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Mechanical Engineering - Posters

A SIMPLE FUZZY CONTROL DESIGN FOR SERIES HYBRID ELECTRIC VEHICLE

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Abstract
This paper proposes a simple fuzzy control design for a hybrid electric vehicle with a series connected powertrain system. In course of the research a complex system model was used which consists of three main components, i.e. the driver modeling subsystem, the control subsystem, and the subsystem modeling the hybrid vehicle. The primary objective was to develop a controller that ensures a low level dissipation in case of a predefined driving cycle by controlling the electric motor, the internal combustion engine, and the generator. In order to minimize fuel consumption and to take into consideration some other requirements a complex cost function was defined as objective function for the tuning process. A hill climbing type optimization approach was used for the tuning of the system.

Keywords:
fuzzy control, hybrid vehicle

1. Introduction

Hybrid electric vehicles (HEVs) have become commercially feasible products because they can combine some advantageous features of the conventional internal combustion engine vehicles (ICEVs), i.e. large driving range and rapid refueling, with the advantages of electric vehicles (EVs), i.e. low emission of harmful pollutants [4]. Although the development of EVs that ensure zero level emission is considered as the long term objective in medium term the development of HEVs is significantly motivated by the practical limits of the current battery and fuel cell technologies [16].
HEVs can be classified into four basic kinds: series [2] [3], parallel [7][12][16][22], series-parallel [9], and complex [4]. In our research, we adopted the series hybrid concept owing to its simplicity. Its details are described in Section 2.
Computational intelligence based solutions have been applied for a wide range of problems like control [14][15][17], expert systems [5][19], risk assessment [13], decision making systems [20], etc.. The objective of this paper is to present a simple fuzzy control solution for a series HEV. The controller has to ensure a low level dissipation in case of a predefined driving cycle by controlling the electric motor, the internal combustion engine, and the generator. The proposed solution was tried using simulations with a complex vehicle system model created in Simulink.
The rest of this paper is organized as follows. Section 2 presents shortly the structure of the whole model. Section 3 introduces the main steps of the control system design. The simulation and performance evaluation results are presented in Section 4 and the conclusions are drawn in Section 5.

2. System structure

Fig. 1 shows the functional block diagram of the series HEV. Its key feature is that the ICE is coupled with the generator (G), which produces electricity used either for charging the battery (B) or for providing power for the electric motor (EM). The later also can be used for power generation in case of braking. The vehicle has pure electric propulsion. The link between fuel tank (FT) and ICE is hydraulic; between ICE and generator as well as between electric motor and transmission system (T) is mechanical, while the links between generator, battery and electric motor are electrical. This engine assisted EV concept makes possible an extended driving range that is comparable to the driving range of ICEVs [4].

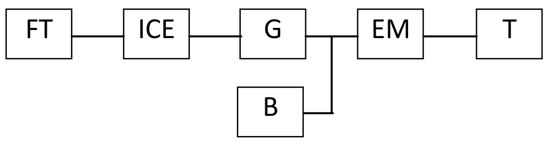

Figure 1. Block diagram of the whole system

The architecture of the whole system created in Simulink is given in Fig. 2. The first block produces the reference speed values prescribed by the applied driving cycle. The second block (Driver) models the driver and is responsible for tracking the driving cycle. The third block (Fuzzy_Control_HV_2) contains the fuzzy control presented in the following sections and the fourth block (Hybrid_system_continuous) contains the

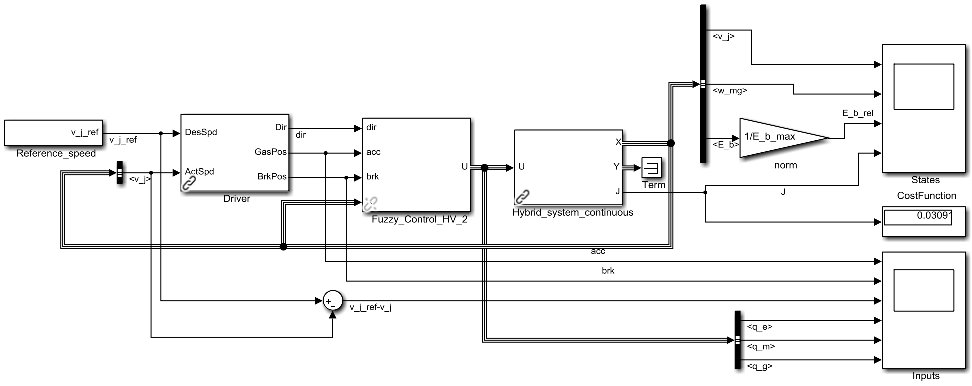

Figure 2. Block diagram of the whole system

series hybrid model. The first two blocks and the last block are described in [18]. The last three elements (right hand side) serve the visualization of the signals (see Fig. 8 and 9) and the cost function used for the evaluation of the control structure. Our study focuses on the third block; therefore the rest of this paper will be related only to this topic.

3. Fuzzy control system design

The Fuzzy-Control subsystem (block Fuzzy_Control_HV_2 in Fig. 2) implements the fuzzy logic using standard blocks from Matlab's Fuzzy Logic Toolbox, as well as some pre- and postprocessing operations that are necessary to ensure a normalized input to the fuzzy blocks and the transmission (further use of the normalized output of the fuzzy block).

3.1 Controller Inputs and Outputs

After the analysis of the vehicle model we chose the following characteristics as inputs of the control system:

dir the movement direction of the car. Here the positive values indicate the forward movement, while the negative values indicate the reverse movement.

acc a value belonging to the interval [0,1] indicating the position of the gas pedal.

brk a value belonging to the interval [0,1] indicating the position of the brake pedal.

X a vector with multiple components from which we use an indicator of the energy stored in the battery (E_b).

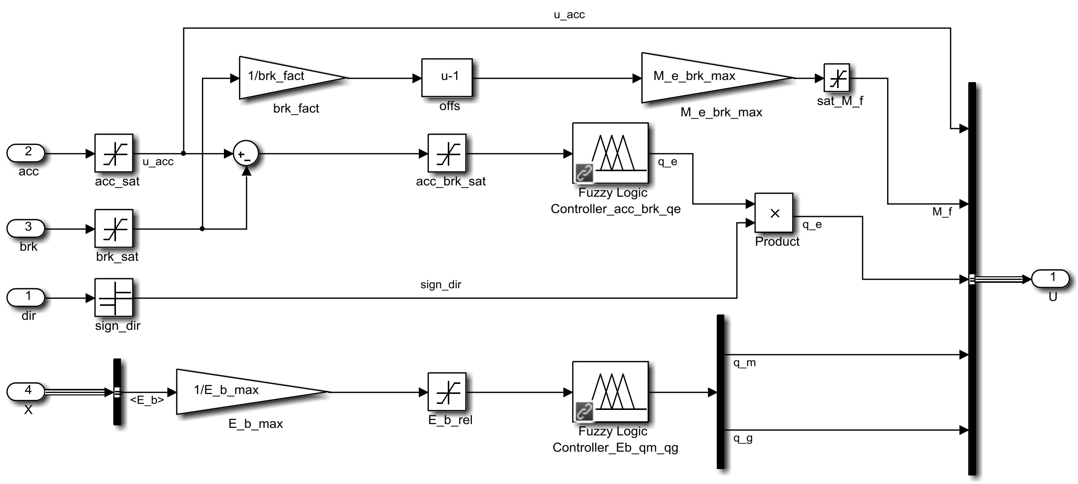

Figure 3. Block diagram of the control subsystem

Similarly the outputs of the controller are:

M_f the torque of the friction brake.

q_e a value belonging to the interval [0,1] indicating the control input of the electric motor.

q_m a value belonging to the interval [0,1] indicating the control input of the ICE.

q_g a value belonging to the interval [0,1] indicating the control input of the generator.

3.2 Definition of the structure of the control subsystem

The block diagram of the fuzzy subsystem is shown in Fig. 3. The control subsystem contains two fuzzy logic controller blocks, i.e. a SISO (single input single output) and a SIMO (single input multiple output) fuzzy system.

The first fuzzy block controls the electric motor by the means of the q_e signal based on the actual values of the gas and brake pedal positions (*acc_brk_sat*). The second fuzzy block controls the ICE (q_m) and the generator (q_g) based on the relative state of charge of the battery (E_{brel}). The *dir* parameter defines the sign of the q_e signal through a product block.

The acceleration signal was needed by the next subsystem (series hybrid model) too. Therefore its value is led out through the bus creator block. The torque of the friction brake (M_f) is calculated from the saturated value of the brake signal. The constant values used in course of the calculations are presented in Table 1.

Table 1. Constants

Constant	*Value*	*Unit*
M_{ebrk}^{max}	300	NM
brk_fact	0.5	-
E_b^{max}	$4.3\ 10^6$	J
B^{max}	0.0014	kg/s
e_{CO}^{max}	$4.5747\ 10^{-4}$	kg/s
e_{HC}^{max}	$6.8620\ 10^{-4}$	kg/s
e_{NOx}^{max}	$5.7907\ 10^{-4}$	kg/s
ξ_j^{max}	2.7500	m/s^2

3.3 Preprocessing Operations

In case of the first input (*dir*) we need only two discrete values that symbolize the forward (+1) and reverse (-1) movement of the vehicle. It is achieved with a sign block (see Fig. 3). In order to ensure an acceleration and a braking signal belonging to the [0,1] interval saturation blocks are applied. Furthermore, supposing that the driver does not press at the same time the gas and the brake pedals we could aggregate the two signals taking the brake signal with negative sign. The result is also saturated to the [-1,1] interval.

In case of the last input (E_b) that was taken from the bus signal *X* we created a relative (normalized) value for it by dividing the actual value by the maximum possible value given as a constant parameter of the vehicle system. In order to avoid the possibility of functioning errors of the fuzzy blocks we had to ensure that the resulting relative values always belong to the unit interval. This demand was fulfilled by the application of a saturation block.

3.4 Operational Characteristics of the Fuzzy System

In case of both fuzzy blocks we started with Ruspini type partitions and the parameters of the fuzzy sets were optimized for the cost function (1) using a simple hill climbing type algorithm. Further on only the characteristics of the resulting (optimized) fuzzy systems are going to be presented.

First Fuzzy System

In case of the first fuzzy system that controls the electric motor for both the antecedent and consequent universes of discourses we used trapezoid and triangle shaped membership functions (see Figs. 4~5). Partitions with six fuzzy sets were created in order to ensure a proper distinction between the braking and acceleration.

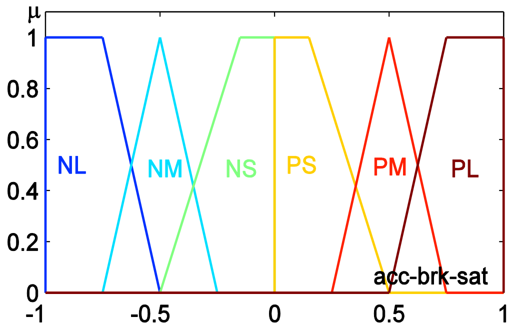

Figure 4. Antecedent partition of the first fuzzy block

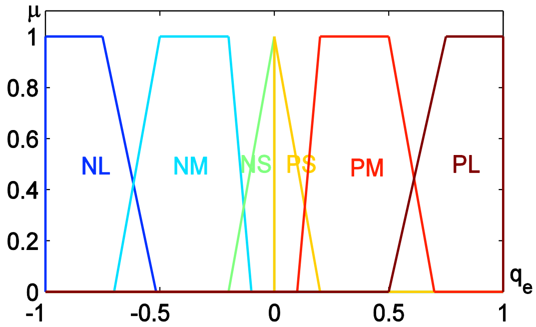

Figure 5. Consequent partition of the first fuzzy block

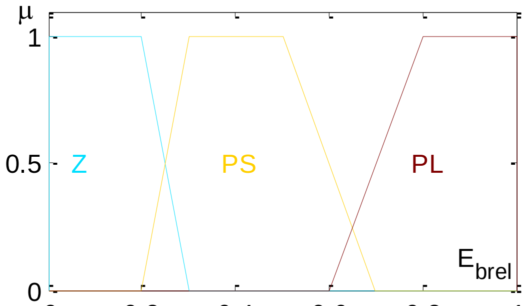

Figure 6. Antecedent partition of the second fuzzy block

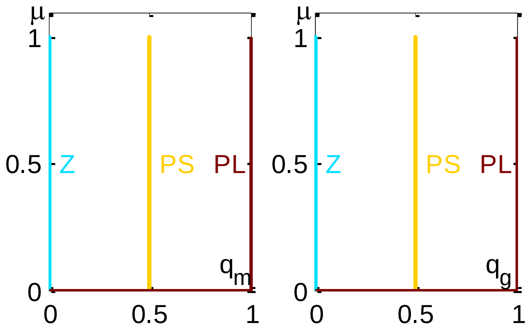

Figure 7. Consequent partitions of the second fuzzy block

We used the conventional simple notation mode (linguistic values) for the three sets, i.e. *NL* (Negative Large), *NM* (Negative Medium), *NS* (Negative Small), *PS* (Positive Small), *PM* (Positive Medium), and *PL* (positive large) in case of both dimensions.

Second Fuzzy System

In case of the second fuzzy system that controls the ICE and the generator we used triangle and trapezoid shaped membership functions (see Figs. 6~7). We used the conventional simple notation mode for the three sets, i.e. *Z* (zero), *PS* (Positive Small), and *PL* (positive large) in case of both dimensions.

3.5 Rule Base

First Fuzzy System

The first fuzzy block is a SISO fuzzy system of which rule base contains the six rules presented in Table 2.

Table 2. Rules of the first fuzzy block

	acc_brk_sat	q_e
1	NL	NL
2	NM	NM
3	NS	NS
4	PS	PS
5	PM	PM
6	PL	PL

Table 3 Rules of the second fuzzy block

	E_{brel}	q_m	q_g
1	Z	PL	PL
2	PS	PS	PS
3	PL	Z	Z

Second Fuzzy System

The second fuzzy block is a SIMO fuzzy system with two output dimensions. Its rule base contains the following three rules presented in Table 3.

4. Simulation and performance evaluation

In order to minimize fuel consumption and to take into consideration some other requirements a complex cost function (1) was defined as objective function for the tuning process.

$$J = \int_0^T \sqrt{\left(\frac{B}{B^{\max}}\right)^2 + \left(\frac{e_{CO}}{e_{CO}^{\max}}\right)^2 + \left(\frac{e_{HC}}{e_{HC}^{\max}}\right)^2 + \left(\frac{e_{NOx}}{e_{NOx}^{\max}}\right)^2 + \left(\frac{\xi_j}{\xi_j^{\max}}\right)^2 + \left(\frac{E_{brel}}{E_{brel}^{\max}}\right)^2}\, dt \cdot \frac{1}{\int_0^T dt}, \qquad (1)$$

where T is the simulation time, B is the fuel consumption of the ICE, e_{CO} is the CO emission of the ICE, e_{HC} is the HC emission of the ICE, e_{NOx} is the NOx emission of the ICE, ξ_j is the acceleration factor, E_{br} is the battery energy level. All components of the cost function were taken into consideration with equal weights.

The simulation was carried out for T=10 000 seconds. Figs. 8 and 9 show that the ICE was mainly used after t=2 108 s when the state of charge (SOC) E_{brel} fall below 0.7. In long term (between 2 108 s and 10 000 s) the relative SOC was kept between 0.64 and 0.68, which ensures a charge sustainability of the system. Fig. 9 (third row) presents that the driver block and the first fuzzy control block ensures a good tracking of the predefined driving cycle. After an initial fluctuation the value of the cost function stabilized around 0.03. Its final value became 0.03091.

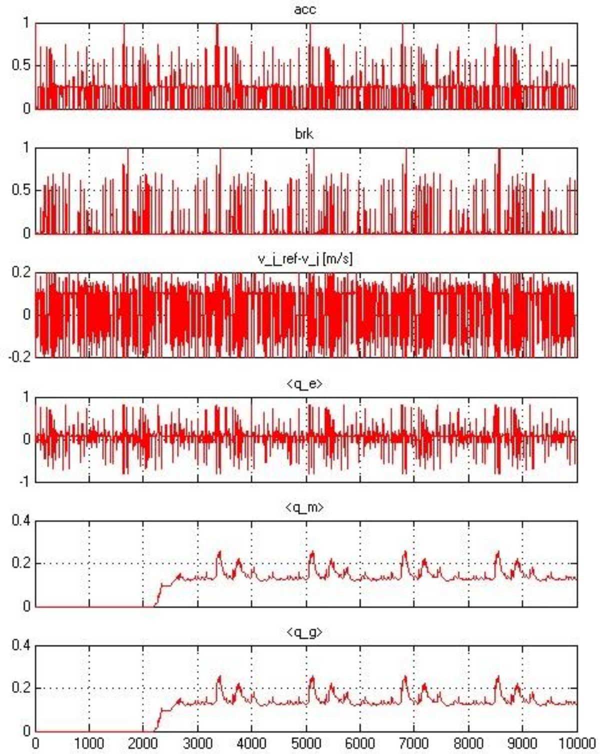

Figure 8. Input and output signals

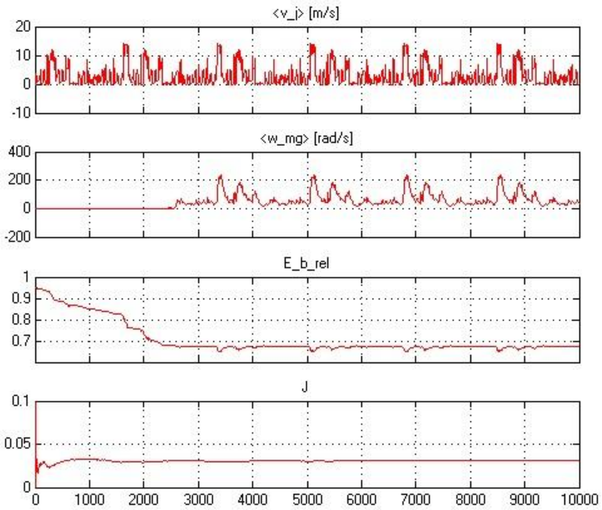

Figure 9. State signals

5. Conclusion

In this paper, a simple fuzzy logic based solution was presented for the controlling of the power management of a series hybrid vehicle. Our objective was to develop a controller that ensures a low level of harmful pollutant emission while the charge sustainability of the system is also ensured. To fulfil this demand a cost function was created and the parameters of the fuzzy control were optimized based on its value. In case of the applied driving cycle the developed system ensured a good solution.

Further research will consider other options regarding the applied HEV type, interpolation based fuzzy inference techniques (e.g. [6][8][11]) and automatic rules base generation and optimization methods (e.g. [21][1]). The research on the optimal weights of different factors taken into consideration in equation (1) is also subject to further research work.

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