Optimal Neuro-Fuzzy Control of Parallel Hybrid Electric Vehicles

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Abstract-**In this paper an optimal method based on neuro-fuzzy for controlling parallel hybrid electric vehicles is presented. In parallel hybrid electric vehicles the required torque for driving and operating the on-board accessories is generated by a combination of internal-combustion engine and an electric motor. The power sharing between the internal combustion engine and the electric motor is the key point for efficient driving. Therefore, we are dealing with a highly nonlinear and time varying plant. Moreover, the estimation of the state of charge of the battery pack is a very important point, which has been considered in this paper. The control strategy will be implemented using the ANFIS method. The controller will be designed based on the desired torque for driving and the state of charge of batteries. The output of controller adjusts the throttle in the combustion engine. The main contribution of this paper is the development of optimal control based on neuro-fuzzy, which maximizes the output torque of the vehicle while minimizing fuel consumption used by the internal combustion engine. Simulation results show very good performance of the proposed controller.**

I. INTRODUCTION

Nowadays automobiles are an important part of our everyday life. But, the exhaust emissions of conventional Internal Combustion Engine (ICE) Vehicles are to blame for the major source of urban pollutions that cause the greenhouse effects leading to global warming. The dependence on oil as the only source of energy for passenger vehicles soon may lead to a global crisis, when the oil reserves in the world wane. The increasing number of automobiles being introduced on the road every year is adding to the pollution problem. There is also an economic factor inherent in the poor energy conversion efficiency of ICEs [1].

These problems of ICE vehicles provide a forced motive to develop clean and high efficient vehicles for urban transportations. Electric Vehicles (EVs) that have no emissions attracted the attention of many car industries for many decades. However, EVs have some drawbacks, such as short driving distance, long recharging time for batteries and high costs.

In 1990s, a large number of automobile industries started developing Hybrid Electric Vehicles (HEVs) to overcome the problems of EVs. HEVs produce the power required to drive the vehicle by a combination of two sources, an ICE and an electric motor. HEVs seem to be viable alternative to the ICE automobiles at the present. They can be generally classified as series or parallel hybrid vehicles. In series HEVs, same as EVs, all the torque required to drive the vehicle is provided by an electric motor. On the other hand, in Parallel Hybrid Electric Vehicles (PHEVs), the torque obtained from the ICE is mechanically coupled to the torque produced by an electric motor [2]. In PHEVs, operation style of each sources (ICE or electric motor), and amount of their contribution in production of torque at any time, will be decided by a controller. This controller determines the contribution of each driving source based on the requested torque and the State Of Charge (SOC) of batteries. In this case, in order to optimize the fuel economy and emissions of ICE, it is necessary that the controller adjusts ICE in optimal point at all times.

In this paper, we will use an intelligent method to design controller for PHEVs that minimizes the fuel consumption. But, minimizing fuel consumption, could lead to torque reduction, which may not yield a very pleasant driving. Therefore, in addition to fuel minimization, it is necessary to maximize the torque as well. Simulation results demonstrate very good trade off between fuel consumption and torque maximization. That is, a good optimal solution has been achieved using the proposed method in this paper.

In the rest of this paper, section II describes the model of the system. Section III explains the proposed controller in this paper. Simulation results are presented in section IV, followed by conclusions in section V.

II. SYSTEM MODEL DESCRIPTIONS

In this section, the model of PHEV powertrain parts is presented. In following sections, first in part A, the PHEV powertrain architecture, and then in parts B to D the models of each part of vehicle, that will be used in our simulation, are briefly explained.

A. Parallel Hybrid Electric Vehicle Architecture

Fig. 1 presents the block diagram of a PHEV powertrain with an electrical machine and an ICE that are combined together to drive the vehicle [3]. The electrical machine works as generator when the state of charge (SOC) of batteries is low and there is need to charge the batteries, and works as motor when a torque is needed for driving the vehicle. The controller, designed by neuro-fuzzy method, controls the engine by changing the throttle angle in order to produce the required torque. The torque requested from electric motor is calculated by subtracting the real engine output torque, from the desired torque at any time.

B. Engine Dynamic Model

We use a simple model of engine introduced in [4]. This model includes a two-state dynamic model, whose output is the ICE torque. The states of the model are the speed of engine (x_1) and the manifold pressure (x_2).

$$\dot{x}_1 = -280.92 - \frac{3337.3}{x_1} + 818.77x_2 - 307.29x_2^2 + 0.91185x_1x_2 + 0.24428x_1 - 0.00076429x_1^2 - 7.1429T_{load} \quad (1)$$

$$\dot{x}_2 = 0.15126 - 0.0371x_1x_2 + 0.01393x_1x_2^2 - 0.00004133x_1^2x_2 + 0.41328g(x_2)u \quad (2)$$

$$g(P_m) = \begin{cases} 1, & P_m \le \frac{P_{amb}}{2} \\ \frac{2}{P_{amb}}\sqrt{P_{amb}P_m - P_m^2}, & P_m > \frac{P_{amb}}{2} \end{cases} \quad (3)$$

$$u = f(\theta) = 2.821 - 0.05231\theta + 0.10299\theta^2 - 0.00063\theta^3 \quad (4)$$

$$T_{eng} = -39.32 - \frac{467.22}{x_1} + 114.62x_2 - 43.02x_2^2 + 0.1276x_1x_2 + 0.03419x_1 - 0.000107x_1^2 \quad (5)$$

where T_{eng} is the ICE torque, T_{load} is the load torque, θ is the throttle angle, P_{amb} is the ambient pressure, and $g(\cdot)$ is a function introduced in (3).

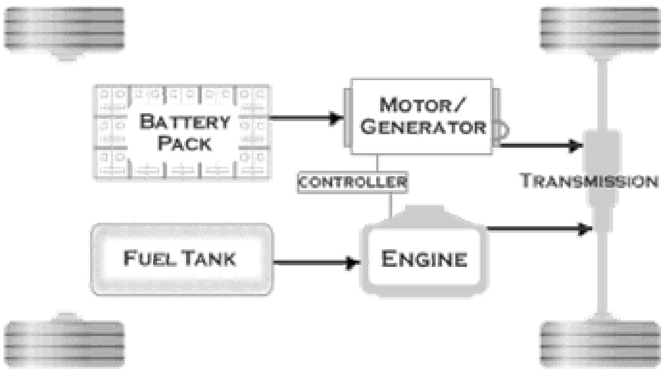

Fig. 1. The block diagram of a PHEV powertrain

C. Battery Dynamic Model

The dynamic model of battery has following state equations [5, 6]:

$$\tilde{R}C_p\dot{x}_1 = V_{oc} + \frac{\tilde{R}}{R_b}x_2 - \left(\frac{R_b + \tilde{R}}{R_b}\right)x_1 \quad (6)$$

$$R_bC_i\dot{x}_2 = x_1 - R_bI - x_2 \quad (7)$$

where x_1 is an internal state; x_2 is the terminal voltage of battery; V_{oc} is the open circuit voltage of battery, which is a function of SOC and temperature, I is the input or output current (input in charge mode and output in discharge mode), $\tilde{R}$ is charge or discharge resistance defined in (8). For battery internal variables, we assume numeric variables of $R_b = 0.4, C_i = C_p = 1$ in our simulations.

$$\tilde{R} = \begin{cases} R_{charge} \cong 0.7 & I < 0 \\ R_{discharge} \cong 0.3 & I > 0 \end{cases} \quad (8)$$

It should be noted that SOC is a function of current and temperature and can be estimated with variety of methods. In this paper, we use Ampere-hour counting technique for calculating the SOC [7].

D. Electric Motor and its Controller Model

We use an AC-75 electric motor and its controller model, which has been defined in ADVISOR 2002 software [8]. In this software, the losses in the electric motor and its controller as well as the rotor inertia, and the dependency of speed to the toque have been considered. Power losses are given as a 2-D lookup table indexed by rotor speed and output torque. The maximum motor torque is enforced using a lookup table indexed by rotor speed. Motor controller ensures that the maximum motor current is not exceeded and that the electric motor is not working when it is not needed [9].

III. DESIGN OF OPTIMAL CONTROLLER

In the control of a PHEV, the main goal is to set the ICE operation in its peak efficiency region. This improves the overall efficiency of the powertrain. The ICE operation must be set according to the road load and the SOC. Therefore, the controller will use two inputs: the desired torque and the battery pack SOC. Based on the above inputs, the ICE operation point is set (by changing the throttle angle). The desired electric motor torque can be given as

$$T_{EM\_Desired} = T_{desired} - T_{ICE\_Set} \quad (9)$$

where $T_{desired}$ is the desired powertrain torque, and T_{ICE_Set} is the desired torque of the ICE, defined by the controller [9].

In order to control PHEV, there are three goals: 1) maximizing fuel economy, 2) reduction of vehicle output emissions, and 3) maintaining acceptable powertrain performance by maximizing the vehicle output torque. In contrast to this, in [10] and [11] the only goal is to optimize the energy management strategy of the vehicle. Also, in [12] and [13] the goal is to maximize the torque of vehicle. In this paper, on the other hand, we try to find a compromised solution to these goals by designing an Adaptive Neuro-Fuzzy

Inference Systems (ANFIS) controller [14]. For designing the controller, there are 5 membership functions for the inputs: the desired torque, and the SOC. These membership functions have been shown in Figs. 2 and 3. The output of controller is the throttle angle of the ICE.

The required data to train the ANFIS has been collected from two controllers in ADVISOR: fuel-minimizing (fuel-mode) controller, and efficiency-mode (eff-mode) controller, which maximizes the output torque. In this paper the goal is to find a compromised solution to these objects. Therefore we collect data from both of these controllers and use them to train the ANFIS controller. The general structure of ANFIS has been shown in Fig. 4.

IV. SIMULATIONS AND RESULTS

In the simulation, we have used ADVISOR software, available in [8], in which certain blocks have been replaced by dynamic equations, given in section II.

The block diagram of the proposed method is presented in Fig. 5.

The simulation results of the desired speed of vehicle and the actual vehicle speed, and their error has been shown in Figs. 6 and 7, respectively, which show good performance of the proposed controller. Moreover, the SOC of batteries plotted in Fig. 8, shows very small changes, resulting in longer life-time of batteries. The fuel consumption of the vehicle is shown in Fig. 9. Integrating the fuel consumption over the traveled distance (6.4 Km), we find that the fuel consumption is 4.1 liters per 100 Km.

In addition to that, a significant improvement in the emissions, shown in Fig. 10, can be observed. The amounts of emissions have been given in table I. Fig. 12 shows that the torque with respect to desired vehicle speed has been maximized. Comparing the results of ANFIS with the results of two controller modes in ADVISOR shows a very satisfactory performance of the proposed controller in this paper.

V. CONCLUSIONS

In this paper we presented a method for controlling PHEVs in order to find an optimal solution between minimizing fuel consumption, maximizing vehicle torque, and minimizing exhaust emissions. For this reason, an ANFIS controller was designed and used in a modified version of ADVISOR software. The data for training ANFIS network gathered from two methods used in ADVISOR that one of them designed only for minimizing the fuel consumption and another one is designed only for reaching maximum torque and efficiency of engine. Simulations show promising results as compared to two different control modes in ADVISOR.

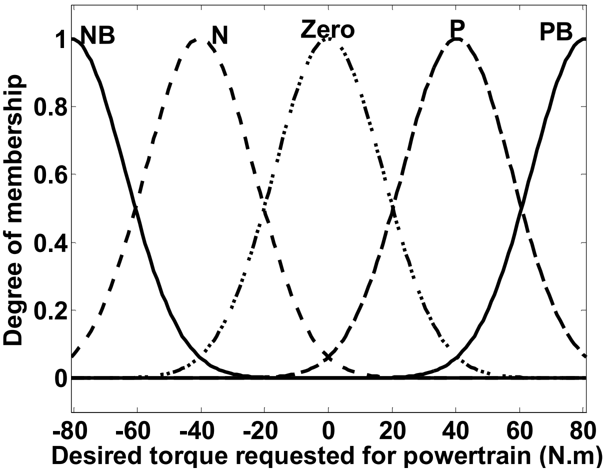

Fig. 2. Membership functions of desired torque (input 1)

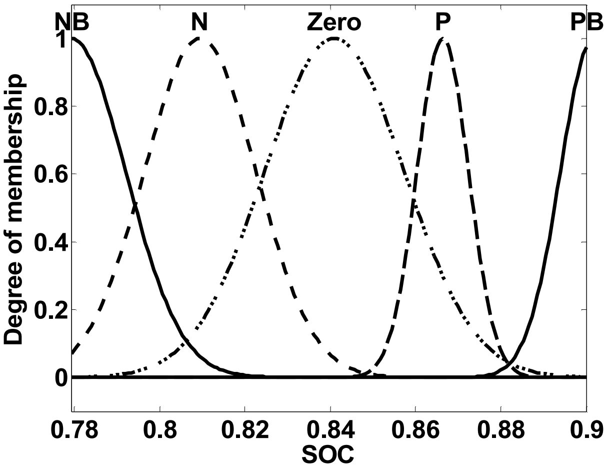

Fig. 3. Membership functions of SOC of batteries (input2)

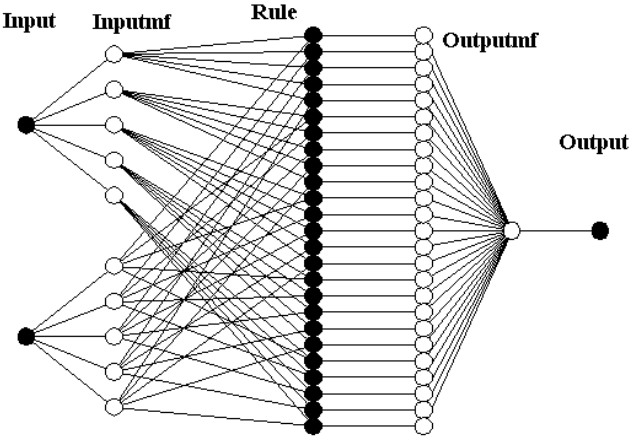

Fig. 4. The general structure of ANFIS

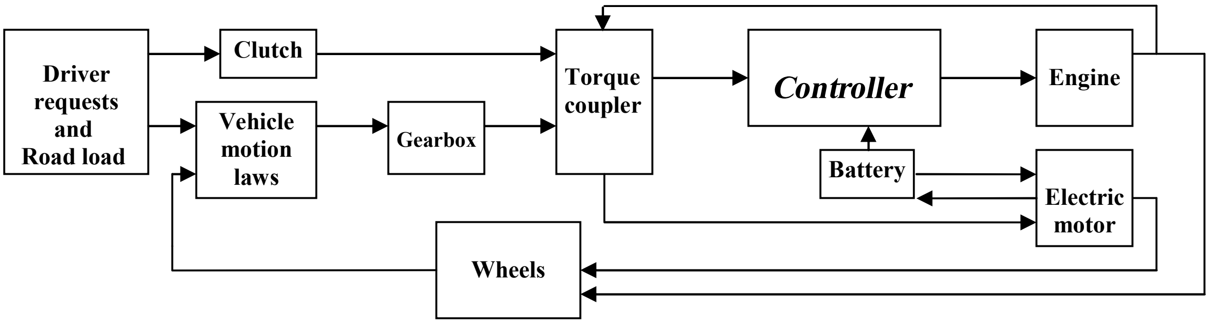

Fig. 5. The block diagram of the proposed controller for PHEV

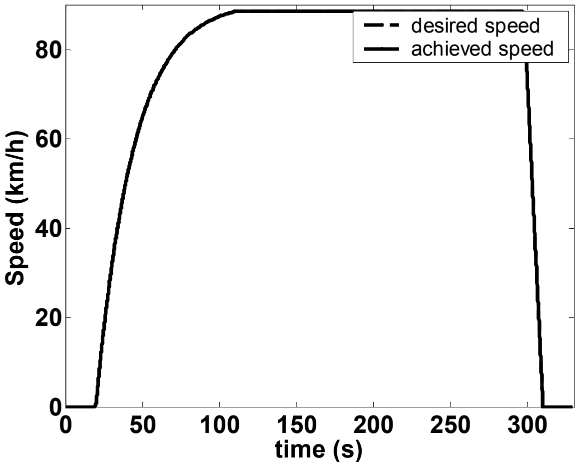

Fig. 6. The desired and achieved vehicle speeds

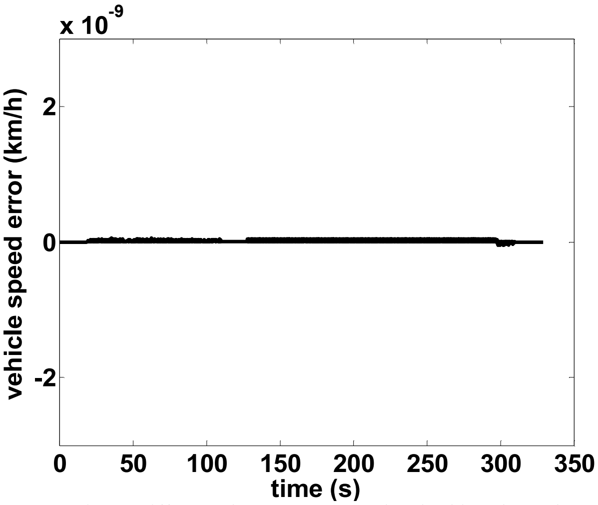

Fig. 7. Difference between requested and achieved speeds

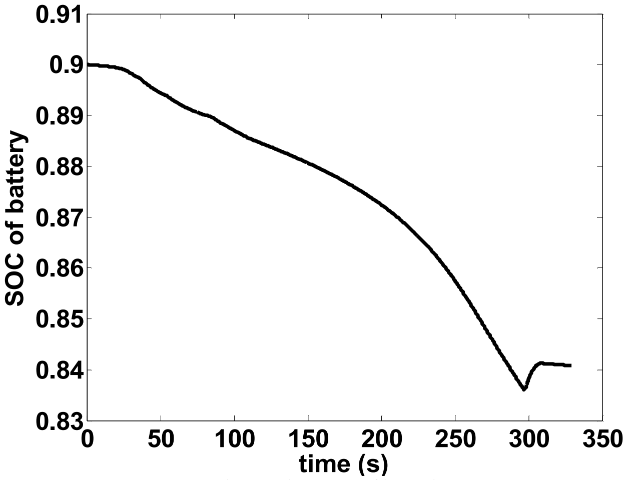

Fig. 8. The SOC of batteries

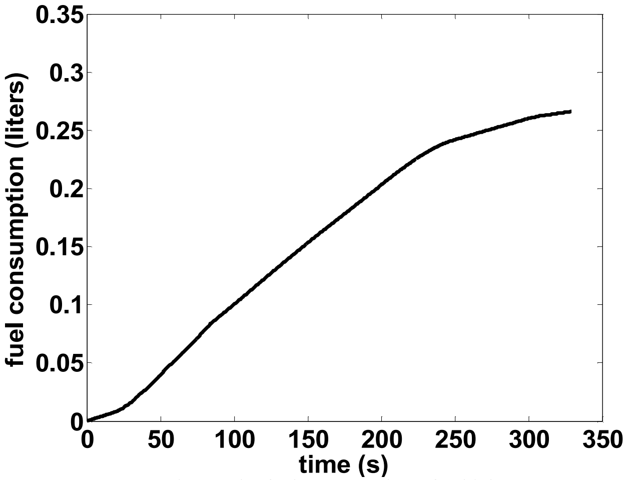

Fig. 9. The fuel consumption of vehicle

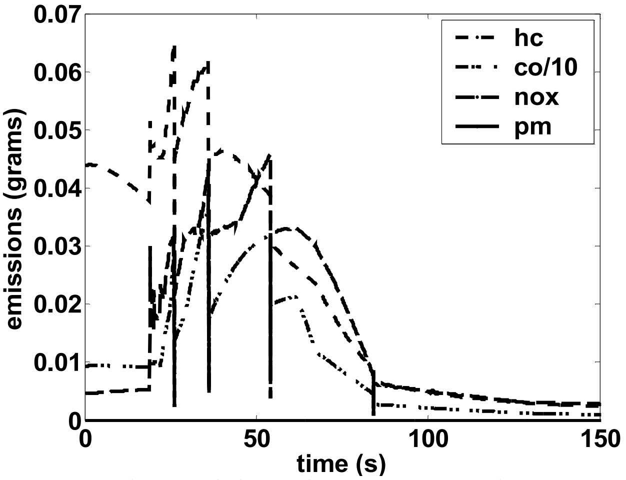

Fig. 10. emission results (HC, CO, NOx, and PM)

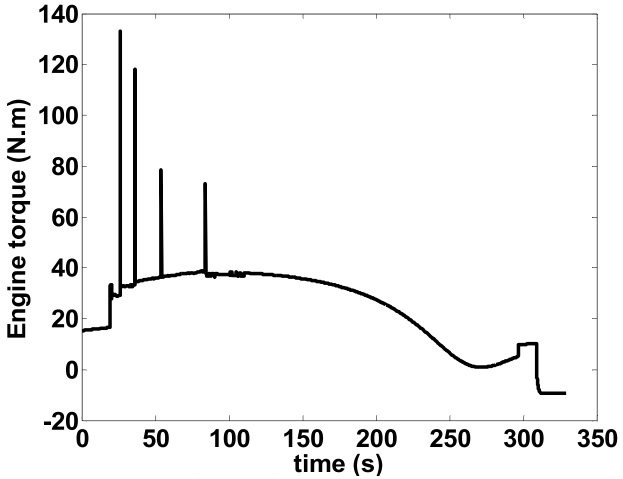

Fig. 11. The engine output torque

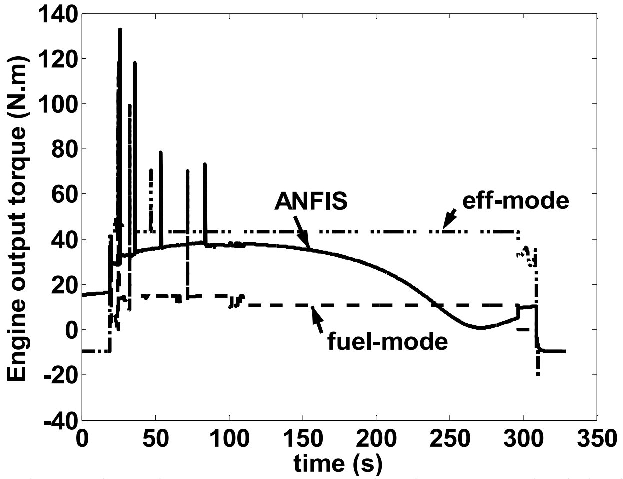

Fig. 12. The engine output torque comparison between our simulation by ANFIS controller and two ADVISOR controllers (fuel-mode and eff-mode)

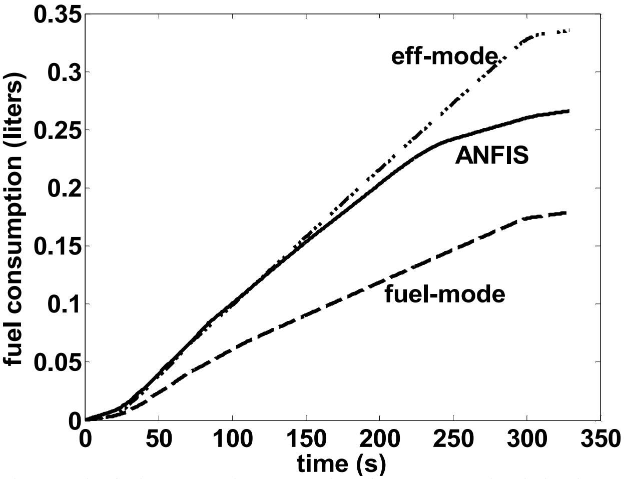

Fig. 13. The fuel consumption comparison between our simulation by ANFIS controller and two ADVISOR controllers (fuel-mode and eff-mode)

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