A Simple Fuzzy Logic Based Power Control for a Series Hybrid Electric Vehicle

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***Abstract* — Hybrid electric vehicles became popular owing to their capability to combine the advantages of electric propulsion and legacy internal combustion engines. The main objective of the research work reported in this paper was to find a fuzzy logic based control solution for the power management of a specific series hybrid electric vehicle. The developed controller was modelled in Simulink and it was evaluated through simulation runs for different initial battery energy levels and different usage profiles. Basically we tried two different approaches. In the first case the aim was to keep the state of charge (SOC) of the battery at a constant level, while in the second case the SOC had to follow a prescribed function of time. The developed fuzzy system ensured good results in both cases.**

Keywords - fuzzy control; hybrid electric vehicle

I. Introduction

Hybrid electric vehicles (HEVs) have come into the focus of vehicle related research owing to their potential to take advantage of some beneficial features of electric vehicles (EVs) and internal combustion engine based ones (ICEVs). Such features in case of EVs are the zero local and minimal global exhaust emission, high energy efficiency, and quiet operation while ICEVs excel in low initial cost, long driving range, and capability of rapid refueling [5].

There are four basic types of HEVs regarding links between the different components and the applied propulsion type. They are the series [3][4], parallel [8][14][17], series-parallel [10], and complex [5] HEVs. In our research, we adopted the series hybrid concept owing to its simplicity. Its details are described in Section II.

The efficiency of a HEV, i.e. the utilization of the previously mentioned advantages, can be achieved only through a proper management of the different energy sources. The power control strategy of the HEV determines how the energy is produced, used, and saved [14].

Computational intelligence based solutions have been successfully applied for a wide range of problems like control [11][15][16][18][23], expert systems [6][20], risk assessment [13], decision making systems [21], optimization [1] etc. In this paper, a fuzzy logic based control solution is presented, which was developed for the power control of a series hybrid electric vehicle. The main objective of the research was to design a controller that can ensure that the state of charge level of the battery varies conform a given curve as well as the harmful pollutant emission and fuel consumption stays at a low level.. The controller was developed using Matlab's Fuzzy Logic Toolbox while the vehicle system was modeled in Simulink.

The rest of this paper is organized as follows. Section II presents the main components of the applied SHEV model. Section III introduces the fuzzy logic based control solution. The details and results of simulations are discussed in Section IV while the conclusions are drawn in Section V.

II. System Structure

Generally an SHEV is built up from six main components conform to the block diagram presented in Fig. 1. The specialty of this vehicle type is that its propulsion is pure electrical. There are only two mechanical links, one between the electric motor (EM) and the transmission system (T), and one between the internal combustion engine (ICE) and the generator (G). In case of braking the electric motor also generates electricity. The links between the generator, battery (B) and electric motor are electrical links. The ICE receives the fuel from the fuel tank (FT) through a hydraulic link.

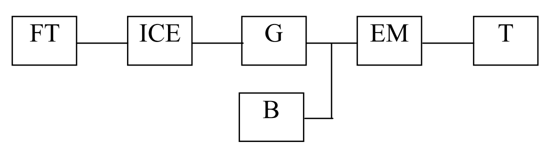

Figure 1. Configuration and components of SHEVs [24].

An SHEV is the closest hybrid solution to an electrical car the ICE is used only for battery charge, which allows a driving range comparable to the driving range of an ICEV [5].

In course of the preparation of this paper an SHEV modelled in Simulink was used. Please refer to [19] for its detailed specification. The block diagram of the whole system created in Simulink is presented in Fig 2.

The driver module controls the position of the gas and brake pedals based on the driving cycle data in order to ensure the tracking of the prescribed speed profile. The task of the power control module is to ensure the usage of the ICE so that the state of charge level of the battery follows a predefined profile and a possible low level of harmful pollutant emission (see cost function presented in Section IV) would be ensured. Our study focuses on the power

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control block; therefore the rest of this paper will be related only to this topic.

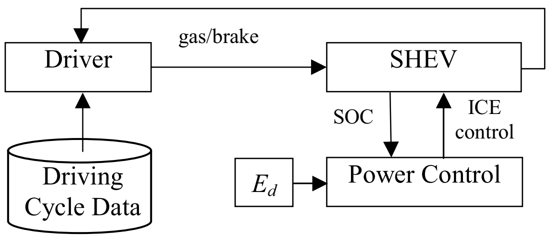

Figure 2. Configuration and components of the whole system.

III. Power Control Block

Our research was focused on the development of a fuzzy power control solution that ensures an adherence to a prescribed SOC level profile in course of a predefined driving cycle. After studying the applied SHEV structure a simple control solution was chosen. The controller has two inputs.

Undoubtedly the most important factor determining the usage of the ICE is the level of the energy stored in the battery (E_b) from which we calculate a relative value by dividing it by a presumed $E_b^{\max}$ maximal value using E_{bmax}=4.3 10^6 [J]. For safety purposes saturation to the unit interval is also included. The second input is a reference value (E_d) for the relative value of SOC. It can be considered as the desired SOC level. Its actual value is defined by a subsystem that will be presented in Section IV.

The difference between E_{brel} and E_d is later multiplied by a gain g_E that gives an additional tuning possibility for the controller. The resulting value is saturated to the [-1,1] interval and is used as first input for the fuzzy logic block. The second input of the fuzzy block is the previously sampled value of the control signal (q_{mold}). The output of the fuzzy controller is a value between 0 and 1 that controls the ICE. The block diagram of the whole power control is presented in Fig. 3.

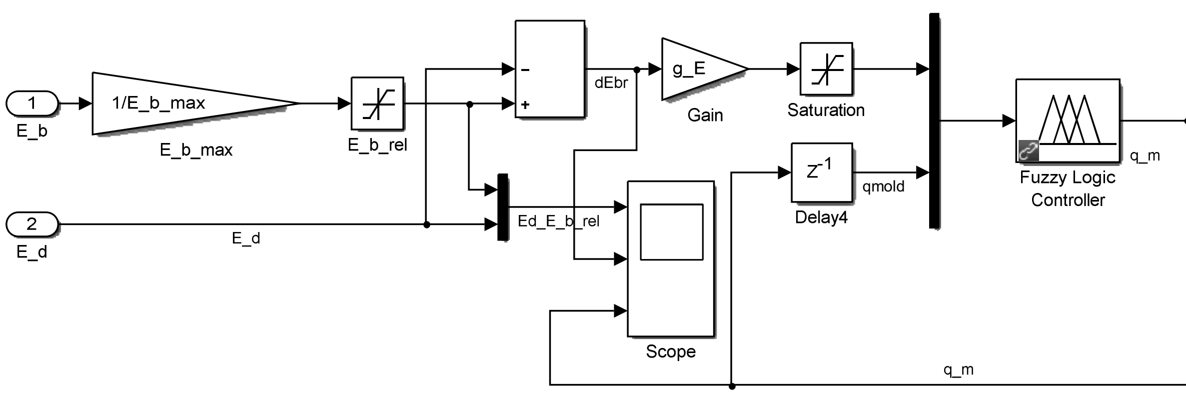

Figure 3. Block diagram of the power control (fuzzy subsystem).

All fuzzy partitions contain simple (singleton, triangle, or trapezoidal shaped) membership functions in order to speed up the calculations. In case of the first antecedent partition (linguistic variable dE_{br}) six fuzzy sets were used (see Fig. 4) to ensure a proper granularity. The linguistic terms were named using conventional notation (*NL*- negative large, *NM* – negative medium, *NS* – negative small, *PS* – positive small, *PM* – positive medium, *PL* – positive large).

The second antecedent (q_{mold}) and the consequent linguistic variables have identical partitions (see Figs. 5 and 6) representing the same characteristic but at different sample times. Here four sets were created because we tried to reduce the number of necessary rules. The linguistic terms were named using conventional notation (*Z* – zero, *S* – small, *M* – medium, *L* – large). The first membership function was chosen to be of singleton type because we intended to ensure that in some specific cases the ICE will stand still.

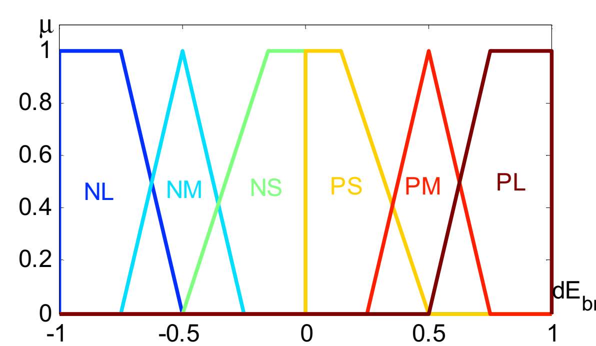

Figure 4. First antecedent partition (dE_{br}).

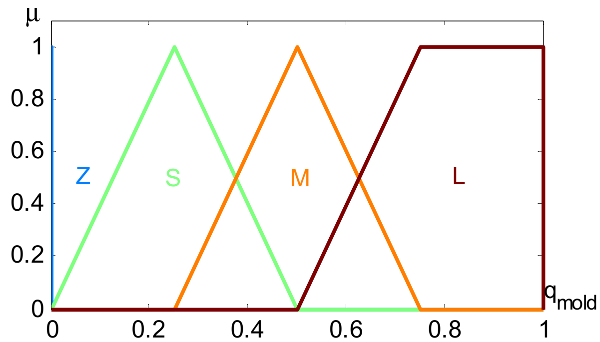

Figure 5. Second antecedent partition (q_{mold}).

The fuzzy system applies Mamdani type inference with the default settings, i.e. min type t-norm, max type s-norm, max type aggregation method, and centroid type defuzzification method.

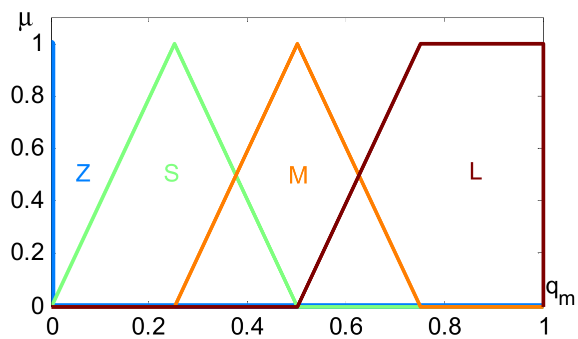

Figure 6. Consequent partition.

The rule base consists of 24 rules that ensure a full coverage of the antecedent space by rule premises which is a requirement of the Mamdani method. The rules are described by Table I.

TABLE I. RULE BASE

dE_b \ $q_{m\,old}$	**Z**	**S**	**M**	**L**
NL	M	M	L	L
NM	S	M	M	M
NS	Z	S	M	M
PS	Z	S	S	M
PM	Z	Z	Z	S
PL	Z	Z	Z	Z

We tried to achieve a smooth change between two consecutive q_m control values as far as it was possible. It could be reached at least in the neighborhood of the zero difference between the desired and the actual SOC level.

IV. SIMULATION RESULTS

We used the HTDC (Heavy Traffic Driving Cycle) [2] profile with a simulation time of T= 10 000 s in course of the research project. In order to examine the SOC level profile tracking capability of the developed control solution we created a Simulink subsystem able to provide either a constant E_d signal or a reference value that is a function of time. We chose a sinusoidal function for this purpose. The block diagram of the subsystem is presented in Fig. 7. One can choose between the two reference signal generation types using a manual switch. The sinusoidal curve can start at an arbitrary SOC level which is defined by the E_{off} offset value.

Beside trying to achieve the desired SOC level profile we were also interested in examining the performance related to the harmful pollutant emission and fuel consumption in case of the applied SHEV. In case of this problem the quality of a given control solution was measured by using the cost function (1). It calculates an average value taking into consideration five relative components, three related to the exhaustion, one to fuel consumption and one to the deviation from the desired SOC level profile.

$$C = \int_0^T \left(\frac{e_{CO}}{e_{CO}^{\max}} + \frac{e_{HC}}{e_{HC}^{\max}} + \frac{e_{NOx}}{e_{NOx}^{\max}} + \frac{B}{B^{\max}} + \frac{E_{bi} - E_{bd}}{E_b^{\max}} \right) dt \cdot \frac{1}{5 \cdot T}, \qquad (1)$$

where T is the simulation time, e_{HC} is the HC emission of the ICE, e_{NOx} is the NOx emission of the ICE, B is the fuel consumption of the ICE, e_{CO} is the CO emission of the ICE, E_{br} is the battery energy level. All components of the cost function were taken into consideration with equal weights. Lower cost function values represent lower fuel consumption and harmful pollutant emission and therefore correspond to better control solutions. The maximum values used for normalization were taken from [19] (see Table II). The subsystem that calculates the value of the cost function is presented in Fig. 8.

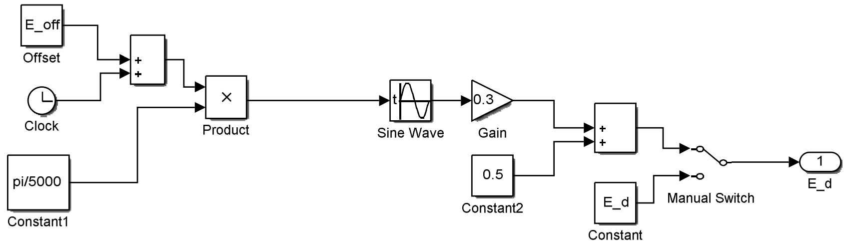

Figure 7. Reference Signal Generator Subsystem.

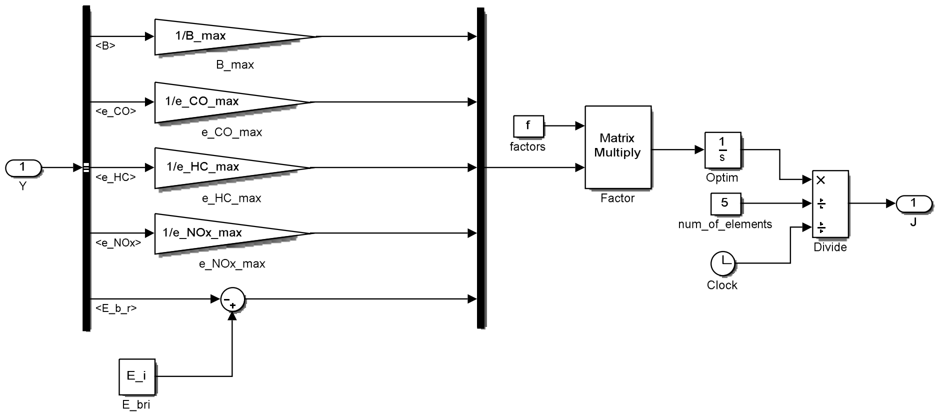

Figure 8. Reference Signal Generator Subsystem.

TABLE II. CONSTANTS USED FOR NORMALIZATION [19]

Constant	Value	Unit
$B^{\max}$	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]
$E_b^{\max}$	4.3 10^{6}	[J]

The constant type E_d signal was first tried. Simulations were done with three relative SOC levels (0.2, 0.5, and 0.8) and four g_E gain values (1, 5, 10, and 30). In each case the initial SOC level (E_i) was identical with the desired level (E_d). Table III summarizes the resulting cost function values. One can state that in case of gain values bigger than 1 the value of the cost function did not depend on the chosen SOC level.

Figs. 9 and 11 show the variation of the relative SOC level in course of the simulations in case of E_d=0.5. The gain values were g_E=1 and g_E=30, respectively. The desired relative SOC level is shown with a green continuous horizontal line. Figs. 10 and 12 show the control signal of the ICE for the same cases.

TABLE III. COST FUNCTION VALUES FOR CONSTANT TYPE E_D VALUES BASED SIMULATIONS

E_i, E_d \ g_E	1	5	10	30
0.2	0.0392	0.0645	0.0651	0.0648
0.5	0.0766	0.0645	0.0651	0.0648
0.8	0.0815	0.0645	0.0651	0.0648

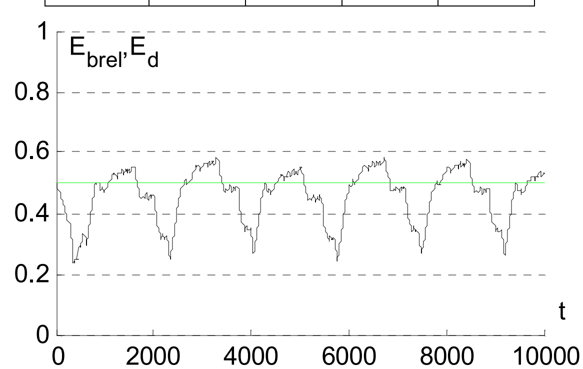

Figure 9. Variation of SOC for E_d=0.5 and g_E=1.

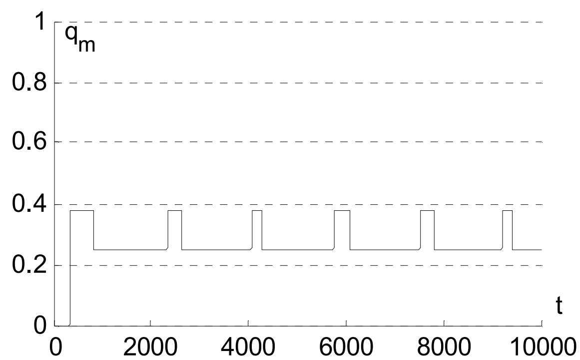

Figure 10. ICE control signal for E_d=0.5 and g_E=1.

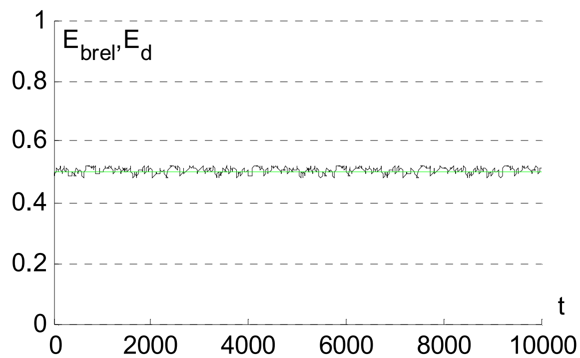

Figure 11. Variation of SOC for E_d=0.5 and g_E=30.

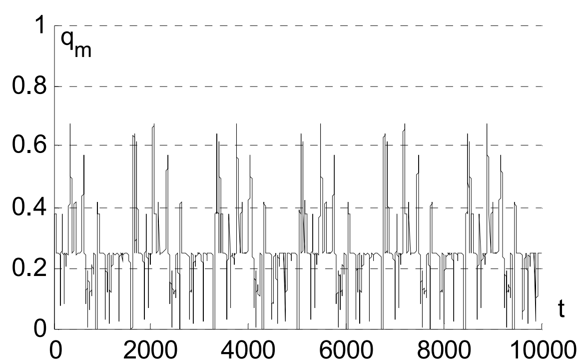

Figure 12. ICE control signal for E_d=0.5 and g_E=30.

The second set of simulations used a sinusoidal E_d signal. Here also the same three relative SOC levels (0.2, 0.5, and 0.8) and four g_E gain values (1, 5, 10, and 30) were tried. Table IV summarizes the resulting cost function values. One can state that in case of gain values bigger than 1 the value of the cost function did not depend on the chosen SOC level.

Figs. 13 and 15 show the variation of the relative SOC level in course of the simulations in case of initial relative SOC level E_i=0.5. The gain values were g_E=1 and g_E=30, respectively. The desired relative SOC level is shown with a green continuous line. Figs. 14 and 16 show the control signal of the ICE for the same cases.

TABLE IV. COST FUNCTION VALUES FOR SINUSOIDAL TYPE E_D VALUES BASED SIMULATIONS

E_i \ g_E	1	5	10	30
0.2	0.0168	0.0067	0.0057	0.0042
0.5	0.0669	0.0652	0.0651	0.0642
0.8	0.1236	0.1262	0.1259	0.1242

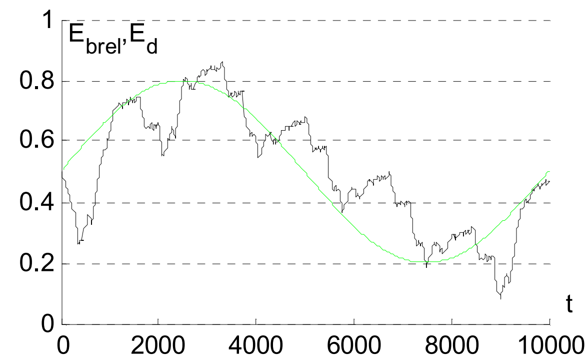

Figure 13. Variation of SOC for E_i=0.5 and g_E=1.

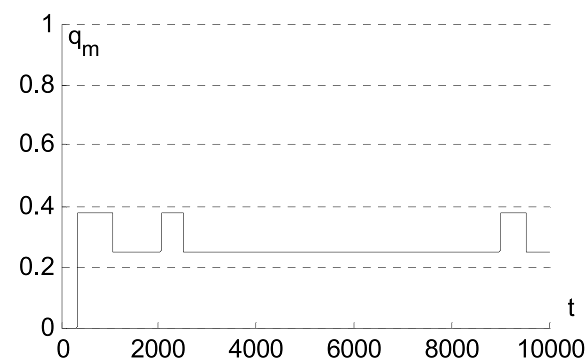

Figure 14. ICE control signal for E_i=0.5 and g_E=1.

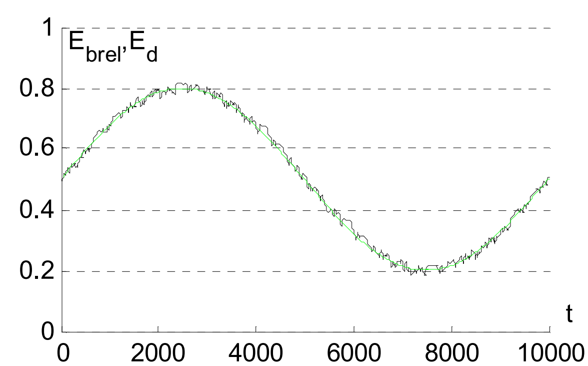

Figure 15. Variation of SOC for E_i=0.5 and g_E=30.

Generally with the increase of the gain the variation interval of the energy level became significantly reduced; however, parallel with this the ICE control signal contained quick changes in short intervals of time.

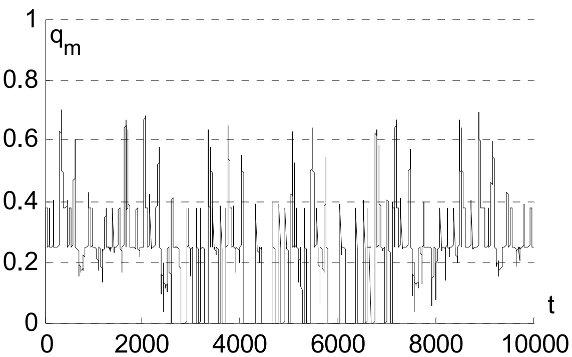

Figure 16. ICE control signal for E_i=0.5 and g_E=30.

V. Conclusions

The goal of this research was to develop a fuzzy logic based system for the power control of a series hybrid electric vehicle. The main objective was to ensure the variation of the relative state of charge of the battery conform a prescribed function. Besides, we also examined the value of a cost function that was related to fuel consumption and harmful pollutant exhaustion. The simulation runs clearly showed that the proposed subsystem was able to track the prescribed two function types by a proper selection of the gain values. Results showed that a trade-of has to be made between the need for exact track of the prescribed function and the need for reducing the values of the cost function.

Further research will consider the applicability of fuzzy rule interpolation based inference techniques (e.g. [7][9][12][22]) in order speed up the fuzzy inference.

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