A Control Strategy for Reducing Fuel Consumption in a Hybrid Electric Vehicle

Babici Leandru Corneliu Cezar[1] and Alexandru Onea[2]
[1]Institute of Problem Solving, "Gh. Asachi" Technical University, Str. Prof. dr. doc. Dimitrie Mangeron nr. 27, Iasi, Romania
[2]Department of Automatic Control and Applied Informatics, "Gh. Asachi" Technical University, Str. Prof. dr. doc. Dimitrie Mangeron nr. 27, Iasi, Romania

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Abstract: Hybrid electric vehicles are one of the most suitable alternative for conventional automobiles. This paper describes a control strategy for a hybrid electric vehicle, in order to reduce the fuel consumption, and to maintain a reasonable state of charge (SOC), at the end of the drive cycle. The main goal is to split the requested power from the driver between the internal combustion engine, and the electric motor, such way to decrease the fuel consumption, and to maintain the dynamic performances. The algorithm was tested using Matlab Simulink and ADVISOR interface. The results include statistical comparisons of the standard drive cycles using default model and the modified control strategy.

1 INTRODUCTION

Hybrid electric vehicles (HEVs) receive increasing attention due to their potential for reduced fuel consumption and low emissions. Increasing fuel cost and emissions standards across the globe have popularized this trend in transportation. According to a recent survey, 36% of motorists worldwide wish to buy a car with hybrid drive, while 46% of them showed interest in buying full-electric cars. Energy efficiency and performances of the automobiles depend on the control strategies, journey type, and driver behavior (Chan, 2002). A typical HEV powertrain has an internal combustion engine (IC) with an associated fuel tank and an electric motor with its associated energy storage devices such as batteries and/or ultracapacitors. Because a hybrid powertrain is much more complicated than a conventional powertrain, the coordination and appropriate control strategy for the energy components have significant influences on vehicle dynamic performance, fuel economy, and emissions (Johnson et al., 2000). In HEV designing configuration, the commonly constraints are: vehicle range, acceleration, maximum speed, and road grades. All these factors are directly related to driving patterns. The required specifications in HEV design are usually divided into two categories. The first depends on consumer's demand such as acceleration performance, maximum speed and fuel economy. This category of specifications is used in sizing the vehicle components such as, electric motor (EM), internal combustion engine (ICE) and transmission system. The second category is based on ecological issues such as vehicle emissions. The control strategies should maintain vehicle emissions within the regulation limits. There are three major types of hybrid systems that are being used in the hybrid vehicles market as: series, parallel and series-parallel hybrid types. The real world drive cycle data for this study was obtained using the National Renewable Energy Laboratory's (NREL) vehicle level simulation software. ADVISOR, was used to evaluate and compare the simulated performance of the hybrid electric vehicle, on different drive cycles using different strategies (Markel et al., 2002). In parallel configuration the internal combustion engine can assist the electric motor during times of high power demand, according to the control strategy, if first is sized with less power than the second one. Energy storage system (ESS) and the electric motor, are capable of providing all of the vehicle's power demands. Recent study has shown that a vehicle can meet its performance requirements with minimum power rating if the power train operates mostly in constant power. The power rating of a motor that

Leandru Corneliu Cezar B. and Onea A..
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deviates from the constant power regime can be much higher than of a motor, operating at constant power throughout its speed range in a vehicle. In its normal operation mode, the electric motor, can provide constant rated torque up to its base or rated speed. At this speed, the motor reaches its rated power limit. The operation beyond the base speed, up to the maximum speed, is limited to this constant-power region. The range of this constant-power operation depends primarily on the particular motor type and its control strategy. An electric machine should be able to perform a long constant-power operation in order to be suitable for HEV

2 HYBRID ELECTRIC VEHICLE SIZING AND CONTROL STRATEGY IN ADVISOR

An effective HEV design requires optimal sizing of its key mechanical and electrical components. In the design process of an HEV, there are a range of design variable choices, including HEV configuration, key mechanical, electrical components sizes, and control parameters. On the other hand, the HEV design problem is focused at several simultaneous objectives such as the minimization of fuel consumption (FC) and exhaust emissions (e.g., HC, CO, and NOx) while maintaining driving performance. However, these aspects are often in conflict with each other. The minimum FC does not necessarily result in the minimum emissions. Several approaches and methods have been reported to optimize HEV component sizes and control strategy parameters, with the aim of simultaneously reducing FC and exhaust emissions (Banvait, 2009). A parallel hybrid powertrain is used in this paper, where two mechanical powers are added together in a mechanical coupler. The control strategy of a parallel HEV is responsible for distributing the driver's required torque between the IC engine and electric motor while sustaining a charge in the batteries. The IC engine is the primary power plant, and the batteries and the electric motor drive constitute the energy bumper. Both IC engine and electric motor may deliver power to the vehicle wheels. In addition, the electric motor may also be used as a generator to charge the battery by either regenerative braking or absorbing the excess power from the engine when its output is greater than the output required to drive the wheels. For simulations, it was used ADVISOR 2003 and Matlab 2011. In order to reduce the fuel consumption, less required torque from the ICE was calculated in the control strategy, and more required torque from electric motor. In ADVISOR the cumulative fuel use (CFU), expressed in Laplace is calculated like below:

$$CFU = 1/s*x*3.785*231/r*61.02 \tag{1}$$

where r is the fuel density (749), and x is the fuel use (FU), measured in L/s. 1/s means that the function is integrated.

$$FU=y*(0.1*pow((m-n)/(m-20), 0.65)+1) \tag{2}$$

where y is the hot fuel use (HFU), m is the engine coolant thermostat set temperature(96 Celsius degrees), and n is the coolant temperature. HFU is obtained from a 2-D lookup table with the inputs arguments: fc_map_spd (speed map), and fc_map_trq (torque map). The torque available (T) from the ICE is calculated as below:

$$T=max(min[(Tr+Ei), maxt], Tcl)-Ei \tag{3}$$

where Tr is the required torque, Ei is the engine inertia, maxt is the maximum torque required, and Tcl, is the torque when the throttle is closed. In the torque coupler block in Advisor, the needed power from the driver is divided between the requested power from the ICE and the requested power from the motor. The inputs in the torque coupler bloc are: torque and speed required, torque and speed available from the ICE, and torque and speed available from the electric motor (EM).

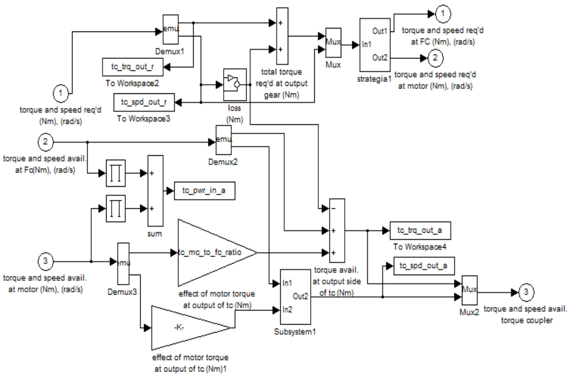

Figure 1: Torque Coupler in Advisor.

The outputs are torque and speed available at torque coupler, torque and speed required from ICE, and the required torque and speed from EM. Torque available at torque coupler (Ta) is the sum of the torque available from the ICE and EM, minus the losses in this bloc, because of the friction force.

$$Ta=Ti+Te*tc\_mc-L \tag{4}$$

where Ti is the torque available from ICE, Te is the available torque from EM , tc_mc is the constant ratio of speed at motor torque input to speed at engine torque input, and L is the parameter according to the losses due to the friction force. Speed available at the torque coupler (Sa) is the minimum of the speed available of the ICE and the EM:

$$Sa=\min(Sf, Se/tc\_mc) \qquad (5)$$

where Sf is the speed available from the ice, Se is the speed available from the EM. First parameters that we used are: fuel converter with maximum power of 41 Kw, 25 modules off lead batteries with maximum power 25 Kw, and nominal voltage of 308 Volts, and a 75 Kw electric motor. Because the maximum power of the electric motor is almost double than the ICE, in the control strategy proposed, the electric machine is used as the primary source of power, and the mechanical machine is used to recharge batteries and to sustain the request of torque and speed as much as possible.

The control strategy that it was used is illustrated in the figure 2 below.

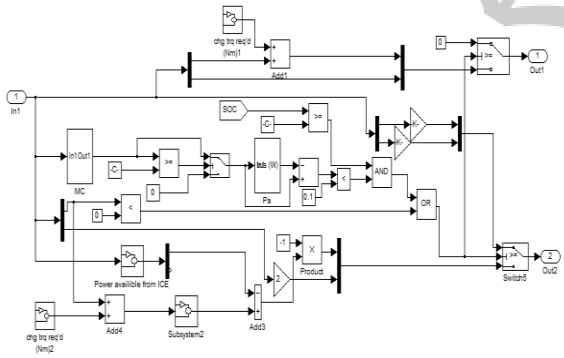

Figure 2: Control Strategy in Torque Coupler.

When the driver presses the acceleration pedal, a torque and speed will be requested from the power sources. At the requested power from the electric motor it was added the electric power for the accessory loads. If the required torque and speed is less than maximum torque and speed available from the electric motor, and the necessary power from the batteries is less than actual power, and SOC is greater than 0.64, or the requested torque is negative, then only the electric machine is used. In these conditions, the internal combustion engine is shut down. As long as the controller is using only the electric motor (EM), the system is a zero emission vehicle. If SOC is below the low limit, and the required power is greater than the power available, then both ICE and EM are running together to overcome the need of torque and speed. A logic scheme of the control strategy is presented below.

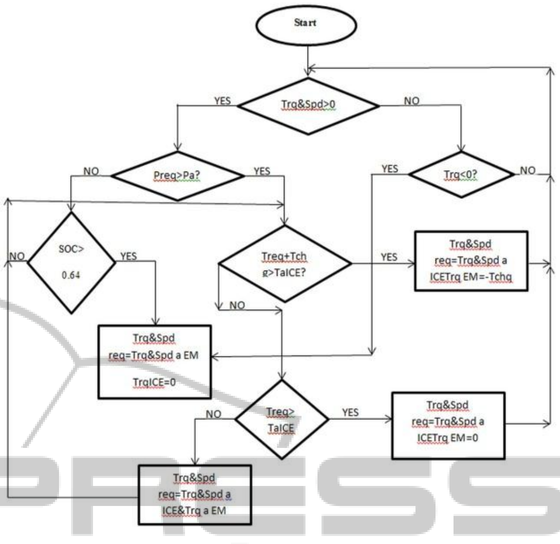

Figure 3: Control strategy logic scheme.

In the above scheme, a Rule Based Energy Management Control strategy is presented, which was used by the ADVISOR model in the drive cycle tests. The engine's ON/OFF condition is dependent on the SOC of Battery, power requested and vehicle speed (Banvait, 2009). Trq&Spd is the torque and speed required, Preq is the power required, Pa, is the available power, Tchg is the torque necessary to recharge the batteries, TaICE is the available torque from ICE, Trq&Spd a EM, is the available torque and speed from EM. When the required torque is below 0, meaning that the vehicle is moving and the driver is no longer pressing the acceleration pedal, the ESS is charging. 0.64 is the lower limit of SOC, for keeping a long life of the batteries. When the current SOC is higher than its low limit L_{SOC} and if the required speed is less than a certain value, the engine will turn off. This specific speed is called the electric launch speed V_e. Furthermore, if the required torque is less than a cutoff torque $F_{off} \times T_{max}$, the engine will also turn off. When the battery SOC is lower than its low limit, an additional torque Tchg is

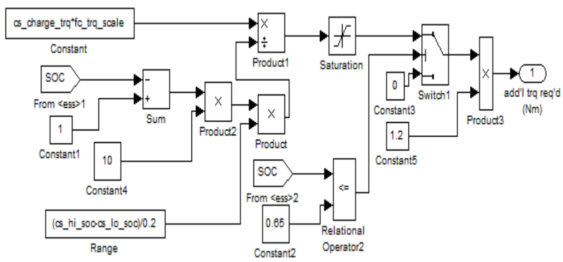

Figure 4: Charge torque required.

required from the engine to charge the batteries like in the figure 4 below:

$$\text{Tchg} = \text{cs\_chg-trq}/(50*(1-\text{SOC})*(\text{cs\_hi\_soc}-\text{cs\_lo\_soc})) \quad (6)$$

where cs_chg_trq is 15.2, cs_hi_soc is 0.7, and cs_lo_soc is 0.65.

Several approaches and methods have been reported to optimize HEV component sizes and control strategy parameters, with the aim of simultaneously reducing FC and exhaust emissions (Gao and Mi, 2007; Montazeri et al., 2006; Poursamad and Montazeri, 2008). However, in most of the recent studies found in the open literature, the conflicted optimization targets such as FC and exhaust emissions are aggregated into a multi objective function (Desai and Williamson, 2009)-(Hu et al., 2004).

3 TESTS AND RESULTS

The advanced vehicle simulator (ADVISOR), which is one of the most popular HEV simulators worldwide, is used as the modeling and simulation tool in this paper. ADVISOR employs a combined forward/backward-facing approach for vehicle performance simulation. In the following simulations some fixed parameters are used in the parallel HEV (Desai and Williamson, 2009), (Fan et al., 2009):

- rolling resistance coefficient: 0.009;
- aerodynamic drag coefficient: 0.335;
- vehicle front area: 2.0 m2;
- wheel radius: 0.282 m;
- cargo mass: 136 kg;
- gear ratio: 2.48, 3.77, 5.01, 5.57, and 13.45;
- efficiency of the gearbox: 95%;
- gearbox: five-speed manual gearbox;
- gear ratio: 2.48, 3.77, 5.01, 5.57, and 13.45;
- efficiency of the gearbox: 95%;

As the ICE, a Geo Metro 1.0 L SI engine with a maximum power output of 41 kW and a peak efficiency of 0.34 is used. In addition, as the electric motor, a Westinghouse ac induction motor with a maximum power output of 75 kW and a peak efficiency of 0.92 is used. In this paper, according to the charge and discharge resistance curve of the lead-acid battery the SOC target value is set to 0.65.

Driving cycles are defined as test cycles that are used to standardize the evaluation of vehicle fuel economy and emissions. Driving cycles are speed–time sequences that represent the traffic conditions and driving behavior in a specific area. In this paper, three cycles of NYCC, WVUINTER, and UDDS were used to evaluate the FC and exhaust emissions. These cycles are the currently used cycles in the U.S. and European communities. First test was made under the NYCC drive cycle conditions.

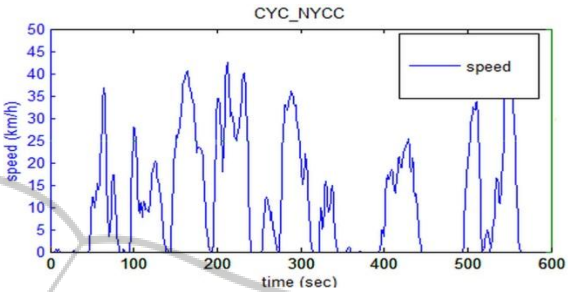

Figure 5: Drive Cycle CYC_NYCC.

During this drive cycle, the vehicle stopped 18 times, had the maximum speed 44.58Km/h, and an average speed of 11.4km/h. The results were as follows: fuel consumption is 4.4 L/100Km and a remaining SOC of 0.6495 at the end of the drive cycle. Using the standard control strategy under the same conditions, it was obtained a fuel consumption of 11.7L/100Km and a remaining SOC of 0.66. The difference in fuel consumption between the two control strategies is substantial.

4 CONCLUSIONS

Hybrid electric vehicles are the most viable solution for the world fuel economy, and emissions. A lot of control strategies are develop every day, to improve in a continuous way the dynamic performances of the vehicles, and to reduce, or to maintain as much as possible the lowest consumption (Morteza and Poursamad, 2006),(Fan et al., 2009). In this paper the electric motor was used most in the control strategy, with the restriction of maintaining a reasonable state of charge in the batteries. As the tests showed, the biggest difference in matter of fuel consumption was obtained in the NYCC drive cycle. There the vehicle had a lot of stops and goes, and it matches perfectly with the real urban traffic in the hardest conditions. The fuel consumption was more than satisfactory, and the remaining SOC also. In the future it is very likely that the full electric vehicles to run on the streets bun until then, the hybrids are in the trend, and the control strategies are and will be improved (Ehsani et al., 2010), (Chan et al., 2010).

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