Regenerative Braking Strategy for Electric Vehicles

Jingang Guo, Junping Wang and Binggang Cao

Abstract—**Regenerative braking is an effective approach for electric vehicles to extend their driving range. The control strategy of regenerative braking plays an important role in maintaining the vehicle's stability and recovering energy. In this paper, the main properties that have influence on brake energy regeneration are analyzed. Mathematical model of brake energy regenerating electric vehicles is established. By analyzing the charge and discharge characteristics of the battery and motor, a simple regenerative braking strategy is proposed. The strategy takes the braking torque required, the motor available braking torque, and the braking torque limit into account, and it can make the best use of the motor braking torque. Simulation results show higher energy regeneration compared to a parallel strategy when the proposed strategy is adopted.**

I. Introduction

REGERATIVE braking is the process by which some of the kinetic energy stored in the vehicle's translating mass is stored in the vehicle during deceleration. In most electric and hybrid electric vehicles on the road today, this is accomplished by operating the traction motor as a generator, providing braking torque to the wheels and recharging of the traction batteries. The energy provided by regenerative braking can then be used for propulsion or to power vehicle accessories. Therefore, regenerative braking is an effective method to improve the driving range of electric vehicles (EVs).

Regenerative braking has to be carried out together with the conventional friction braking. In brake system design for EVs, two basic questions must be concerned [1]. One is properly applying braking forces on front and rear wheels to quickly reduce the vehicle speed, and meanwhile, maintaining the vehicle traveling direction stable and controllable through the steering wheel on various road conditions. The other is recovering the braking energy as much as possible in order to improve the energy utilization efficiency, especially while driving with stop-go driving pattern in urban areas. The distribution and control strategy of braking forces plays an important role in achieving its goals.

In order to coordinate the regenerative torque of the motor and the friction torque of the hydraulic unit, various control strategy have been developed, which can be roughly divided into two types [2]: series and parallel. Series braking allows independent modulation of the hydraulic brakes to each wheel, allowing application of regenerative braking torque to the driven wheels up to the maximum that the tire and road surface interface can accept; the remaining braking torque required can be made up hydraulically at the driven or non-driven wheels. A parallel braking system applies regenerative braking torque, to the driven wheels, in addition to hydraulic braking torque provided by the foundation braking system. Parallel braking does not have the same potential for energy recovery as the series braking system.

In the research area of the brake system of EVs, Reference [3] focused on control braking forces for optimal braking performance. Reference [4] presented regenerative braking strategy to make maximum use of the braking energy. Reference [5] investigated the relation between the regenerated brake energy and the related properties and presented a computational procedure using genetic algorithm to maximize the regenerated brake energy.

In this paper, a simple regenerative braking strategy is proposed. The strategy takes full advantage of the motor torque and can obtain maximum energy recovery. Simulations are carried out on typical driving cycles. The effectiveness of the strategy is proved.

II. Properties Affecting Brake Energy Regeneration

A. Braking Force Distribution Limit

In order to obtain short braking distance and prevent the rear wheel being locked earlier than the front wheel being locked to maintain the vehicle directional stability, braking theory and design principle emphasizes distribution of total braking force on front and rear wheels. According to the theory, the distribution of braking forces should be limited in a reasonable range, as illustrated by grey area in Fig.1. If braking forces on the front and rear axles follow the ideal distribution curve, the front and rear axles will be locked simultaneously when the braking forces reach the adhesive limit between the road and the tires. Such a distribution can obtain maximum braking stability of the vehicle. If the ratio of braking forces on the front and rear axles is above the ideal distribution curve, the rear wheels will be locked before the front wheels, which tends to cause vehicle instability. Therefore, this case should be avoided. In order to prevent the front wheels being locked too early and lead to low road adhesion utilization, a minimum rear braking force limit has been set up. This is demonstrated by ECE regulation curve in Fig.1. The curve labeled front wheel locked curve in Fig.1

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J. Guo is with the School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China (e-mail: guojg@chd.edu.cn).

J. Wang is with the School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China (e-mail: wangjunping@tsinghua.org.cn).

B. Cao is with the School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China (e-mail: inte-cao@mail.xjtu.edu.cn).

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illustrates the situation that the front wheels are locked and the rear are not.

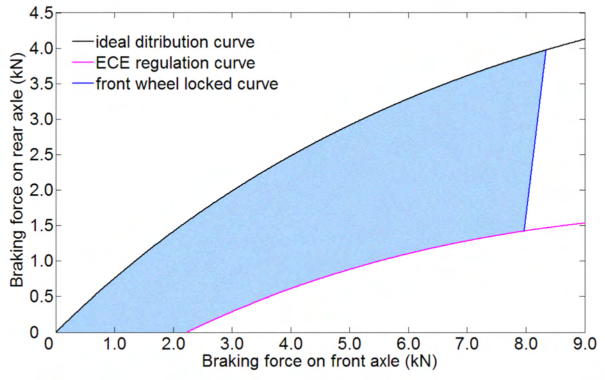


Fig. 1. Permitted area of force distribution

B. *Motor Available Braking Torque*

The motor maximum torque is determined from the motor characteristic curve. This is described by

$$T_{m\max} = \begin{cases} T_N \text{-----} \omega_m \leq \omega_b \\ P_N / \omega_m \text{---} \omega_m > \omega_b \end{cases} \quad (1)$$

where $T_{m\max}$ is the motor maximum braking torque, T_N is the motor rated torque, ω_b is the motor base angular speed, ω_m is the motor angular speed, P_N is the motor rated power.

However, it is difficult for a motor to generate electricity and deliver to the on-board energy storage, because of the very low electric motive force (voltage) generated at low motor rotational speed, which is proportional to the vehicle speed. Thus, a weight factor K_v is used. Similarly, when the battery state of charge (SOC) is considered, a weight factor K_{SOC} is introduced to protect the battery from overcharging that may affect the battery life. The weight factors K_v and K_{SOC} are shown in Fig.2.

Therefore, the available regenerative braking torque given by the motor is obtained as

$$T_{mavail} = T_{m\max} K_v K_{SOC} \quad (2)$$

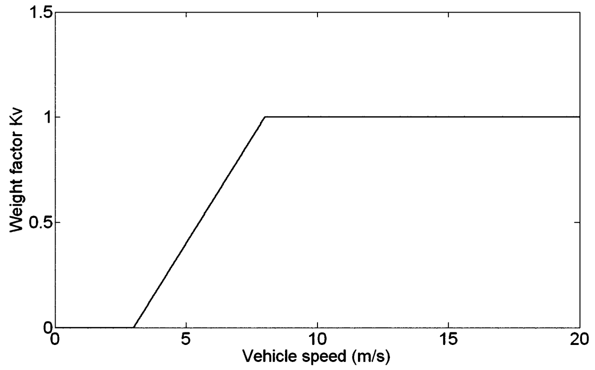
C. *Mathematical Model of Brake Energy Regenerating EVs*

In this paper, a front wheel-drive configuration is considered.

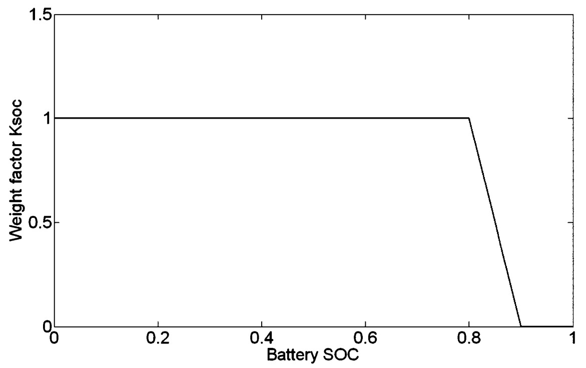
When a deceleration is required, torque is transferred from the motor and mechanical brakes to the wheels. The braking torque applied by the motor is converted to electric energy and transferred to the battery.

For a given deceleration, a force F_{req} has to be applied at the wheels to match it[6]. This is described by

$$F_{req} = F_a - F_r - F_w - F_h \quad (3)$$



(a) Weight factor of the vehicle speed



(b) Weight factor of the battery SOC

Fig. 2. Weight factor

where F_{req} is the braking force required, F_a is the force required to give the deceleration, which has a reasonable approximation when the angular acceleration is ignored, F_r the rolling resistance force, F_w is the aerodynamic drag, F_h is the hill climbing force.

The power required to slow the vehicle is calculated by

$$P_{req} = F_{req} v \quad (4)$$

where v is the vehicle speed.

P_{req} is split up between the front and rear axles according to the distribution strategy of braking forces, and it is expressed as

$$P_{req} = P_f + P_r \quad (5)$$

where P_f is the power provided by the front wheels, P_r is the power provided by the rear wheels.

The electric power from the motor is smaller than P_f because of the efficiency of the gear system and the motor. This is described by

$$P_{mot\_ele} = P_f \eta_g \eta_m \quad (6)$$

where P_{mot_ele} is the motor electric power, η_g is the efficiency of the gear system, and it is assumed to be constant, η_m is the efficiency of the motor, and it is modeled by the equation

$$\eta_m = T_m \omega_m /(T_m \omega_m + k_c T_m{}^2 + k_i \omega_m + k_\omega \omega_m{}^3 + C) \tag{7}$$

where T_m is the motor braking torque, k_c is the copper losses coefficient, k_i is the iron losses coefficient, k_w is the windage losses coefficient and C represents the constant losses that apply at any speed.

The power that charges the battery is the summation of contribution of electric power from the motor and electric power needed to run other electrical systems. This is described by

$$P_{ch} = P_{mot\_ele} - P_{ac} \tag{8}$$

where P_{ch} is the charge power of the battery, P_{ac} is the average power of the accessories. It should be noted, P_{ch} is charge power when it is positive, otherwise it is discharge power.

When braking, a certain power is dissipated into the battery. Here, an internal resistance battery model is adopted, which characterizes the battery with a voltage source and an internal resistance.

Considering the situation that the current I is flowing into the battery, charge power of the battery is obtained as

$$P_{ch} = EI + I^2 R \tag{9}$$

where E is the open circuit voltage, and it changes with the battery SOC, I is the charge current, R is the internal resistance of the battery.

The reasonable solution to (9) is

$$I = (-E + \sqrt{E^2 + 4RP_c})/2R \tag{10}$$

The battery SOC is represented as follows

$$SOC = SOC_0 + \delta t \times I / C_P \tag{11}$$

where SOC_0 is the battery initial SOC, δt is the sampling time, C_P is the Peukert capacity.

The regenerated power of the battery is described as

$$P_b = P_{ch} - I^2 R \tag{12}$$

To evaluate the ability of regenerated brake energy for a full driving cycle, regenerated energy efficiency is defined, and expressed by

$$\eta = \int P_b \Big/ \int P_{req} \tag{13}$$

III. Braking Torque Distribution Strategy

From analysis above, the amount of regenerated brake energy depends on multiple factors in EVs. To achieve high regeneration during braking without sacrificing the stability of the vehicle and fulfill the requirements of the factors, it is reasonable to distribute the braking torque required between the front and rear axles, between regenerative braking and friction braking by optimization algorithm. However, it will consume large computing time and is difficult to accomplish real-time application. In following, a simple braking torque distribution strategy is presented.

A. Charge and Discharge Characteristics of the Battery and Motor

Fig.3 shows the relation between the regenerated power and the charge power of the battery. Maximum charge and discharge powers of typical driving cycles are listed in Table I. In Table I, the driving cycles include ECE Driving Cycle (ECE), New European Driving Cycle (NEDC), Supplemental Federal Test Procedure (SFTP), New York City Cycle (NYCC) and Urban Dynamometer Driving Schedule (UDDS). From Fig.3 and Table I, it is found that for the typical driving cycles, the regenerated power increases with the increase of the charge power of the battery. That is to say, if the charge power of the battery is the maximum, the regenerated power of the battery will be the maximum.

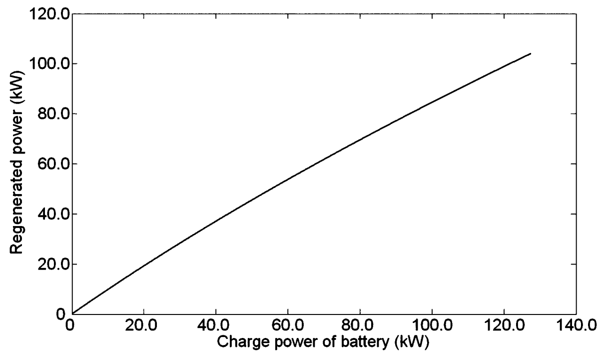


Fig. 3. Relation between the regenerated power and the charge power of the battery

TABLE I
MAXIMUM CHARGE AND DISCHARGE POWERS OF TYPICAL DRIVING CYCLES

Driving Cycle	ECE	NEDC	SFTP	NYCC	UDDS
Maximum discharge power (kW)	4.50	12.91	17.61	9.97	12.11
Maximum charge power (kW)	16.0	38.49	49.80	38.34	39.09

However, there exists a situation that the motor is generating, while the battery is discharging. The reason for this is that the electric power generated by the motor is smaller than the average power of the accessories, which results in the batteries need to consume power. In this case, it is desired that the consumed power of the battery the more little the more good. From the relation between the consumed power and the discharge power of the battery (Fig.4), it is found if the discharge power of the battery is the minimum, then the consumed power of the battery is the minimum. The minimum discharge power of the battery corresponds to the maximum electric power generated by the motor.

In a word, for both situations, the electric power generated by the motor the more big the more good.

Fig.5 shows the electric power generated by the motor during braking. It can be seen, for the same motor angular speed, the electric power of the motor increases with the increase of the motor torque under the circumstance that the motor torque is below the motor maximum torque.

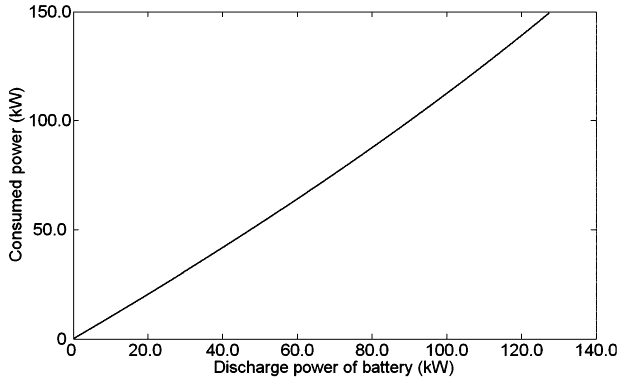


Fig. 4. Relation between the consumed power and the discharge power of the battery

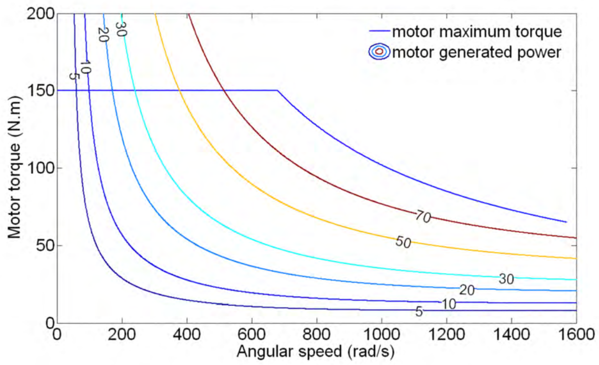


Fig. 5. Electric power generated by the motor during braking

B. *Braking Torque Distribution Strategy*

Analysis above indicates that, if the regenerative braking torque of the motor is the maximum, the optimum energy recovery will be obtained. In other words, optimizing energy recovery requires maximizing regenerative braking torque. Braking torque supplied by the motor during regenerating can be maximized, using hydraulic foundation brakes only to the extent necessary to meet the driver's brake command and to achieve vehicle stability.

Fig.6 shows the frame of the braking torque distribution strategy. At the beginning, the braking torque required, the braking torque limit of the front axle and the motor available braking torque are calculated. Then, the smallest of above braking torque will be the motor actual braking torque. As for the friction braking torque on the front and rear axles, they can be determined when the braking torque limit of the front axle and the braking torque required are considered. It should be noted, the distribution of the front and rear braking forces must be in the grey area illustrated in Fig.1. Finally, the regenerated power of the battery and the battery SOC is calculated.

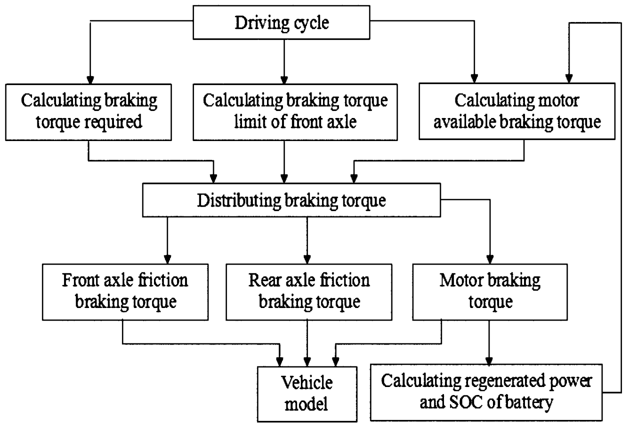


Fig. 6. Frame of the braking force distribution strategy

IV. Simulation and Analysis

The presented strategy is evaluated by comparing with a parallel strategy on several driving cycles. The parallel strategy distributes the braking forces required between the regenerative and friction braking with a fixed relation, which is a function of the vehicle speed, as shown in Fig.7. Of course, the fraction of the braking force done by the motor and the friction brakes are chosen so as to keep their fractions of total braking force the same as specified, and are subject to their maximum braking force limits.

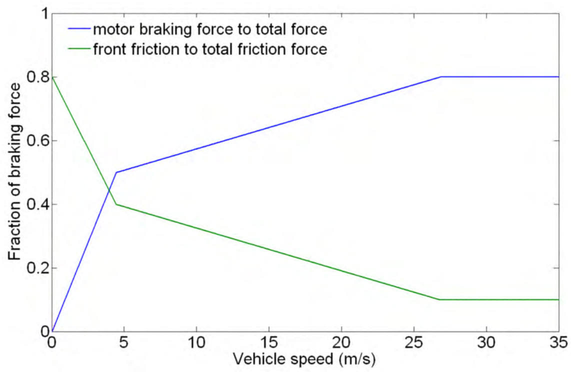


Fig. 7. Parallel braking force distribution strategy

Fig.8 shows the driving cycle of NEDC, which the simulations have been implemented on. Fig.9 demonstrated the braking forces distribution of both strategies. As it can be seen, when the strategy in this paper is adopted, the regenerative braking force of the motor is bigger than the parallel strategy. The proposed strategy takes advantage of the motor maximum torque and can obtain maximum energy recovery. However, either the proposed strategy or the parallel strategy, the motor braking force must meet the requirement of vehicle stability. In other words, they must be smaller than the force limit.

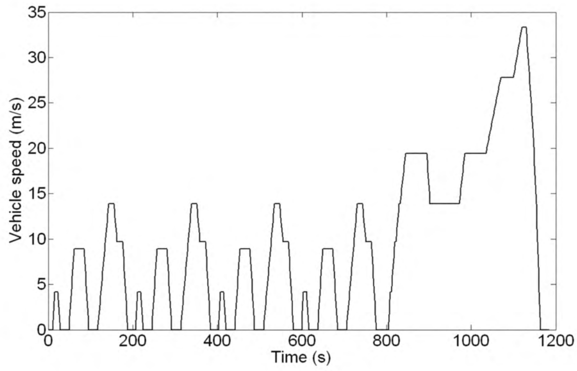
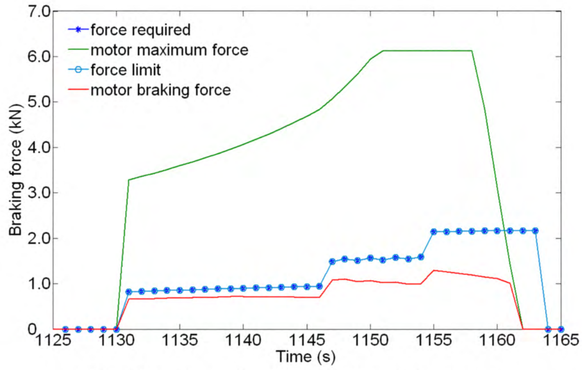
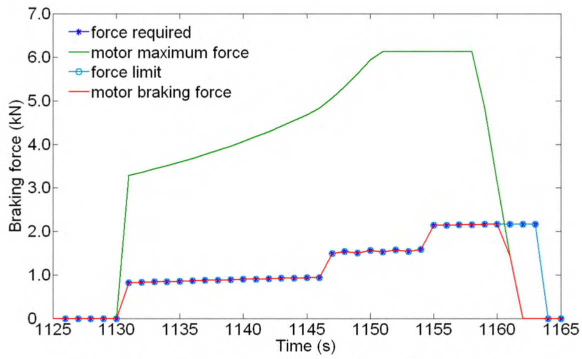


Fig. 8. New European Driving Cycle



(a) Braking forces distribution of parallel strategy



(b) Braking forces distribution of proposed strategy

Fig. 9. Comparison of braking forces distribution

Fig.10 shows the comparison of the battery SOC. Comparing to no recovery, both the parallel and the proposed strategy can improve the battery SOC. The effect of the proposed strategy is better.

In Fig.11, the regenerated energy efficiency is compared on several typical driving cycles. It can be seen, comparing with the parallel strategy, the regenerated energy efficiency have remarkable improvement for each driving cycle when the proposed strategy is adopted.

Simulation results indicate, because the proposed strategy is able to use the motor braking torque to the full extent, the proposed strategy has resulted in higher energy regeneration in all cases.

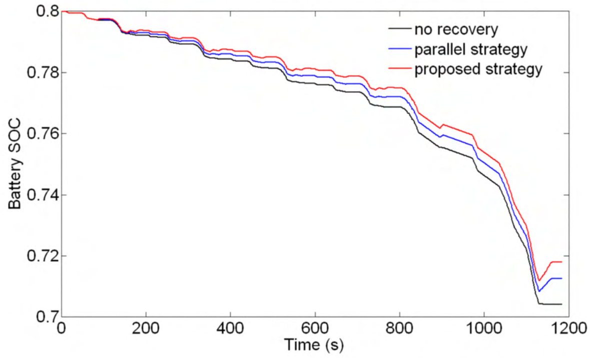


Fig. 10. Comparison of the battery SOC

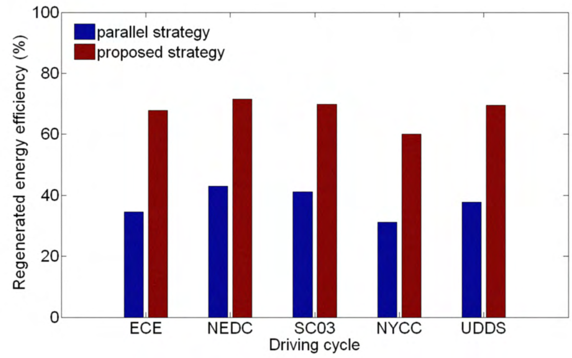


Fig. 11. Comparison of regenerated energy efficiency

V. CONCLUSION

Properties affecting braking energy regeneration are analyzed. The mathematical model of brake energy regenerating EVs is established. By analyzing the charge and discharge characteristics of the battery and motor, a simple regenerative braking strategy is proposed. The strategy takes advantage of the motor torque and can obtain maximum energy recovery. The effectiveness of the strategy is verified by comparing with the parallel strategy. The proposed strategy can improve the battery SOC and regenerated energy efficiency remarkably.

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