HEV - AI Based Real Time Control Strategy

N. Al-Aawar and A. A. Arkadan, Fellow IEEE
Rafik Hariri University,
Mechref, P.O. Box 10, Damour-Chouf, 2010, Lebanon
E.mail: awarnf@rhu.edu.lb

***Abstract*- A control strategy is developed to minimize fuel consumption while maintaining good performance and drivability of Hybrid Electric Vehicle, HEV. The optimal control strategy is found in two stages. The first utilizes a mathematical search algorithm based on the calculus of variation to minimize fuel consumption and develop needed torque to achieve good performance. The second stage employs an artificial intelligence fuzzy logic based algorithm to ensure comfort and good drivability. The superiority of the optimization algorithm is demonstrated by applying it to a prototype HEV configuration and by comparison to readily available benchmark data.**

***Index Terms*--Optimization and Design, HEV and Applications.**

I. INTRODUCTION

Much work was done to optimize the design and performance of HEV's due to the demand for more environmentally friendly and fuel efficient vehicles [1]. The main principle is to design a power train that can develop the total tractive force necessary to operate the vehicle. The optimization of the powertrain is highly dependent on the design of the system components and the control strategy used to drive the HEV, Fig. 1. The powertrain components design optimization mainly addresses the design of the Electric Drive System, EDS, to provide maximum torque for different driving cycles in order to reduce the size of the ICE [2]. The real time AI based optimal control strategy presented in this work utilizes a calculus of variation algorithm which requires a continuous search space. Accordingly, a continuous mathematical model based on the Generalized Notion of Power, GNP is used to characterize the ICE and the Electric Motor - Generator, EMG, of the HEV's powertrain [2]. The proposed AI based control strategy is used to allocate the total tractive force between the ICE and EDS, in order to operate close to the Optimal Operating Line, OOL, [2] and to ensure good drivability.

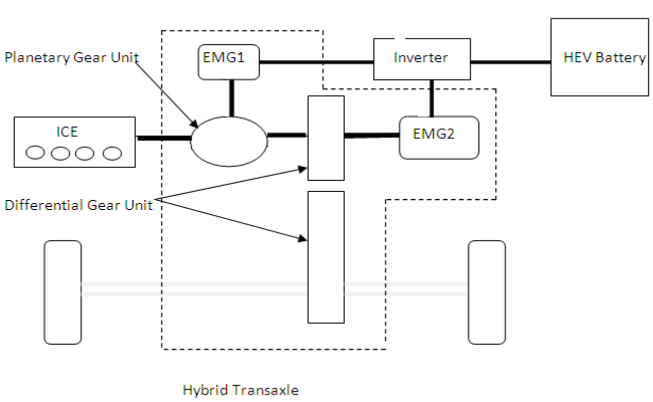

Fig. 1 Toyota Prius Split Power Configuration

II. THE OPTIMIZATION PROBLEM

The optimization problem is of two folds. The first addresses the need to minimize fuel consumption and to achieve good performance. The second is centered on the issues of comfort and good drivability. The first objective is addressed by developing a control strategy that allocates torque between the ICE and the EDS so as to minimize fuel consumption while meeting the required power demand for various driving cycles and maintaining batteries sustainability and satisfying the State Of Charge, SOC constraint. Accordingly, the calculus of variation cost function that correlates with the above objective is given as follows:

$$J = \int_{t_0}^{t_f} (\dot{m}_f + \gamma_1 (S - S_{\max}) hard\lim(S - S_{\max}) + \gamma_1 (S_{\min} - S) hard\lim(S_{\min} - S) \quad (1)$$

where S is the SOC of the batteries and $\dot{m}_f$ is the rate of fuel consumption. In addition, the good road performance is achieved by fulfilling the required power, $P_{req,}$ for the HEV to follow the given real time driving cycle. This is equivalent to satisfying the following power constraint:

$$P_{ice} + P_{eds} = P_{req} \quad (2)$$

The second objective is addressed by developing an AI based fuzzy logic algorithm to ensure good drivability (comfort). The good drivability is achieved by minimizing the torque hole (torque deficiency during shifting) [3]. This is done by predicting the speed schedule of the real time driving cycle and by computing the optimum gear ratio. A summary of the optimization process flow chart is shown in Fig. 2.

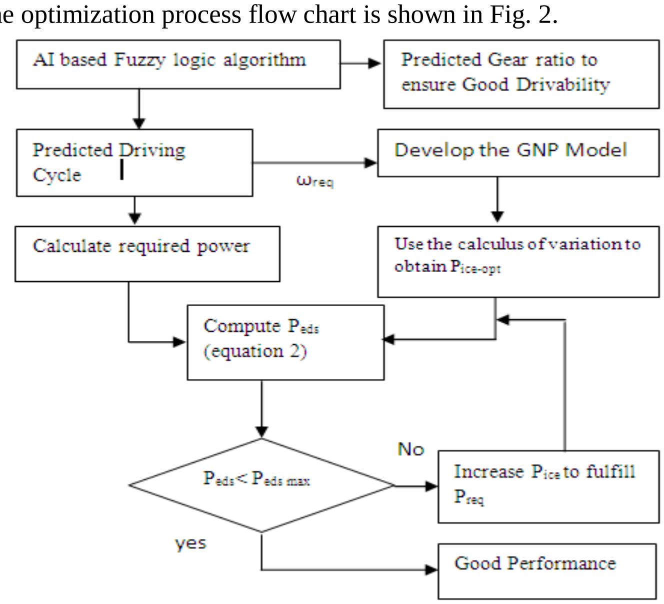

Fig. 2 Optimization process Flow chart

III. Application and Results

The proposed algorithm of Fig. 2 is used on the split – power configuration of Fig. 1 for a prototype Toyota Prius. The implementation of the real time optimization algorithm and the calculus of variation of equation (1) above necessitate the use of a continuous model based on the Generalized Notion of power, GNP. The GNP is used to unify the notation for both the EDS and the ICE systems so it can be modeled in one state space equation [2]. The GNP is implemented as the vector multiplication of the effort variable vector e and the generalized displacement variable vector q to arrive at the needed power and torque of the HEV's powetrain. The parameters of the state space can be computed from a series of magnetic field solutions or from measured data [2], in order to account for the magnetic material nonlinearities and complex geometry of the motor-generator components of the EDS. The GNP also uses the second law of thermodynamics to account for the irreversibility of the entropy generation by the ICE [2].

A. Optimal Control Algorithm-Calculus of Variation

The calculus of variation is used to obtain the sate and co-state equations of the defined cost function of equation (1). These equations are then solved for the optimum Hamiltonian shown below:

$$H = \frac{(P_{ice} + P_{ml})}{e.H_v} - \frac{\lambda}{2R_i.Q_{batt}} \cdot \begin{Bmatrix} (U_0 - \sqrt{K/\eta_{em}}) & discharging \\ U0 - \sqrt{K.\eta_{em}}) & Recharging \end{Bmatrix} \quad (3)$$

where, $K = U_0^2 - 4R_i(P_{req} - P_{ice})$, I is the electric machine current in A, Q is the battery capacity in C, R_i is the battery internal resistance in Ω, Uo is the battery open circuit voltage in V, η_{em} is the EMG efficiency, e is the intrinsic ICE energy conversion efficiency, H_v is the lower heating value of fuel in J, and P_{ml} is the mean friction pressure in Pascal.
The optimum Hamiltonian is mainly function of P_{ice} and thus to obtain the optimum P_{ice} the first and second derivative of the Hamiltonian with respect to P_{ice} are taken. Then the optimum P_{ice} is calculated as follows:

$$P_{ice\_opt} = P_{req} - \frac{U_0^2}{4Ri\,\eta_{em}} + \frac{\lambda^2.e^2.H_v^2.\eta_{em}}{4Ri.Q_{batt}^2} \quad (4)$$

B. Optimal Control Algorithm –AI based FL

The AI based fuzzy logic algorithm is used to ensure good drivability by predicting the speed of the driving cycle ahead and by computing the optimum gear ratio. The prediction of next required speed is done by an ANFIS that computes the key features of the HEV driving schedule and performs a pattern recognition strategy to obtain the correct driving cycle and predicts the corresponding speed schedule. A second fuzzy logic unit is used to improve the comfort of driving by calculating the optimum gear ratio that minimizes the Driving Index, DI. This index summarizes several indicators of good drivability such as noise ratio etc. [3] and is defined by a membership function.

IV. Results

The HEV of Fig. 1 is tested for the Urban Driving Cycle, UDC. The application of the proposed control algorithm resulted in the ICE efficiency Map, and the EDS torque speed characteristics. The predicted results are shown in Fig. 3 to Fig. 5 as compared to available benchmark data for validation [4]. An inspection of the results reveals the superiority of the proposed algorithm as the HEV operates next to maximum efficiency in terms of torque and drivability is higher than 7/10 comfort level. More results and full details will be given in the paper.

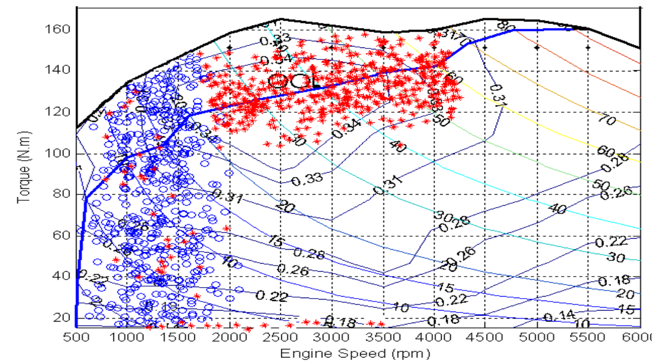

Fig. 3 Optimal engine operating points on fuel consumption map (○ benchmark controller; *: optimal controller)

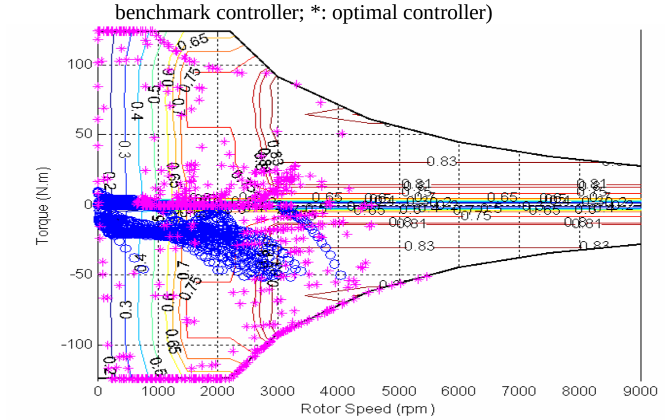

Fig. 4 EDS Torque Speed Characteristic (○ benchmark controller; * optimal controller)

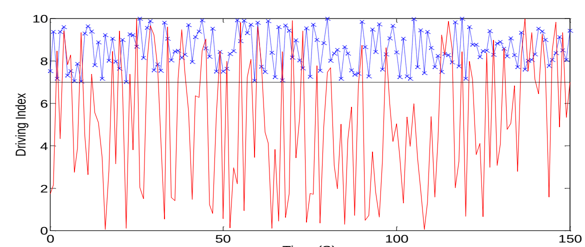

Fig. 5 Driving Index, DI, (- benchmark controller; x optimal controller)

References

[1] S. G. Wirasingha. A. Emadi, *"Classification and Review of Control Strategies for Plug-In Hybrid Electric Vehicles,"* IEEE Transaction on Vehicular Technology, Vol. 6, Issue 1, pp 111-122, Jan. 2011.

[2] N. Al Aawar, A. A. Arkadan, "*Mechatronic Model of HEV Using Generalized Notion of Power: CEFC 2012, Oita Japan* Conference Digest. PP. Wc1-2, Nov. 11-14, 2012.

[3] T. Megli, M. Haghooie, D. Colvin, "*Shift Characteristics of a 4 speed Automatic transmission,"* SAE Paper 1999-01-1060.

[4] U.S. DOE Plug-in Hybrid Electric Vehicle R&D Plan, 2007.