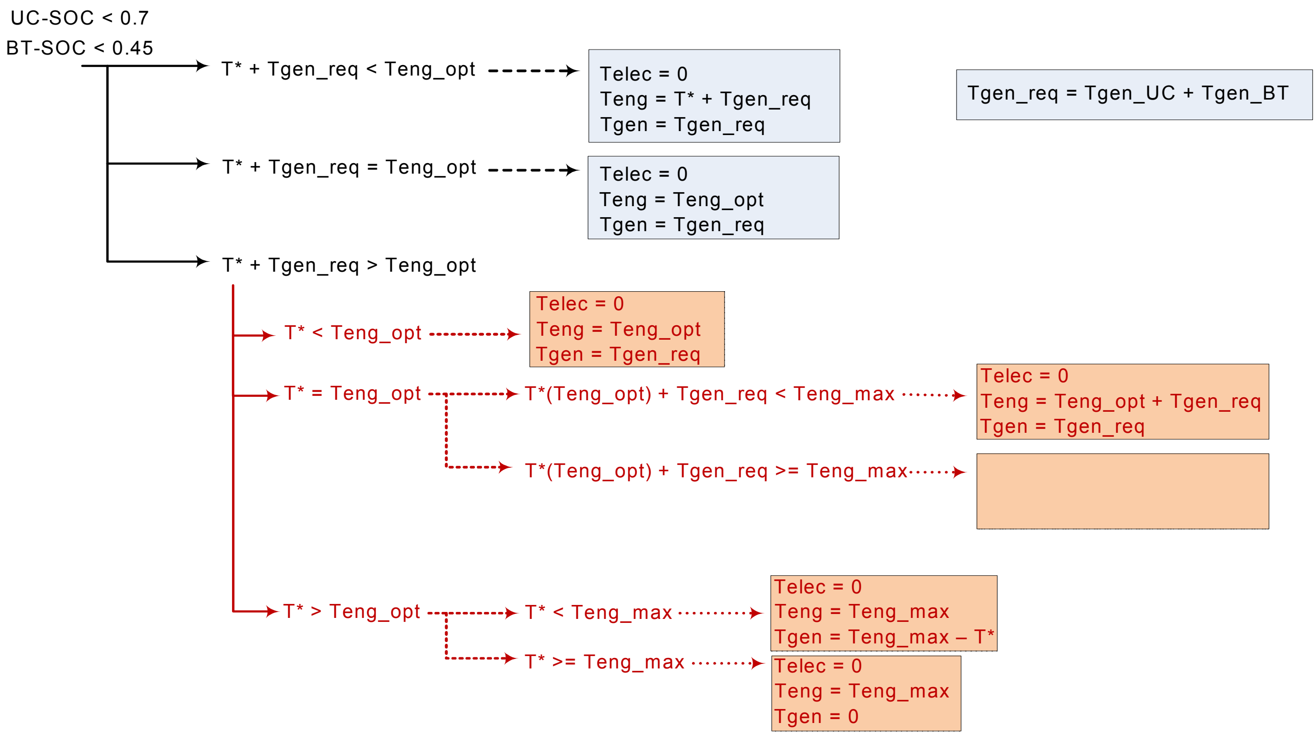

Fig. 4, Power and torque sharing during UC-SOC < 0.7 & BT-SOC < 0.45

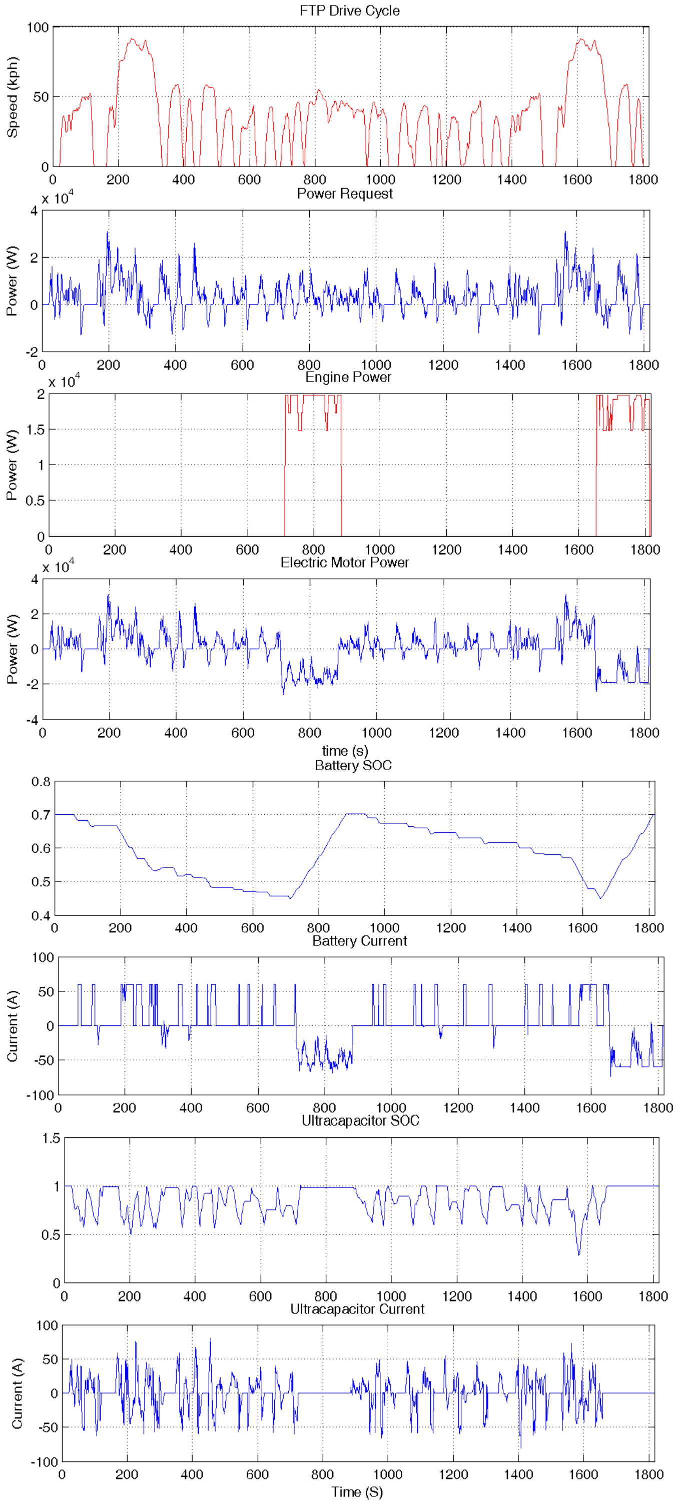

Fig. 5, Simulation results in FTP drive cycle.

A deeper look at the diagrams emphasis this fact that ultracapacitor can support the maximum needed current for electric motor without any physical damaged. Moreover the battery cell voltage stability is another improvement of using ultracapacitor as secondary ESS (see Fig. 5). SOC situations and ESS currents in UDDS drive cycle has been shown in Fig. 6, also. It can be seen that ultracapacitor has fast discharge and charge routine; fast discharging capability enables the ultracapacitor to deliver high instantaneous currents and make it suitable for acceleration times. In braking times maximum available power with higher efficiency can regenerate because of ultracapacitor. As we know batteries, based on their physical structure, have a current limitation for charging which leads to lack of regeneration efficiency, but with take a look at table 1, and 4 it can be find out that ultracapacitor absorbs the high currents and charges itself much faster than battery.

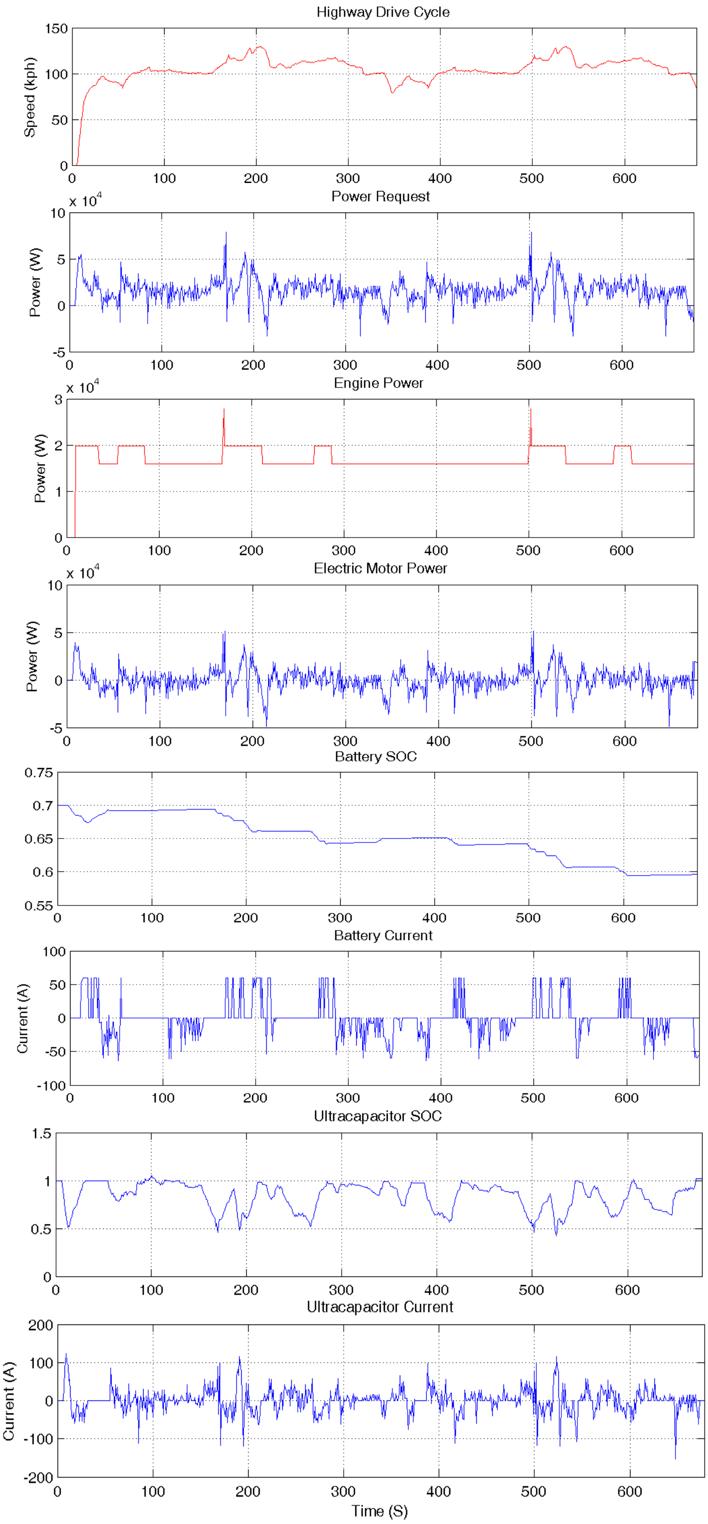

Fig. 6, Simulation results in UDDS drive cycle

V. FUEL CONSUMPTION AND EFFICIENCY CALCULATION

The natural problems of fuel consumptions, like emissions and deviation costs, force the control strategies to reduce the dependency of vehicles from fuel. Two major parameters can help the system to reach this goal, first, using the electric motor in most possible time and second, operating the IC engine in efficient region. In the mentioned strategy, which is explained before, 26 different states may happen and for each one there is a separate control strategy but it can be seen that in 14 states engine operates in optimum points and in 2 states only electric motor works. It means that in 58.4% of different situations engine forces to operate in optimum field beside the fuel consumption reduction this leads to increase the overall efficiency of engine operation and the system. Each engine has a fuel and efficiency map which has used in simulations, the ADVISOR models for 41kw (55hp) engine has been chosen for the calculations. Table 5, shows the fuel consumed in 3 different drive cycles it can be seen that ultracapacitor-battery system in comparison with other strategies can reduce the fuel consumption saliently. Engine operating efficiency also is an important point for the proposed strategy, when the system force to operate only in efficient points the reduction of fuel consumed is accessible. As we know about the mechanical structure of IC engines stop and start of these engines in short period of time besides the damaging effects on the engine, increase the fuel consumption and also decrease the performance and efficiency of engine so the strategy makes the engine start only in very necessary points and work for a dominate period of time to avoid the instantaneous stop and starting. The average engine operating efficiency, in FTP drive cycle, based on ADVISOR results for parallel default and Toyota prius is 25.5% and 30% respectively whereas in the proposed strategy it reaches to 34.5% which is almost the best efficiency for that type of mentioned engine.

Table 5, Fuel Consumption Comparisons

	Fuel Consumption (L/100km)		
Description	FTP	UDDS	Highway
Parallel Default	7.2	7.4	7.8
Prius	5.3	5.4	6.3
Proposed System (Without ultracapacitor)	5.11	5.36	6.15
Proposed System (With ultracapacitor)	4.46	4.72	5.92

In comparison with prius model, the results have shown that 15% fuel consumption has been achieved with this control strategy which is an acceptable improvement.

VI. CONCLUSION

An efficient control strategy model has presented in this paper which focused on fuel consumption and efficiency improvement. Ultracapacitors as secondary energy storage systems has used for improving the capability and capacity of electric part of hybrid vehicles. High instantaneous power delivering, regenerative braking improvement, protecting battery system from high currents are some of the ultracapacitors advantages in HEVs which has been presented in simulation results. At the end, the proposed strategy makes the engine works in efficient points and fuel consumption calculation shows 15% reduction with higher performance for engine and also the whole system.

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