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An Intelligent Regenerative Braking Strategy for Power-split Hybrid Electric Vehicle

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Abstract: Nowadays, hybrid electric vehicle (HEV) is a popularly vehicle due to its advances such as reducing fossil fuel consumption and emissions that affect on environment. Brake energy regeneration system is essential part in HEV and electric vehicle. It assists HEV in reducing fuel consumption and pollution emission. Regenerative braking system aims to discard heat energy from mechanical braking as vehicle decelerated. Therefore, design and develop a suitable regenerative braking system were always intended. The braking control strategies were variation and improvement. The mechanical – electric braking system was utilized. This braking system must achieve the criteria such as safety, stability, maximum energy recovery and the shortest the braking distance. This paper proposed a control strategy for this hybrid braking system. Firstly, braking performances were satisfied by braking torque distribution strategy between front and rear axles. Secondly, maximum energy recovery was computed by compromising between mechanical and electric braking torque. Two issues were implemented by applying fuzzy logic and rule-based to design the braking torque controllers. Two controllers were estimated through the results of simulation in power-split HEV. The controller, applied fuzzy-based, had significant improvements in fuel consumption compare with another one. In addition, this controller was more flexible in various driving conditions.

Keywords: Braking Force Distribution, Hybrid Electric Vehicle (HEV), Fuzzy Logic Control (FLC), Regenerative Braking System (RBS), Mechanical-Electric Braking System

1. Introduction

Research and development of hybrid electric vehicle (HEV) has become popular around the world, due to compromise advantage solutions between conventional and electric vehicle, and overcome their restraints. Therefore, the HEV was supported remarkably from government, automakers, and customers.

For a conventional vehicle, a significant amount of energy is consumed in urban driving cycles during [1, 2]. To improve the energy-saving, the HEV which combines mechanical and electric braking systems is applied. The traction motor will convert kinetic energy to electrical energy for charging the battery during braking. Therefore, regenerative braking is an indispensable technique to improve the efficiency of HEV. Researches indicated that additional energy recycling is achieved from 8% to 25% of total energy use of vehicle, depend on the driving cycle and its control strategies [3, 4]. A study about regenerative braking to improve performances, efficiency and reliability at minimal additional cost for hybrid vehicle [5] and the regenerative braking system of the Hybrid Electric Vehicle (HEV) is a key technology that can improve fuel efficiency by 20~50%, depending on motor size [6].

The braking control algorithm has an essential role to obtain maximum energy recover and maintain stability of vehicle during braking. Various researches have implemented for regenerative braking system to satisfy braking control performances, such as rule based strategy [7, 8], fuzzy control strategies [9, 10], and neural network approaches [11]. However, these researches had mainly focuses on improving the energy recover based on common factors. This means that the objectives of safety, reliability and potential application had not considered expectantly yet.

The proposed braking control algorithm utilizes fuzzy logic and braking distribution in HEV to obtain maximum energy recycling, safety, as well as easy application. During braking conditions, the vehicle can achieve optimal regenerative energy efficiency. It can also prevent the wheel lock and slip situations by distributing suitable braking force to the front and rear wheels according to operated conditions. The result of simulation can verify the efficiency of the proposed braking control strategy in ensuring braking safety and stability, and improving energy efficiency.

2. Control Principles for Braking Force

2.1. Structure of the Proposed Braking System

The HEV has a hybrid braking system, which combines the mechanical and electric braking systems to attain the maximum braking force, maximum recover energy, and safety. Figure 1 shows the braking system, which can independently control the braking torque of front and rear wheels. The standard hydraulic brakes divide braking force to every wheel separately thank to the braking distributor. In this system, the front wheels use both mechanical and electrical braking, the rear wheels only use mechanical braking. Thus, regenerative energy only recovers on front wheels by electric motor (EM). The contributed braking is mutually complemented between rear wheels and front wheels. Braking performance is affected by the load movement, which is caused by deceleration, and the resistant load of vehicle. To maintain the stability of vehicle during the braking, the rear wheels must be unlocked during the deceleration process. Therefore, the braking system control is studied the distribution of braking force between front wheels and rear wheels, and between the mechanical system and electric system.

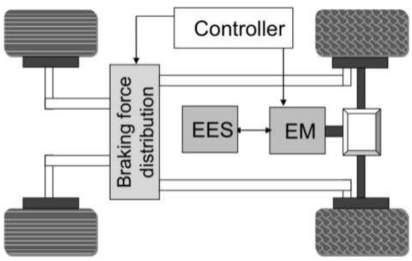

Figure 1. *Braking distributed schema of proposed HEV.*

2.2. Principle of Braking Force Distribution

Figure 2 shows the load movement which occurs when the braking is operated on flat road. Rolling resistance and aerodynamic drag are ignored due to they are very small compared to braking forces. j is the deceleration of vehicle during braking, M is mass of vehicle, the affected force of vehicle can be expressed as equation (1). Moreover, there is load transfer (m) from the rear axle to the front axle as defined in equation (2). The front wheel braking force F_f and rear wheel braking force F_r are derived from equations (3) and (4). W_f[kgf] and Wr [kgf] are front and rear loads, respectively, and μ is the friction coefficient between tire and the road surface.

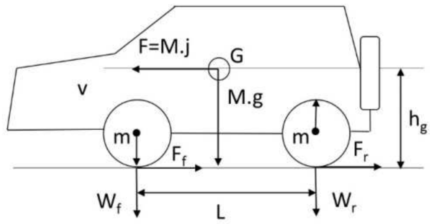

Figure 2. *Load movement when the braking is operated on the flat road*

$$F = M.j \tag{1}$$

$$m = \frac{F.h_g}{L} \tag{2}$$

$$F_f = \mu.(W_f + m) = \mu.\left(W_f + \frac{F.h_g}{L}\right) \tag{3}$$

$$F_r = \mu.(W_r - m) = \mu\left(W_r - \frac{F.h_g}{L}\right) \tag{4}$$

To attain high effect and stability of vehicle during braking, the controller must distribute maximum braking force, which can make the front and rear wheels lock simultaneously for each friction coefficient. In order to distribute braking force according to the idea curve, it is necessary to determine how the friction coefficient continuously changes following operation states. On the other hand, it is difficult to measure the changing friction coefficient directly. Thus, it necessary to determine the brake distribution ratio of front wheels (R_f) and rear wheels (R_r). The ratios are expressed as equations (5) and (6). Evidently, the ratios do not depend on friction coefficient.

$$R_f = \frac{F_f}{F_f+F_r} = \frac{M_f.g+m}{M.g} \tag{5}$$

$$R_r = 1 - R_f \tag{6}$$

From equation (7) and (8), the braking force only depends on load transfer, which depends on deceleration j. The braking torque at front and wheels are derived as equations (9) and (10).

$$F_f = F.R_f \tag{7}$$

$$F_r = F.R_r \tag{8}$$

$$T_{br} = k.F_r \tag{9}$$

$$T_{bf} = k.F_f \tag{10}$$

where:

$$k = \frac{r.g}{i_d} \tag{11}$$

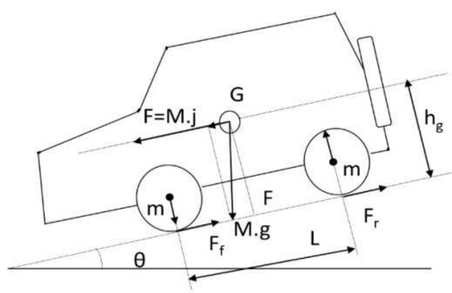

Figure 3. *Load movement when braking are operated on the slop road.*

r is the effective radius of a tire [m], g is the acceleration due to gravity [m/s^2], and id is the differential gear ratio.

Similarly, the calculations are implemented on slop road, as shows in Figure 3. In this case, the deceleration is measured by acceleration sensor (a_{sen}), equation (12). The braking force is derived as equation (14).

$$a_{sen} = g.\sin\theta + j \tag{12}$$

$$M.j = M.g.\sin\theta - F \tag{13}$$

$$F = M.g.\sin\theta + M.j = M.a_{sen} \tag{14}$$

Therefore, as the load movement is estimated by using the acceleration sensor, the ideal braking force distribution can be realized, even when running on the road with a slope. From the above discussions, the ideal braking force control can be performed by estimating the amount of the load movement and actual car weight using the measured acceleration [12].

2.3. Control Strategy for Optimal Energy Recovery

The principle of control strategy aims to distribute more braking force to front wheels during braking. Meantime, the front wheels must never lock earlier than rear wheels on the road with any adhesive coefficient. The more braking force allocates on front wheels; the more energy is recovered to charge battery. The braking performance requires that no wheel is locked and the braking force on the rear wheels is above the ECE regulation curve as shows in Figure 4. The braking forces on the front and rear wheels depend on vehicle deceleration rate and road adhesive coefficient [13].

When the braking strength is less than 0.2g, all the braking force is allocated to the front wheels for regenerative braking, and no mechanical braking force is applied to the front or rear wheels. When the braking strength is greater than 0.2g, the mechanical braking system starts utilizing. The braking force will be distributed to the front wheels and rear wheels following the ideal braking force distribution (curve I). At the same time, the braking force on front wheels will be allocated for electric and mechanical braking with recovering maximum possible energy. The maximum possible braking power must be smaller than maximum power of electric motor and energy storage system (ESS). In addition, the ECE regulation should be considered the minimizing braking force on the rear axle. When the braking strength is greater than 0.7g, for safety situation, all the force is applied for mechanical braking and it is distributed to front and rear wheels following I curve.

Therefore, the braking forces on the front and rear wheels are varied in a certain range. The area is limited by the ideal braking force distribution curve and ECE curve. However, depend on operating conditions; the braking force will be allocated to satisfy the maximum recover energy from front wheels.

Obviously, for braking strength z=0.5 (medium braking) when the road adhesive coefficient adh = 0.8 (concrete road), the maximum braking force on the front wheels is determined by point a, which is limited by ECE curve. The braking torque on the rear wheels can be very small. In certain range of front force a-b, the regenerative braking torque is determined by depending on the maximum torque of motor. On the other hand, maximum regenerative braking torque is achieved, as it is equal maximum torque of motor. As shows Figure 4, the maximum regenerative braking force (Fb_regen_max) produces at point n. It is obvious that the required braking force for front wheels is larger than maximum motor force. Therefore, the mechanical must be applied additional braking force to meet the best braking performance at point m

For other case, with the braking strength z=0.2 (small braking) when the road adhesive coefficient is smaller (wed mud road): adh = 0.3. The maximum braking force on the front wheel is located at point c, and the certain range of braking force on front is c-d. However, due to the maximum regenerative motor torque is larger, all braking force is transfer to regenerative force on the front wheel. On the other hand, no mechanical braking is distributed on front and rear wheels.

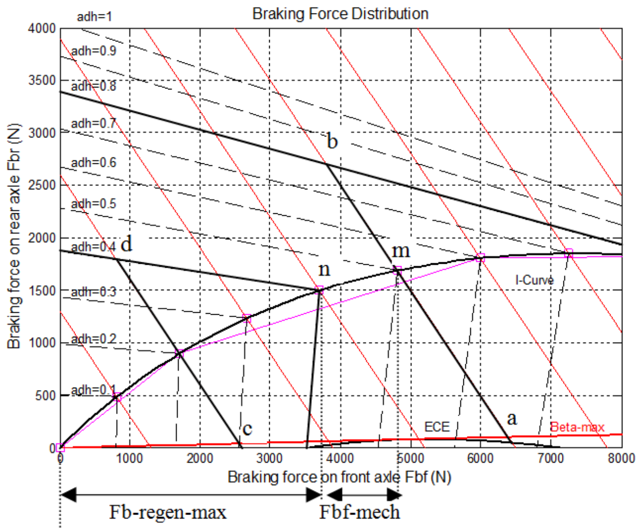

Figure 4. *Braking force distribution between front and rear wheels.*

3. Design and Control Principles of Braking Force Controller

In this research, the braking control was focused on the maximum regenerative braking, and the regenerative braking demand was controlled by several factors, which included vehicle speed, braking torque demand of driver, and battery's SOC. The SOC of battery could affect the efficiency of discharge and charge. The optimal operation of battery should be controlled in the range between 0.5 and 0.7. The relationships between these factors and the regenerative braking torque were executed by the fuzzy logic controller [14].

Relating to the driving safety, if the driver's brake torque command was large (emergency case), regenerative braking torque should be zero (mechanical braking only). Similarly, when vehicle speed was very high, the vehicle applied only mechanical braking. When the vehicle speed is very low, it is hard to produce braking torque due to the electromotive force in the stator windings generate too small. Therefore, in this case, the mechanical is applied to meet the torque requirement [15]. Vehicle specifications were utilized to implement the simulation as shows in Table 1.

Table 1. *Vehicle specifications.*

Term Value	Value
Vehicle gross mass	1325 kg
Wheel base	2.743 m
Center gravity (CG) height	0.77 m
Length from CG to front axle	1.097 m
Length from CG to rear axle	1.646 m
Adhesive coefficient of road	0.2-1

From the above analysis, it preferred three inputs of fuzzy logic controller including demanded torque, SOC, and vehicle speed. To generalize, all inputs and outputs were normalized to range [0, 1]. The definitions of these inputs were listed as following.

The braking torque input was used five membership functions in range [-1, 0], as shows in Figure 5. The braking torque requirement was divided five areas such as VH (torque was very high), H (high), M (medium), L (low), and VL (very low).

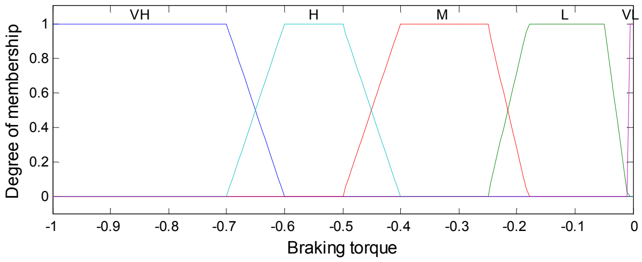

Figure 5. *The braking torque input.*

Similarly, vehicle speed and SOC input also had five membership functions as shows in Figure 6 and Figure 7, respectively.

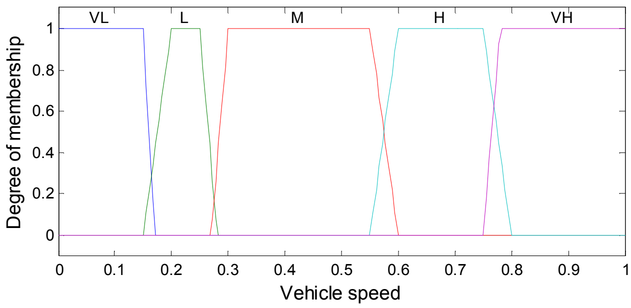

Figure 6. *The vehicle speed input.*

Because the optimal area of battery is from 50%-70% capacity, the SOC input preferred the concourse of SOC, and the universe of discourse was [0, 0.45] and [0.75, 1]. The membership functions could be presented in Figure 7.

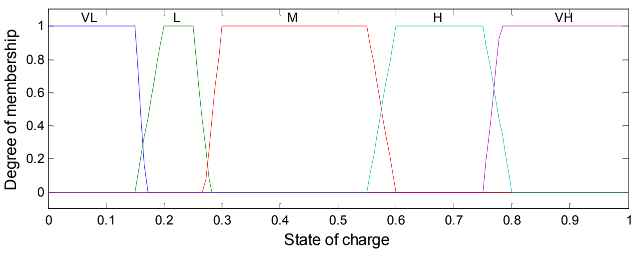

Figure 7. *The SOC input.*

The output of the braking controller is ratio of the regenerative braking torque on front axle to total demanded braking torque. There were five membership functions, VL, L, M, H, and VH, as shows in Figure 8.

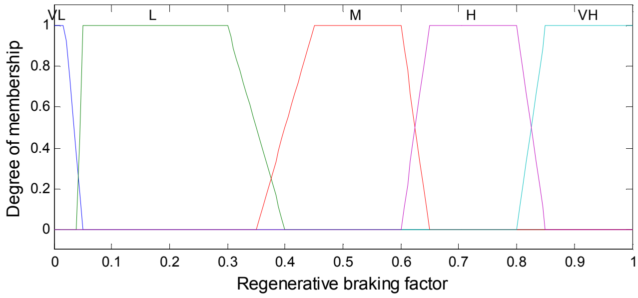

Figure 8. *The output of braking controller.*

Obviously, Figure 9 and Figure 10 shows the relation between output of regenerative braking torque factor and three inputs included braking torque requirement, vehicle speed, and SOC by 3D surface.

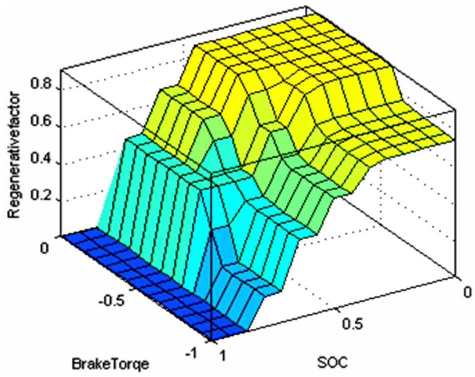

Figure 9. *The effect of braking torque requirement and vehicle speed to regenerative torque factor.*

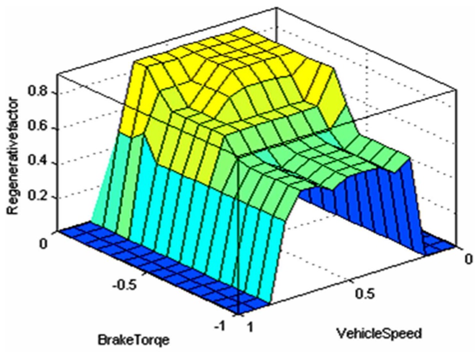

Figure 10. *The effect of braking torque requirement and SOC to regenerative torque factor.*

After using fuzzy-logic calculated the regenerative braking torque on front axle, the remaining braking torque was distributed to the mechanical braking of front and rear axles. The strategy of braking torque distribution was described in flow chart as Figure 11. In this strategy, the I-curve and ECE regulation were applied.

To reduce calculated time, the I-curve should be linearized. Depend on braking performances, the I-curve was divided into three areas. The first one, when vehicle deceleration (j) was less than 0.2, the I-curve was linearized as equation (15). The second one, when vehicle deceleration (j) was more than 0.2 and less than 0.6, the I-curve was linearized as equation (16). The finally, when vehicle deceleration (j) was more than 0.6, the result was linearized as equation (17). Similarly, the ECE curve should be also linearized as shows (18).

$$F_r = 0.5241.F_f \tag{15}$$

$$F_r = 0.2128.F_f + 530.982 \tag{16}$$

$$F_r = 0.0071.F_f + 173.7 \tag{17}$$

$$F_r = 0.0158.F_f \tag{18}$$

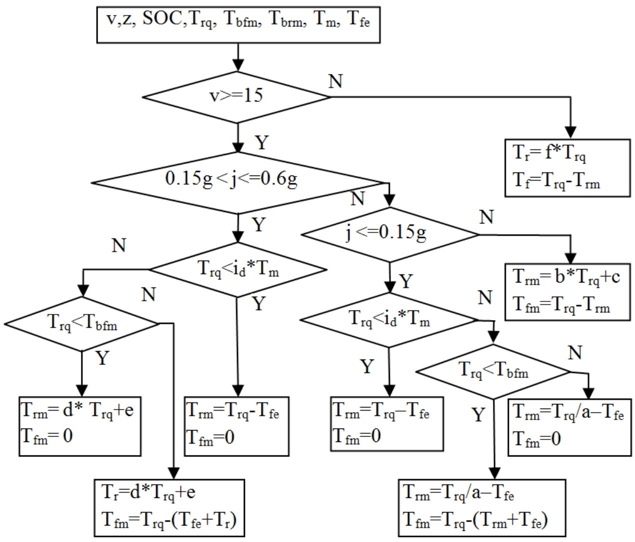

Figure 11. *Distributing strategy of braking torque on front/rear axle.*

Where the factors a, b, c, d and e were calculated by the equations (15), (16), (17) and (18).

In the flow chart, T_{rq}, T_{fm}, T_{fe}, T_{bfm}, T_{brm}, T_{rm} and T_m were braking torque requirement, mechanical braking torque of front axle, regenerative braking torque of front axle, maximum braking torque of front axle, maximum braking torque of rear axle, mechanical braking torque of rear axle, maximum motor torque, respectively.

4. Results and Discussion

Two braking torque controllers had been implemented using Simulink/Matlab. The first controller utilized the rule-based, the second one applied the fuzzy-based. Obviously, Figure 12 to Figure 18 shows the results of simulation for fuzzy-based and rule-based braking torque controllers on specify driving cycle (NEDC). To go into detail, Figure 12 presented the actual vehicle velocity by simulation and the desired driving cycle. The simulated velocity of vehicle was close the desired driving speed. Figure 13 illustrated the ratio of regenerative braking torque to required braking torque of fuzzy-based braking torque controller. The ratio was very high; it means the braking controller recovered most of energy during braking.

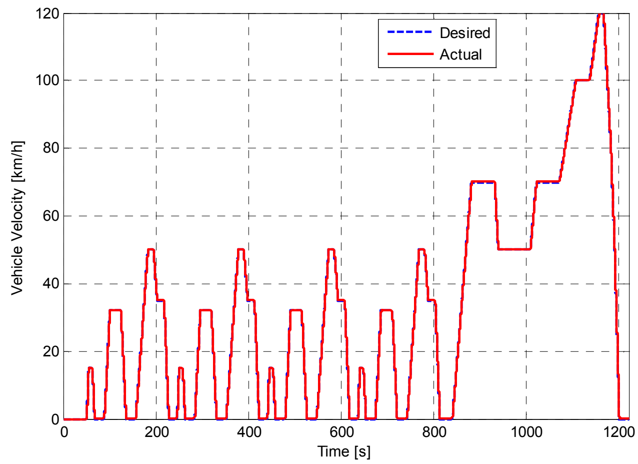

Figure 12. *Simulated and desired vehicle velocity.*

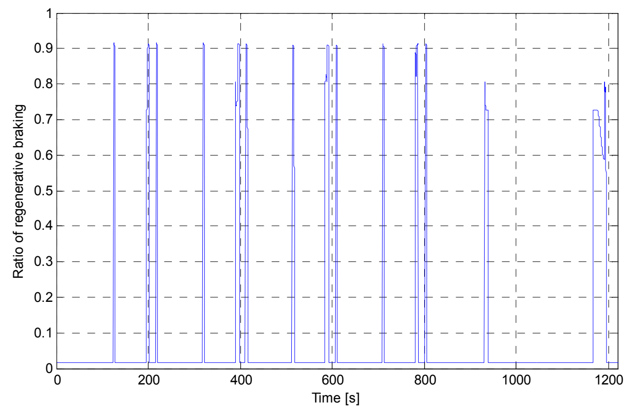

Figure 13. *The ratio of regenerative braking toque to require braking torque.*

Figure 14 presented regenerative braking torque on the front wheels, which applied rule-based controller (magenta line), fuzzy-based controller (blue line) and maximum motor torque (red line). The regenerative braking torque used fuzzy-based was higher than the regenerative braking torque used rule-based was.

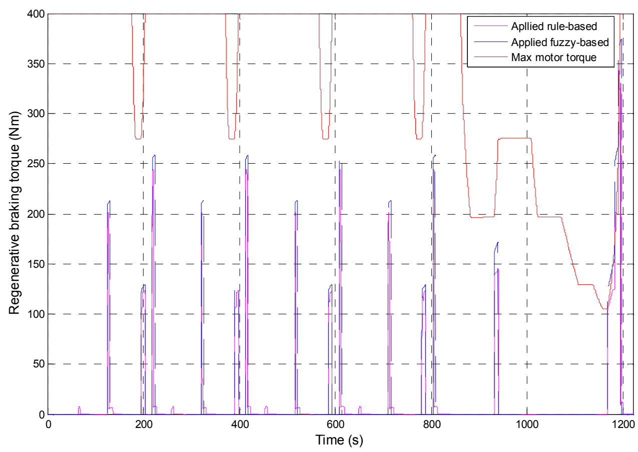

Figure 14. *Regenerative braking toque and maximum torque of Motor.*

Figure 15 indicated the state of charge of battery when the vehicle followed driving cycles. The battery operated in optimal range (0.5-0.7) through the driving cycles. Obviously, the SOC of fuzzy-based was higher than the SOC of rule-based was.

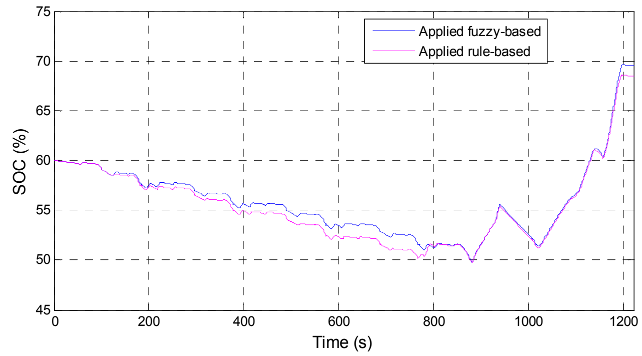

Figure 15. *Battery SOC.*

Figure 16 indicated the torque and speed of electric motor through time of NEDC driving cycle. Moreover, Figure 17 shows the operated points in the efficiency map of electric motor. The operated points of motor were in negative torque that means the motor had role as generator. The motor also was operated in high efficient area.

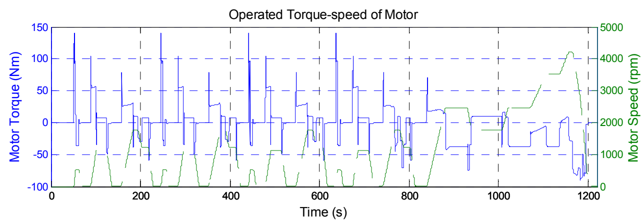

Figure 16. *Torque and speed of electric motor.*

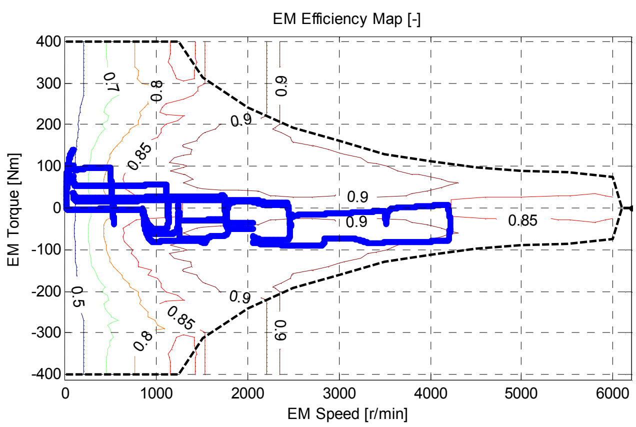

Figure 17. *Operated points of electric motor.*

The Figure 18 shows braking force distribution between front and rear axles. The magenta points presented the result of the model used rule-based braking torque controller, the blue points indicated result of the model used fuzzy-based controller. Obviously, the braking strength was smaller than 0.2, with the adhesive coefficient of concrete road was high (0.8), all the wheels cannot lock. In this case, the braking force should be allocated to regenerative braking system as much as possible to obtain maximum regenerative braking energy. Therefore, the braking force can be distributed small or zero to rear wheel. In the other hand, the fuzzy-based braking controller was better than the rule-based braking controller was.

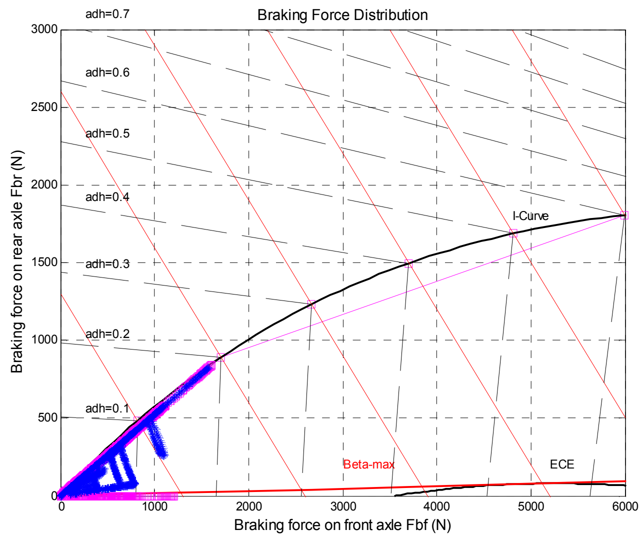

Figure 18. *Braking force distribution between front and rear axle.*

To estimate two braking torque controllers, the power-split HEV model was executed on the typical driving cycles; the first one used in urban (UDDS) and second one used combination of urban and high way (NEDC). Table 2 shows the results of simulation on two specific driving cycles.

From the results, the implemented model used fuzzy-based braking torque controller improved equivalent fuel consumption compare with the rule-based braking torque controller. The model used fuzzy-based saved 5.25% compared with the model used rule-based when implemented on urban driving cycle (UDDS), and saved 4.65% when implemented on combined driving cycle (NEDC).

Table 2. *Fuel consumption when using regenerative and non-regenerative braking.*

Item	Rule-based controlL/100km	Fuzzy-based controlL/100km	Improvement (%)
NEDC fuel consumption	4.43	4.224	4.65%
UDDS fuel consumption	4.76	4.51L	5.25%

5. Conclusions

Two braking torque controllers, used fuzzy logic and rule-based, had been implemented and proven on the power split hybrid electric vehicle. The rule-based braking torque controller was simple in design but it lacked flexible in various driving conditions. The fuzzy-based braking torque controller was more complex but it had adaptable in diverse driving situations. The braking torque controller combined two strategies: optimal braking performance and optimal energy recovery to obtain better performance and save energy dissipation. The proposed strategy recovered the most regenerative braking energy and ensured the braking safety during braking. Therefore, applying fuzzy logic to design the braking controller with proposed control strategy resulted in better performance, safety and maximum braking energy recovery.

The implemented braking controller consistently satisfied driver inputsas signal braking pedal, the sufficient battery for operating, and the stability of vehicle during braking.

Acknowledgements

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Biography

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