Parallel Hybrid Cars with Fuzzy Logic Control

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***Abstract*— This study develops a parallel configuration fuzzy logic controller for hybrid automobiles. A set of rules has been devised in a fuzzy controller to efficiently calculate the split between the two powerplants—electric motor and internal combustion engine—using the driver command, the state of charge of the energy storage, and the motor/generator speed. The basic goal of fuzzy rules is to enhance each component's operational effectiveness when taken as a whole. The results of simulations have been used to evaluate the controller's performance. The controller was implemented and simulated using a futuristic hybrid car concept. Fuzzy logic has the potential to improve fuel economy in comparison to other controllers that just intend to improve engine efficiency.**

Index Terms—Control strategies, emissions, fuel economy, fuzzy logic, hybrid vehicles, optimization.

I. INTRODUCTION

Hybrid technology (both thermal and electrical motorization) has become one of the challenges for the automotive industry as it strives for better fuel economy, reduced emissions, and affordable vehicles without sacrificing performance of the vehicle, safety, reliability, as well as other conventional vehicle attributes. Hybrid systems, using a combination of an internal combustion engine (ICE) and electric motor (EM), have the potential of improving fuel economy by operating the ICE in the optimum efficiency range and by making use of regenerative braking during deceleration.

The automotive industry has created more and more hybrid-powered vehicles during the last 20 years. Several automakers have unveiled numerous concept cars with various hybrid layouts.

There are three distinct hybrid system types:

- Series Hybrid: An ICE-generator combination is employed in this configuration to power the battery and the EM.

- Parallel Hybrid: In this design, the ICE is mechanically attached to the wheels and can thus provide the wheels with mechanical power directly. In order to increase the torque of the ICE, the EM is added to the drive train in tandem with it.

Several national laboratories, research institutions, and universities are actively engaged in this field of study due to the significance and prospective advantages of hybrid technology. Another research area for the Partnership for a New Generation of Vehicles, a joint venture between the US government and the automotive sector, is hybrid technology (PNGV). In order to create a new generation of automobiles, PNGV was founded. These future vehicles should outperform today's average fuel economy (80 miles per gallon or 34 kilometres per litre) by up to three times while still meeting consumer expectations for performance, comfort, safety, quality, and cost of ownership.

The architecture and individual hybrid vehicle parts must be optimised in order to meet these objectives, but the energy management plan utilised to regulate the entire system is just as crucial. The plan for managing energy utilises a power controller to carry out. It maximises power generation and conversion in each component while regulating the flow of energy among all of the components.

The purpose of this study is to create a fuel-efficient power controller for a parallel hybrid vehicle (PHV). The ICE, EM, and battery operations of all significant PHV components will be optimised by the power controller described here.

II. BASICS OF PHVs

Fig. 1 presents a block diagram of a PHV with an EM and an ICE. For this particular configuration, the ICE and EM power are combined downstream of the transmission. Alternatively, the power could also be combined upstream of the transmission.

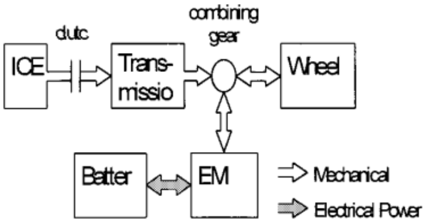


Fig. 1. Block diagram of the parallel hybrid vehicle.

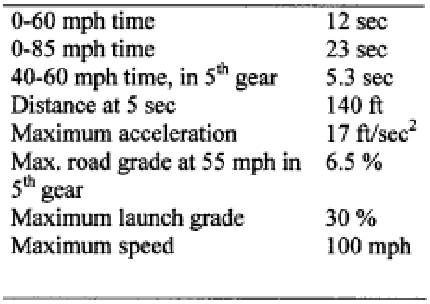
For both the upstream and downstream configuration, there are five different ways to operate the system, depending on the flow of energy: 1) provide power to the wheels with only the ICE; 2) only the EM; or 3) both the ICE and the EM simultaneously; 4) charge the battery, using part of the ICE power to drive the EM as a generator (the other part of ICE power is used to drive the wheels); 5) slow down the vehicle by letting the wheels drive the EM as a generator that provides power to the battery (regenerative braking). A power controller is needed to manage the flow of energy between all components, while taking into account the energy available in the battery. The power controller adds the capability for the components to work together in harmony, while at the same time optimizes the operating points of the individual components. This is clearly an added complexity not found in conventional vehicles. For controller analysis and design, the PNGV systems analysis toolkit (PSAT) models [10] are used to simulate the PHV in the Matlab/Simulink environment. These models were developed under direction and contributions of the three major United States car companies (DaimlerChrysler, Ford, and General Motors) and the United States government. The model architecture is “forward looking,” which is much more suitable for controller analysis and design than a backward looking architecture.

Apart from the model of the PHV, PSAT also includes a model of a driver, and a set of driving cycles given as speed versus time profiles. The driver’s objective is to track the speed versus time profile. The driver achieves his objective by modulating the brake and accelerator pedals. The power controller uses these driver inputs to compute the commands for the several local controllers, such as the ICE, EM, battery, and transmission controllers. The fuel economy for composite urban/highway travel is computed by letting the driver track the profiles described in the SAE J1711 standard. The composite fuel economy (Composite_FE) is given as

$$\text{Composie\_FE} = 1/((0.55/\text{city\_FE}) + (0.45/\text{highway\_FE})).$$

The city-driving test standard starts from ambient initial conditions (also known as “cold start”). It is composed of two urban cycles separated by a 10-min soak. In our analysis, the engine is assumed to be warm and only the second urban cycle is used. For the highway cycle only one cycle with warmed-up engine is used. In order to have a meaningful fuel economy value, it is important to have the battery SOC charge-neutral for each of the cycles. The specific PHV configuration, used throughout the paper, consists of the following components:

TABLE I MINIMUM VEHICLE PERFORMANCE REQUIREMENTS STATED BY PNGV



0-60 mph time	12 sec
0-85 mph time	23 sec
40-60 mph time, in 5th gear	5.3 sec
Distance at 5 sec	140 ft
Maximum acceleration	17 ft/sec^2
Max. road grade at 55 mph in 5th gear	6.5 %
Maximum launch grade	30 %
Maximum speed	100 mph

- compression ignition direct injection (CIDI) engine: 55 kW;
- permanent magnet motor: 20 kW continuous, 40 kW peak;
- advanced battery: 40 kW, 2 kWh;
- manual transmission: five speed;
- total test vehicle mass: 1100 kg. The size of the components was chosen to achieve the PNGV vehicle performance requirements given in Table I.

III. ENERGY MANAGEMENT STRATEGY

The power controller's guiding principle—the energy management strategy—is discussed in this section.

1) The driver inputs (from the brake and accelerator pedals) are fulfilled consistently (driving the PHV shouldn't "feel" different from driving a normal vehicle). Energy in the system should be controlled in such a way that.

2) The battery is constantly fully charged.

3) The four fundamental parts (ICE, EM, battery, and transmission) work together as efficiently as possible.

The power controller should assess the amount of power required to charge the battery and how much is required to move the wheels while the PHV is in operation.

The power should then be divided between ICE and EM. The EM must be given negative power if the battery needs to be charged, and the ICE must supply power for both driving the wheels and charging the battery.

Because it establishes the operating points of the components, the power-split technique can be utilised to maximise the effectiveness of the four fundamental PHV components. After an optimal power split, each component's power generation and conversion must also be optimised.

IV. FUZZY LOGIC POWER CONTROLLER

This section first discusses the basics of the fuzzy logic controller that was used to implement the power controller, and then the power controller itself will be presented in more detail.

A. Fuzzy Logic Control Basics

The general energy management strategy described in the previous section has been implemented using fuzzy logic.

A block diagram of the power controller is shown in Fig. 6, with the fuzzy logic controller (FLC) serving as its central component.

An FLC's fundamental goal is to create human knowledge and reasoning that is computer-implementable and may be modelled as a set of if-then rules. The energy management approach described in the previous section is represented in Table II by a list of if-then rules.

The variables in Table II

preceding "then": SOC, P_{driver}, and ω_{EM}, correspond to the inputs of the FLC (Fig. 6): battery state of charge, driver power command, and EM speed, respectively. The variables following "then": P_{gen} (generator power), and scaling factor correspond to the outputs.

The first part of a rule (preceding "then"), called the antecedent, specifies the condition (i.e., the combination of inputs) for which a rule holds. The second part (following "then"), called the consequent, is the corresponding control action, i.e., the controller output. The antecedents in Table II contain linguistic terms (low, high, optimal, etc.) that reflect human knowledge of the PHV. The antecedents are defined as a combination of individual conditions, using the logical AND and NOT operators (in general, it is also possible to use the logical OR). The linguistic terms, the connectives, and the if–then relations need to be defined in a way tractable for computers.

The linguistic terms are represented by fuzzy sets. Consider the variable "driver power command" in Fig. 7. This variable is represented by the linguistic terms "normal" and "high." These linguistic terms are represented by two fuzzy sets that are defined by the two membership functions in Fig. 7. The membership functions define the degree of membership (μ) of the variable in the two fuzzy sets. For driver power command larger than 50 kW the degree of membership in the fuzzy set "high." equals 1 and the degree of membership in the fuzzy set "normal" equals 0. For normal driver power command less than 30 kW, it is the other way around. One can imagine that there is a gradual transition from normal to high driver power command. This transition is represented by the overlapping interval in Fig. 7 (between 30 and 50 kW). The values in this interval belong to both fuzzy sets with various degrees of membership, e.g., 45 kW belongs to "normal" with membership 0.25 and to "high" with membership 0.75.

Using the fuzzy sets and the fuzzy set operators, it is possible to design a fuzzy reasoning system (inference system) that can act as a fuzzy controller. The reasoning mechanism used in this paper can be separated in four main steps.

1) Fuzzification: The membership degrees of the three input values of the FLC are computed using the membership functions (Figs. 7–9).

2) Degree of Fulfillment: The degree of fulfillment for the antecedent of each rule (Table II) is computed using the fuzzy logic operators.

3) Inference: This operation represents the if–then implication. The degree of fulfillment of the antecedent of each rule is used to modify the consequent of that rule accordingly. This is done by multiplying the degree of fulfillment of the antecedent with the consequent of rule.

4) Aggregation: For each controller output , the results of the inference step are combined into a single value. This is done by taking the average of the inference results weighted by the degrees of fulfillment of the rules.

B. Power Controller

Fig. 6 presents a simplified block diagram of the power controller. The first block converts the driver inputs from the brake and accelerator pedals to a driver power command. The signals from the pedals are normalized to a value between zero and one (zero: pedal is not pressed, one: pedal fully pressed). The braking pedal signal is then subtracted from the accelerating pedal signal, so that the driver input takes a value between 1 and 1. The negative part of the driver input is send to a separate brake controller that will compute the regenerative braking and the friction braking power required to decelerate the vehicle. The controller will always maximize the regenerative braking power, but it can never exceed 65% of the total braking power required, because regenerative braking can only be used for the front wheels. The positive part of the driver input is multiplied by the maximum available power at the current vehicle speed. This way all power is available to the driver at all times. The maximum available power is computed by adding the maximum available ICE and EM power. The maximum available EM and ICE power depends on EM/ICE speed and EM/ICE temperature, and is computed using a two–dimensional look-up table with speed and temperature as inputs. However, for a given vehicle speed, the ICE speed has one out of five possible values (one for each gear number of the transmission). To obtain the maximum ICE power, first the maximum ICE power levels for those five speeds are computed, and then the maximum of these values is selected. Once the driver power command is computed, the fuzzy logic controller (Fig. 6) computes the optimal generator power for the EM in case it is used for charging the battery and a scaling factor for the EM in case it is used as a motor. This scaling factor is (close to) zero when the SOC of the battery is too low. In that case the EM should not be used to drive the wheels, in order to prevent battery damage. When the SOC is high enough, the scaling factor equals one.

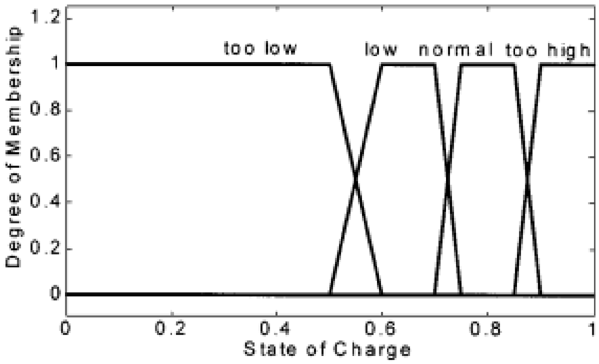


Fig. 8. Membership functions for state of charge.

Fig. 8 presents the MFs for SOC. Fuzzy sets "too low" and "too high" represent the ranges where the SOC should not be. Fuzzy set "normal" represents the range where the SOC should be and "low" acts as a buffer between "normal" and "too low."

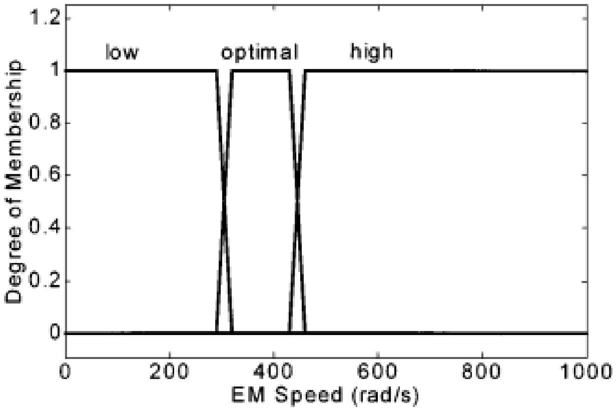


Fig. 9. Membership functions for electric motor (EM) speed.

Fig. 9 presents the MFs for EM speed. Fuzzy set "optimal" represents the optimal speed range. The MF drops relatively fast, since the efficiency also drops fast for speeds outside the optimal range (Fig. 3).

C. Control for Gear Shifting

The gear shifting controller determines the ideal gear number for the automated manual transmission using the desired ICE power level. The optimal ICE speed and torque for the required ICE power level are first calculated using the optimal speed-torque curve. The desired gear ratio is then calculated by dividing the optimal ICE speed by the vehicle speed. The gear number that comes the closest to the specified gear ratio is finally picked.

V. CONCLUSION

A fuzzy logic-based power controller for PHVs has been introduced in this study. The energy flow between the primary PHV components is optimized by this power controller, and it also optimizes the production and transformation of energy in the many components (ICE, EM, transmission, and battery). The controller was designed using the component efficiency maps. The driver's inputs to the accelerator and brake pedals are first converted by the power controller into a driver power command. A fuzzy logic controller uses the driver power command, battery state of charge, and electric motor speed to determine the best generator power and an electric motor scaling factor. The best ICE and EM power are calculated using the driver power command, ideal generator power, and scaling factor. Moreover, the effectiveness of the ICE for an ideal speed-torque curve is used to optimise a given power level, and gear shifting is used to regulate the ICE's speed.

The power controller makes sure that the battery is always fully charged, the driving inputs (from the brake and accelerator pedals) are satisfied consistently, and the PHV's fuel efficiency is optimum.

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