Torque Control Strategy for Parallel Hybrid Electric Vehicles using Fuzzy Logic

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Abstract: - This paper presents a design method of a torque control strategy for parallel hybrid electric vehicles (PHEV) by using fuzzy logic. Taking the driver command, the state of charge (SOC) of the battery, and the motor/generator speed as inputs, a fuzzy controller and relevant fuzzy rules have been developed to effectively determine the torque distribution between electric motor (EM) and internal combustion engine (ICE). The underlying theme of this strategy is to optimize the operational efficiency of all components, considered as one system. The simulation results reveal that, compared with the conventional logic torque control strategy (LTCS) which uses precise threshold parameters, the proposed fuzzy torque control strategy (FTCS) improves fuel economy and maintains battery SOC within its operation range more effectively.

Key-Words: - Parallel hybrid electric vehicle; Hybrid powertrain; Control strategy; Fuzzy control; Torque distribution

1 Introduction

In recent years fuel economy has been one of the dominate issues in automobile performance. Achieving the lowest possible fuel consumption contributes to save natural resources and translates directly into lower emissions, which is often in contrast with customers' requirement in increasing comfort and performance. This has forced the auto industry to search for new types of vehicle that are more efficient compared with conventional vehicles. The potential of so-called zero-emission vehicles include: fuel cell and pure electric vehicle, is limited by fuel cell and battery technology. The hybrid electric vehicle (HEV) which synergizes the electric power with the diesel engine has proved that its overall efficiency is as high as a fuel cell from fossil fuel [1].

Thus the HEV technology has been proposed as the technology for next generation vehicle configurations, and the rule of control strategy in the hybrid drive-train is escalating. A management or control strategy, which is usually implemented in the vehicle central controller, is defined as an algorithm, or a law regulating the operation of the drive-train of the vehicle. Generally, it inputs the measurements of the vehicle operation conditions such as speed or acceleration requested torque by the driver. The outputs of a control strategy are decisions to turn on or off certain components or to modify their operating regions by commanding local component controllers [2][3][4].

The control or management strategies for parallel HEVs can be roughly classified into two categories. The first approach is based on static optimization methods. Commonly, electric power is translated into an equivalent amount of (steady-state) fuel rate in order to calculate the overall fuel cost [5][6]. The optimization scheme then figures out the proper split between the two energy sources (normally the internal combustion engine and the electric motor) using steady-state efficiency maps. But it's very difficult to determine the exact changeover point in the construction of a control strategy. Furthermore, many trial-and-error-based tests modifying the driving strategy should be required to get the effective one. To solve this issue, the second type employs heuristic control techniques such as control rules/fuzzy logic/neural networks for estimation and control algorithm development [7][8][9], which has a means of considering the dynamic nature of the system when performing the optimization.

Regarding a hybrid drive-train as a multi-domain, nonlinear and time-varying plant, fuzzy logic, the usefulness of which for decision making for an uncertain and imprecise plant has already been introduced in many industrial fields, seems to be the most logical and feasible approach to the

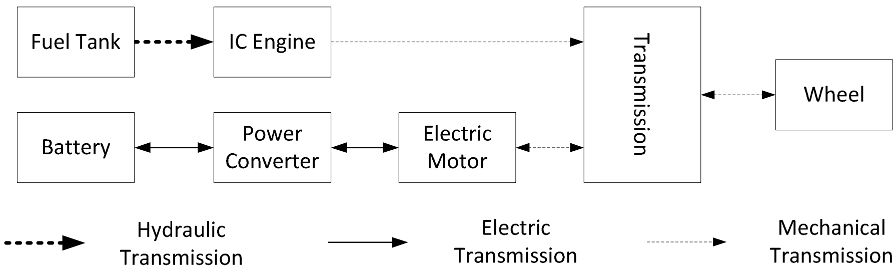


Fig 1. Parallel HEV configuration

problem [10]. In fact, instead of using deterministic rules, the decision-making property of fuzzy logic can be adopted for realizing a real-time and sub-optimal torque split. In another words, fuzzy logic controller is an extension of the conventional rule based controller.

In this paper, a torque control strategy based on fuzzy logic for parallel hybrid electric vehicles is developed to optimize the operation of all major PHEV components. The organization of the paper is as follows. Firstly, introduces the PHEV configuration and briefly describes the simulation model. Subsequently, the torque management strategy is presented. In addition, it followed by the description of the fuzzy logic power controller. Finally, the simulation results are presented to investigate the effectiveness of the fuzzy torque control strategy.

2 PHEV Configurations

There are generally two accepted basic configurations for the hybrid electric vehicles including series and parallel. The multi-mode and complex type which is also known as series-parallel type is considered combines the features of both the series and parallel hybrids [11].

In series HEVs, a generator converts the ICE mechanical output into electricity which either charges the battery or can bypass the battery to propel the wheels via the same electric motor and mechanical transmission. Benefited from the decoupling between the engine and the driving wheels, there is an advantage of flexibility for locating the ICE generator set. Despite its advantage of simplicity of the drivetrain, it needs three propulsion devices, the ICE, the generator, and the electric motor, which definitely damages the efficiency of SHEV. Another disadvantage is that all these propulsion devices need to be sized for the maximum sustained power if the SHEV is designed to climb a long grade.

Fig 1 presents the block diagram of parallel HEVs with the ICE and EM. Differing from the SHEV, the PHEV allows both the ICE and EM to deliver torque in parallel to drive the wheels. Since both of them are generally coupled to the drive shaft of the wheels via two mechanical transmissions, the propulsion torque may be supplied by the ICE alone, by the EM alone or by both. The EM can be used as a generator to charge the battery by regenerative braking or absorbing torque from the ICE when the output torque is greater than that required to drive the wheels. Better than the series HEV, the parallel hybrid uses the ICE to drive the vehicle shaft directly, which avoids the losses in power conversions. Another advantage of the series case is that a smaller ICE and a smaller EM can be used to get the same performance until the battery is depleted. Even for long trip operation such as urban and expressway working condition, only the ICE needs to be rated for the maximum sustained power, while the EM may still be about half. In brief, parallel HEV gets a longer driving range than series HEV at the cost of complicated system architecture, high requirement of control system and the consequent high price.

2.1 Torque Distribution on PHVE

The difference of torque path between the ICE and the EM is explained in Fig 2. When the ICE is used, the torque drives directly from the ICE to the wheels (path 1). When the EM is used as a motor, the EM output positive torque to drive the wheels (path 2). When the EM is used as a generator, the EM absorbs torque to charge the battery (path 3).

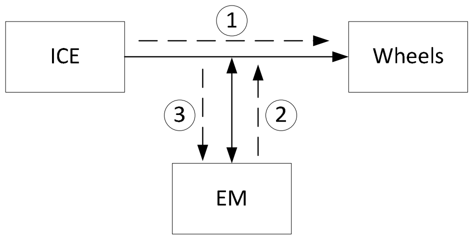


Fig 2. Block diagram of the torque path

Depending on the torque distribution, there are five different ways to operate the parallel HEV system:

1) Provide torque to drive the wheels with only the ICE (path 1);
2) Only the EM (path 2);
3) Both the ICE and the EM simultaneously (path 1 and 2);
4) Charge the battery, using part of the ICE torque (path 1 and 3);
5) Regenerative break by driving the EM as a generator that provides power to the battery (path 3).

So a torque controller is needed to manage the torque distribution between the ICE and EM. The 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.

2.2 System Configuration

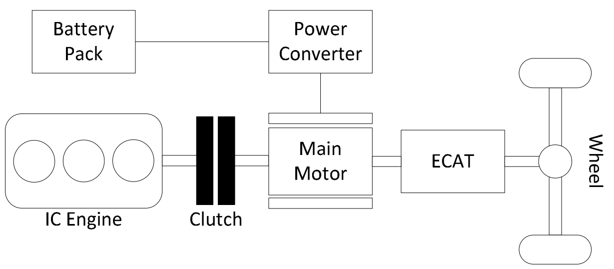


Fig 3. Block diagram of the powertrain for a PHEV

Table 1. Vehicle performance requirements stated by GB/T 19752 - 2005

Maximum speed	110km/h
Acceleration ability 0~50km/h	5sec
Acceleration ability 0~100km/h	13sec
Speed uphill ability in road slope of 4%	80km/h
Speed uphill ability in road slope of 12%	65km/h
Hill starting ability	30%
Uphill ability on maximum road slope	30%

The specific PHEV configuration, used throughout the paper, consists of the following components:

1) 1.4L inline four cylinders and electronic injection gasoline engine: 50kW;
2) AC asynchronous motor: 20kW continuous, 40kW peak;
3) Lithium iron phosphate battery: 300V DC, 10Ah;
4) Electronic control automatic transmission (ECAT): five speed;
5) Total test vehicle mass: 1050kg.

The details of the powertrain system for CQU-PHEV are given in Fig 3.

According to the National Standard of the People's Republic of China: Hybrid electric vehicles – Power performance – Test method (GB/T 19752-2005), this PHEV is designed to fulfill the performance requirements described in Table 1.

3 Torque Control Strategy

This section describes the torque control strategy, which is the philosophy behind the torque controller. Then torque distribution in the system should be managed in such three rules that:

1) The SOC of battery should never drop too low;
2) The driver inputs (form accelerating and brake pedals) are satisfied consistently except where it would conflict with the first rule;
3) The overall efficiency of the main components (ICE, EM, battery, and transmission) is optimized as long as such optimization doesn't conflict with first or second rule.

3.1 Fundamental Operation Modes

While the PHEV is operated, the torque control strategy is required to decide how much torque is needed to drive the vehicle and how much is needed to charge the battery. Then the torque requirement is split between the ICE and EM. This torque-split strategy optimizes the efficiency of all main components of the PHEV, because it determines the operating points of the components. To identify the optimal operating points, the operation modes of vehicle and the corresponding efficiency maps of components were studied.

The Fig 4 illustrates the fundamental operation modes. In particular, these five parts of the curved lines are tied to the appropriate operation modes and form an integral part of the driving cycle as follows:

1) The curve segment AB is the standing start acceleration condition related to the EM separate driving mode;
2) the curve segment BC is the normal acceleration condition related to the ICE separate driving mode;
3) the curve segment CD is the cruising condition related to the ICE driving and battery charging mode (also known as active charging mode);

4)the curve segment DE is the snap acceleration condition related to the ICE and EM parallel cooperating mode (also known as EM assistance mode);

5) the curve segment EF is the breaking condition related to EM regenerate breaking mode.

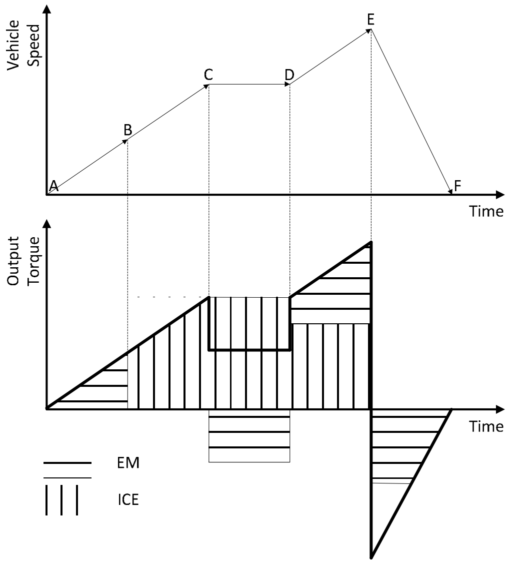


Fig 4. The typical driving cycle and the fundamental operation modes

3.2 Torque Split Strategy

Based on the available output torque, the pedal position is changed into the requiring torque T_{req}. If $T_{req} < 0$, it's regenerate breaking, of which the control strategy is to recover as much energy as possible under the limit of the EM and battery, meanwhile the frictional damping device is supposed to meet the shortage of the breaking torque. If $T_{req} > 0$, the requiring torque is split between the EM and ICE:

$$T_{req} = T_{em} + T_{ice} \tag{1}$$

T_{ice} is the output torque of ICE. T_{em} is the output torque of EM which could be positive in EM assistance mode, and negative in EM generation mode. According to the universal characteristic curve of ICE in Fig 5, T_{em} is adjusted to optimize the ICE load. There are ICE optimal efficiency curve ($T_{ice-opt}$) which is used as the optimal objective of the ICE operating points, maximal torque curve ($T_{ice-max}$) and ICE turnoff curve ($T_{ice-off}$) in Fig 5. When $T_{req} < T_{ice-off}$, the ICE is turnoff to void working at ineffective condition.

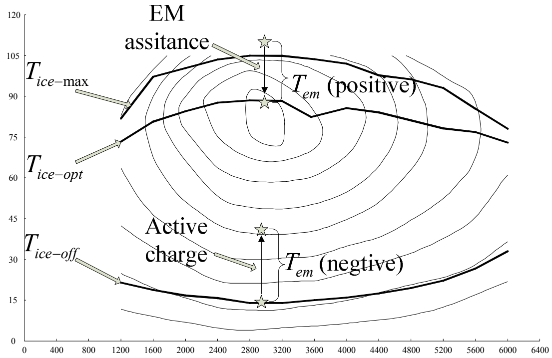


Fig 5. The ICE efficiency map and the rule based control strategy

The ICE drives the EM to charge the battery which calls "active charge" (shown in Fig 5); while in regenerative braking condition, it's "passive charge". The ICE load is adjusted to maintain it in high effective working condition by the means of active charge or EM assistance. It's necessary for control strategy to maintain the battery SOC in working section in which the battery charge and discharge with low internal resistance. The lowest point of battery internal resistance is defined to target SOC in Fig 6. If the SOC is lower than it, the possibility of active charge will increase, while on the contrary it's more inclined to discharge (EM assistance or driving alone).

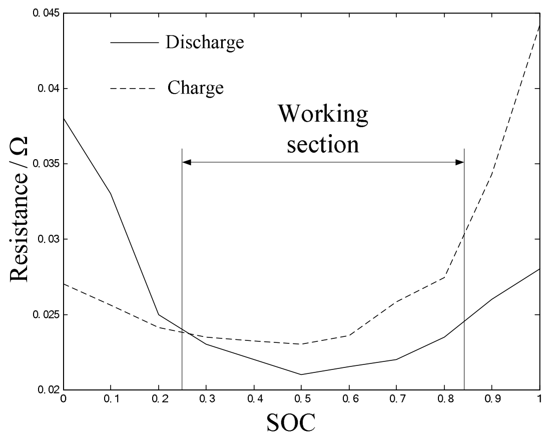


Fig 6. Charge and discharge resistances of the battery

$T_{ice-off}$ could be defined by comparing the energy efficiency η_1 in EM driving mode with η_2 in ICE driving mode as follow:

$$\eta_1 = \eta_{ice}\eta_{em}\eta_{bat}\eta_{em}\eta_{tran} \tag{2}$$

$$\eta_2 = \eta_{ice}\eta_{tran} \tag{3}$$

η_{ice} is the ICE efficiency, η_{em} is the EM efficiency, η_{tran} is the mechanical efficiency of

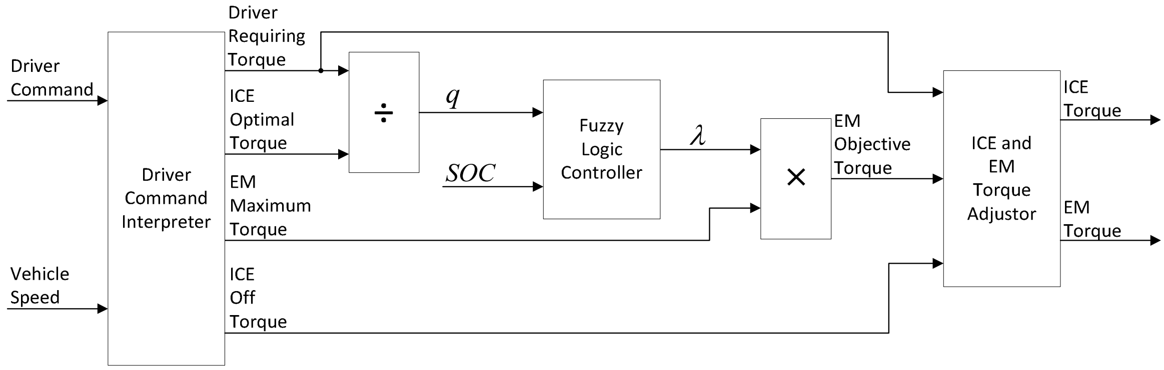


Fig 7. Block diagram of fuzzy torque controller

transmission, η_{bat} is battery charge-discharge efficiency. η_{ice} in (2) is quite higher than the one in (3) owing to ICE is more effective in charging battery than in driving vehicle. When $\eta_2 \le \eta_1$, the ICE works at low effective condition. For instance, if the ICE, EM and battery efficiency in (2) is 0.30, 0.85 and 0.90, the ICE turnoff threshold is set to 0.20 that means ICE should be turnoff if its efficiency was below 0.20. And the corresponding ICE torque is defined as $T_{ice-off}$. But when referring to practical circumstances, it could be much complicated. In active charging mode, the fuel consumption increased by extra load is limited as a result of improvement in ICE efficiency. Furthermore, there is no fuel cost in passive charging mode. Accordingly, actual $T_{ice-off}$ should be a little higher than theoretical value. In the view of the difficulty in real-time quantitative analysis and comparing energy conversion efficiency, it's a practical method to predefine a set of threshold values for prescribing $T_{ice-off}$ and ICE high efficiency area which is around $T_{ice-opt}$.

The gear shifting control strategy divides into two broad categories: when ICE on, the ICE efficiency is the prime consideration to choose the optimal shift; Otherwise (EM separate driving mode), the EM efficiency gets the priority. This strategy will be discussed in more detail at a later chapter.

With the help of logic threshold, the control strategy mentioned above is converted into a set of If-then rules to control the output torque distribution and switchover between the working modes, also known as logic torque control strategy (LTCS). The next section discusses how the driver torque command is computed and how fuzzy logic is applied to compute the optimal ICE torque.

4 Fuzzy Logic Torque Controller

On the grounds of LTCS described in the previous section, a fuzzy torque control strategy (FTCS) is built by replacing the boolean logic and accurate parameters with the fuzzy logic and fuzzy parameters [12][13]. A block diagram of the FTCS controller is presented in Fig 7, and the fuzzy logic controller (FLC) being the main part. The basic idea of an FLC is to formulate human knowledge and reasoning, which can be represented as a collection of if-then rules, in a way tractable for computers.

4.1 Driver Command Interpreter

The first block of fuzzy torque controller (FTC) is Driver Command Interpreter (DCI) which converts the driver inputs from the brake and accelerator pedals to a driver torque requiring. The signals from the pedals are normalized to a value between zero and one (One: the fully pressing position, zero: the initial position). The breaking pedal signal is subtracted from the accelerating pedal, so that the driver input takes a value between -1 and +1.

When the driver input below zero, it is send to a separate brake controller (not shown in Fig 7) which computes the regenerative braking and the friction braking torque required to decelerate the vehicle. And the driver requiring torque sends to FLC is forced to zero.

On the contrary, the positive driver input is multiplied by $T_{ice-\max}$ at current vehicle speed to get T_{req}. The ICE speed and temperature perform collaboratively on $T_{ice-\max}$ which is computed using a tow-dimensional look-up table with speed and temperature as in puts. However, for a given vehicle speed, the ICE speed has one out of five possible values (one for each gear number of the transmission). At first, the maximum ICE torque levels for those five speeds are computed. Then the maximum of these values is selected as $T_{ice-\max}$, while T_{req} is divided by the corresponding $T_{ice-opt}$ and the quotient q (between 0 and 2) is sent to Fuzzy Logic Controller (FLC). There is one exception to the gear shifting control strategy: when vehicle works at EM separate driving mode, the gear number is chosen to maximize the EM output torque instead of the ICE.

4.2 Fuzzy Logic Controller

Once the driver torque command q is arrived, the second block of fuzzy torque controller, namely FLC, calculates the optimal EM torque in the form of normalized value (λ) between -1.5 and 1.5. Because the EM speed is equal to the ICE speed, $T_{em-\max}$ is selected along with $T_{ice-\max}$. Therefore, the EM objective torque could be defined as follow:

$$T_{em-obj} = \lambda T_{em-\max} \quad (4)$$

4.2.1 Membership Functions

The crisp inputs are converted to fuzzy in Fuzzification process by using trapezoid membership functions which are described by the uniform equation.

$$\mu_{A_n}(x) = \begin{cases} 0, & x < \min_{A_n} \ or \ x > \max_{A_n} \\ y_1, & y_1 < 1 \ and \ K1_{A_n} \neq 0 \\ 1, & (y_2 > 1 \ or \ K2_{A_n} = 0) \ and \ (y_1 > 1 \ or \ K1_{A_n} = 0) \\ y_2, & (y_2 < 1 \ and \ K2_{A_n} \neq 0) \ and \ (y_1 > 1 \ or \ K1_{A_n} = 0) \end{cases} \quad (5)$$

$$y_1 = (x - \min_{A_n}) K1_{A_n} \quad (6)$$

$$y_2 = (x - \max_{A_n}) K2_{A_n} \quad (7)$$

$\max_{A_n}$ and $\min_{A_n}$ are the upper and lower limits respectively of one fuzzy set. $K1_{An}$ and $K2_{A_n}$ are the slopes of line 1 and line 2 respectively to the x axis in Fig 8. If line 1 or line 2 is vertival to the x axis, $K1_{An}$ or $K2_{A_n}$ is zero.

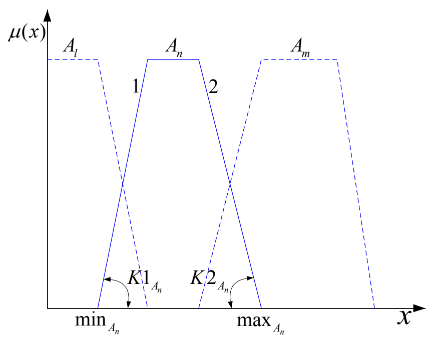
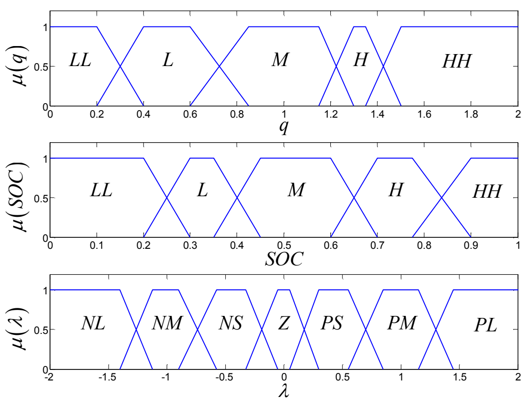


Fig. 8 Trapezoid membership function

As the x is within $\min_{A_n}$ and $\max_{A_n}$, this equation firstly calculates the degree y_1 of membership by the line 1 using the linear equation of line 1. If y_1 isn't greater than 1, the degree of μ_{A_n} is equal to y_1; otherwise it will be recalculated by the linear equation of line 2. If y_1 and y_2 are both greater than 1, μ_{A_n} is equal to 1. The fuzzy set will be easy to adjust by calibrating the numerical array $\{\min_{A_n}, \max_{A_n}, K1_{An}, K2_{A_n}\}$.

In this paper, the two inputs of the FLC are: q and SOC, while the output is: λ. Fig 9 presents the membership functions (MFs) for q, SOC and λ.



LL : very low L : low
M : moderate H : high
HH : very high NL : negative large
NM : negative medium NS : negative small
Z : zero PS : positive small
PM : positive medium PL : positive large

Fig. 9 The membership functions for the inputs and output of the FLC

4.2.2 Fuzzy Rules

The rule base is presented in Table 2. According to previous study [14], the fuzzy rules are divided into six parts which are as follow:

I. If the SOC is low, the battery is supposed to be charged to a higher level. Especially when the SOC drops to very low, charging the battery should be a top priority. This will result in a relatively fast return of the SOC to moderate level.

II. If T_{req} drops to very low level, in another word, q is very low, the ICE works quite inefficient. It should be turned off using the EM to supply T_{req} alone (EM separate driving mode).

III. If T_{req} is slightly lower than $T_{ice-opt}$, the EM work as a generator (EM active charging mode) to add extra load. So that the ICE working point could be raised to approach the ICE optimal efficiency curve.

IV. If T_{req} is close to $T_{ice-opt}$, the ICE works quite effectively already. No heavy extra load should be added in (ICE separate driving mode), or else it could damage the efficiency.

V. If T_{req} is slightly higher than $T_{ice-opt}$, it's similar to *III*, except the EM output torque is positive (EM assistance mode).

VI. If T_{req} rises to a very high level, all torque should be available to maintain the requirement, regardless of the efficiency.

Table 2. Fuzzy rules for fuzzy torque controller

λ (SOC \ q)	LL	L	M	H	HH
LL	NL	NL	NM	NM	NS
L	NL	NM	NS	PS	PM
M	PL	NM	Z	PM	PL
H	PL	NS	PS	PM	PL
HH	PL	Z	PS	PL	PL

4.2.3 Fuzzy Inference

Assume the total number of the fuzzy rules is N and A_n, B_n, C_n denote respectively the input value: q, SOC and output value: λ of the FLC in rule n (n = 1, 2, ... , N). The fuzzy reasoning mechanism used in this paper can be separated in five main steps.

1) Fuzzification: The membership degrees of the two inputs of the FLC are computed via the membership functions.

$$\mu_{A_n}(q),\ \mu_{B_n}(SOC) \tag{8}$$

2) Rule strength: According to the fuzzy rules, the fuzzified inputs are combined to establish the rule strength ω_n which is the degree to which antecedent part of a fuzzy rule is satisfied and also known as the degree of fulfillment.

$$\omega_n = \min(\mu_{A_n}(q), \mu_{B_n}(SOC)) \tag{9}$$

3) Inference: This operation represents the if-then implication. The rule strength 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 (ω_n) with the consequent ($\mu_{C_n}(\lambda)$) of rule n.

$$\mu_{C_nO}(\lambda) = \omega_n \mu_{C_n}(\lambda) \tag{10}$$

4) Aggregation: The outputs of all of the fuzzy rules are combined to obtain one fuzzy output distribution. This is done by taking the summation of the inference results of each rule.

$$\mu_C(\lambda) = \sum_{n=1}^{N} \mu_{C_nO}(\lambda) \tag{11}$$

5) Defuzzification: This operation takes the output distribution and finds its center of mass to come up with one crisp number (λ). w_n is the mass centre of $\mu_{C_nO}(\lambda)$.

$$\lambda = \frac{\int \lambda \mu_C(\lambda) d\lambda}{\int \mu_C(\lambda) d\lambda} = \frac{\sum_{n=1}^{N} w_n \int \mu_{C_nO}(\lambda) d\lambda}{\sum_{n=1}^{N} \int \mu_{C_nO}(\lambda) d\lambda} \tag{12}$$

4.3 ICE and EM Torque Adjustor

The third block in Fig 7 computes the final values for the ICE torque (T_{ice}) and EM torque (T_{em}), using T_{req}, T_{em-obj}, $T_{ice-off}$. Normally, T_{em} equals to T_{em-obj}, and T_{ice} is $T_{req} - T_{em}$. But there are two exceptions:

1) When $T_{em-obj} > 0$ and $T_{req} - T_{em-obj}$ is smaller than $T_{ice-off}$, then $T_{ice} = 0$ and $T_{em} = T_{req}$. This means the vehicle works at EM separate driving mode, and the gear shift should be recomputed to make the maximum EM torque possible.

2) When $T_{req} - T_{em-obj}$ is larger than $T_{ice-\max}$ which is selected in the first block of FTC, then $T_{ice} = T_{ice-\max}$ and $T_{em} = T_{em-obj}$.

5 Simulation Results

The proposed FTCS has been implemented and simulated by the advanced vehicle simulator (ADVISOR) in MATLAB/SIMULINK environment. ADVISOR employs a combined forward/backward facing approach for the vehicle performance simulation. The simulation parameters as well as the vehicle components model are consistent with the configuration in chapter 2. And its simulation results have been compared with the LTCS's, so as to get a better view of the advantage and improvements in FTCS.

Fig 10 presents the comparison of the torque distribution in FTCS and LTCS under the New European Driving Cycles (NEDC) with the initial SOC of 0.65. T_{ice} in FTCS is more homogeneous than the one in LTCS. Especially under urban driving cycle (0s – 800s), T_{ice} in LTCS stays at a

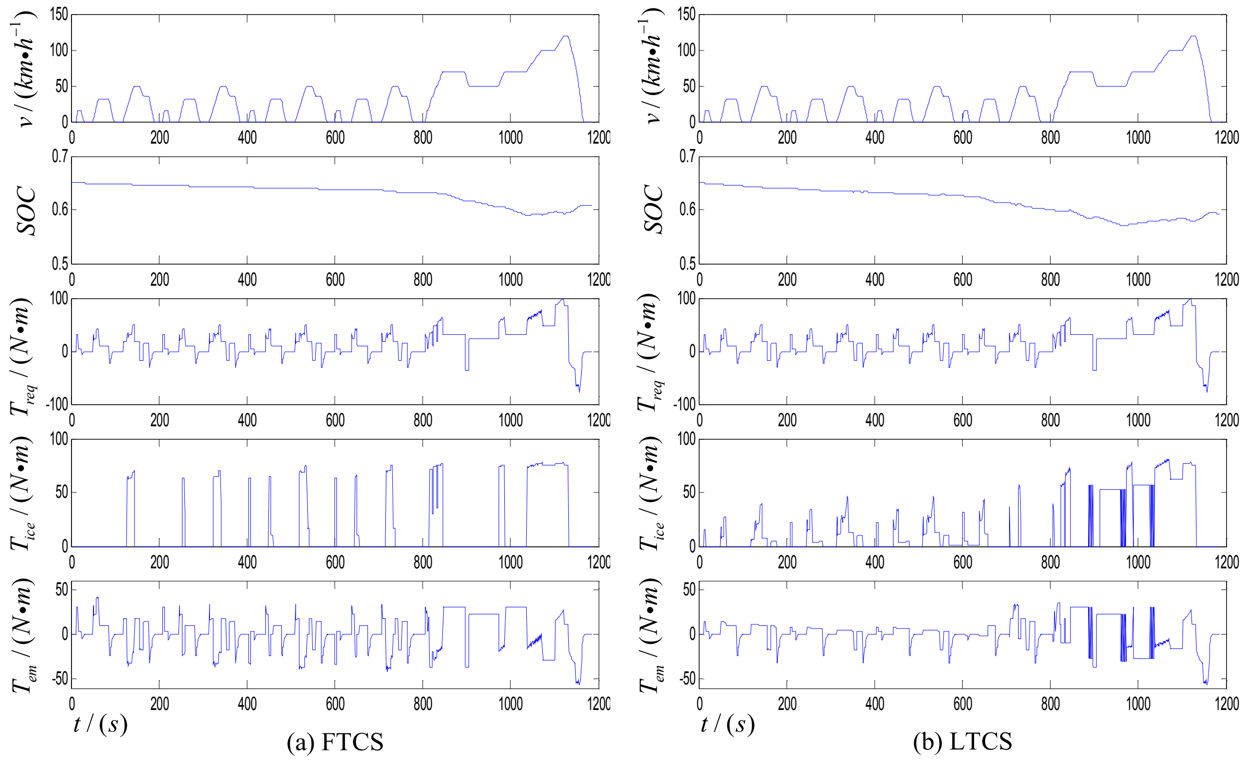


Fig 10. Simulation results for FTCS and LTCS under NEDC

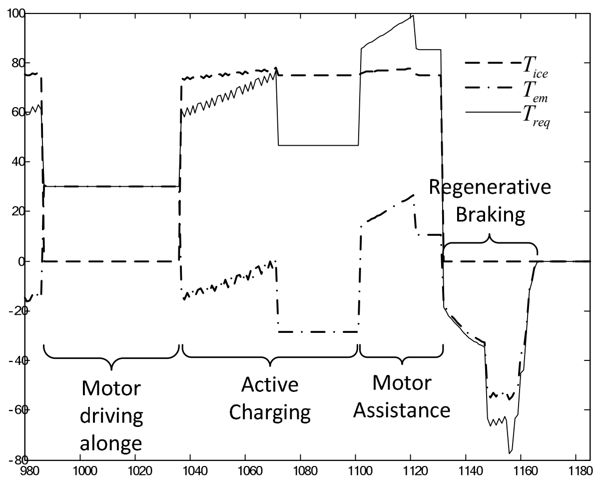


Fig 11. Torque distribution by FTCS in different working mode

low level, which indicates the ICE work at low effective zone in low speed driving condition.

In order for full understanding of the torque distribution discipline in FTCS, Fig 11 illustrates the details in Fig 10 (a) from 980s to 1185s.

1) From 987s to 1036s, T_{req} maintains at a low level and the SOC remains moderate, so the EM provides all of the driving force.

2) From 1037s to 1101s, T_{req} increases and the ICE starts up, following the vehicle speeds up. But T_{req} is insufficient to maintain the ICE works at high effective zone, so the EM performs active charge to raise the ICE load.

3) From 1102s to 1132s, as the vehicle speed continues to increase, T_{req} climbs up to approach $T_{ice-\max}$. The EM should provide extra torque to assistant the ICE to meet the requirement.

4) From 1133s to 1167s, as the vehicle begins to parking brake, the EM charges the battery again and outputs as much negative torque as possible to ensure always maximizes the regenerative braking power.

Fig 12 presents the ICE operating points on efficiency map of the simulation experiment illustrated in Fig 10. The operating points in Fig 12 (a) are close to the optimal curve, which indicates that the ICE has been operated close to optimal efficiency. By comparison, the operating points in Fig 12 (b) are farther from the optimal curve than those for the FTCS. What is worse is that most of the operating points are spread out all over the map rather than stick with the optimal curve in the low speed zone of Fig 12 (b). This echoes the conclusion proposed before that the ICE efficiency for FTCS is definitively higher than the one for LTCS in low speed driving condition, which could reflect on a significant gap in the ICE efficiency.

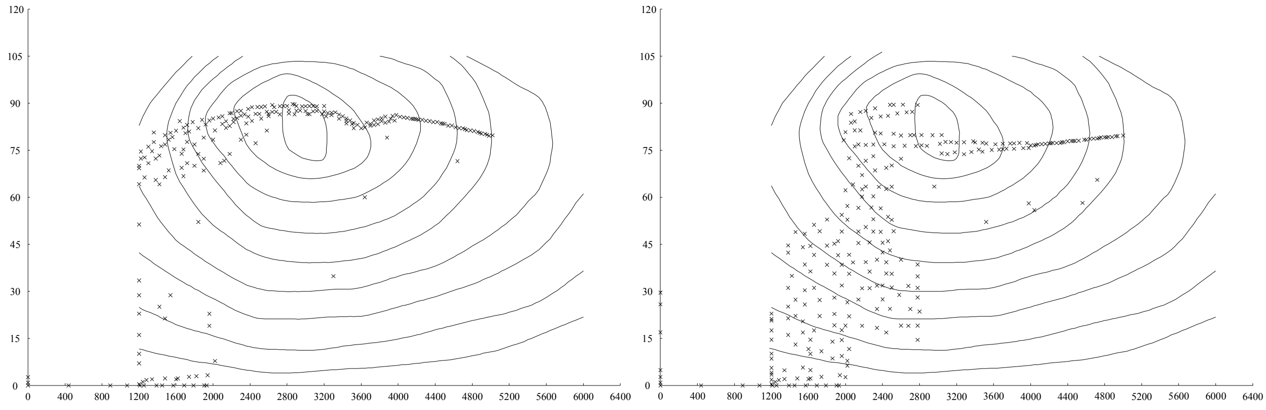


Fig 12. ICE operating points for FTCS and LTCS on efficiency map

Table 3. The main components efficiency and fuel economies under NEDC

	FTCS	LTCS
η_{ice}	0.244	0.197
η_{em}	0.875	0.866
η_{bat}	0.907	0.889
η_{tran}	0.796	0.776
$F_{revised}(L/100km)$	5.86	6.47

The efficiency of the main components under NEDC is shown in Table 3. Since the EM and battery's high effective zone is relatively widespread and their efficiency is insensitivity to driving load, the efficiency variance in EM and battery between FTCS and LTCS isn't as remarkable as it for ICE. However, there is still some advantage for FTCS in EM and battery, and therefore the FTCS overall efficiency is better than the LTCS. To be able to compare the vehicle fuel economy of FTCS and LTCS, the battery energy at the beginning and the end of each cycle has to be the same. Therefore, a series of test with SOC form 0.7 to 0.35 is carried out. Through linear regression analysis of the relationship between the fuel consumption and SOC changes, we obtain the fuel consumption with SOC unchanged ($F_{revised}$) for FTCS and LTCS, respectively. The overall improvement of FTCS than LTCS equals 9.4% which exemplifies the advantage of Fuzzy control strategy over conventional control strategy.

6 Conclusions

In this paper, a fuzzy torque control strategy for parallel hybrids has been presented. To implement this strategy, the accelerator and brake pedal inputs of the driver are converted to a driver requiring torque at first. And then the requiring torque is divided by the ICE optimal torque which is selected in gear shifting control strategy with the ICE maximum torque. Their quotient and state of charge of the battery are used by a fuzzy logic controller to compute the normalized value of EM objective torque. In the end, the EM objective torque, driver requiring torque, and ICE off torque are used to compute the ICE torque and EM torque which is send to ICE controller and EM controller, respectively.

The torque control strategy trades off between the ICE efficiency and the efficiency of the other components, meanwhile ensures that the battery is sufficiently charged at all times, the driver inputs (form brake and accelerator pedals) are satisfied consistently, and the fuel economy of the PHEV is optimized.

The simulation results under NEDC show potential improvement by applying fuzzy logic, over conventional strategy that relies on Boolean logic. In further research, the robustness of the fuzzy logic controller will be investigated in more detail. And neural network or genetic algorithms will be added to controller, to enable on-line controller optimization.

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