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Research on Electric Vehicle Regenerative Braking System and Energy Recovery

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Abstract

To improve driving ability of electric vehicle, a braking regenerative energy recovery of electric vehicle was designed and the structure of it was introduced, the energy recovery efficiency of whole system was defined and a highly efficient control strategy was put forward, then it was embedded into the simulation of ADVISOR2002. The recovery efficiency of the system was up to 60%, the electric vehicle energy recovery efficiency was effectively improved.

Keywords: *electric vehicle, control system, energy recovery control strategy, simulation*

1. Introduction

As we know it will not be able to realize the dream of popularization of cars if only using limited petroleum resources. Therefore, the important method to solve problems is to develop electric vehicle and it is of great significance [1].

For electric vehicle its power source is batteries. The mileage is still a "curse" for development of electric vehicle. As one of the major factors to decide the driving mileage, the battery technology has made great development, but due to restriction of technology and economic factors, recently there will be no big breakthrough. So another major factor to reduce energy consumption and improve driving mileage, the research of brake energy recovery technology has become popular and braking energy can be up to 50% of the total energy to drive according to related literature. The driving mileage will be increased if the part of waste energy can be reused [2-4].

The system structure is introduced and the energy recovery is researched, then the energy recovery control strategy is put forward. Finally, the control strategy is simulated in ADVISOR2002 simulation platform and the result is evaluated [5-6].

2. The Structure and Working Principle of Regenerative Braking System

Figure1 is a front-wheel drive vehicle regenerative braking structure diagram. When the electric vehicle spending up, the motor controls the current output by the battery through the sensor signal, and then its speed is adjust for providing power. The motor becomes generator when electric vehicle braking, transmits the electric power which is converted by the motor to the battery, recharging the battery. Energy recovery system working schematic diagram is shown in Figure 2 [7]. The hardware structure includes permanent magnet motor, controller, three-phase controlled bridge rectifier filter circuit, inverter, three-phase bridge rectifier circuit and so on. When the control signal changes from 1.0 V to 3.5 V, the controller controls permanent magnet motor rotating work, driving vehicle, when the value below 1.0 V, control energy recovery system works and generates electromagnetic braking force and finally realizes the driving wheel braking.

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The specific work flow for the electric vehicle energy recovery system is that the controller controls the permanent magnet motor together with three-phase controlled bridge rectifier filter circuit working through wire connection, the rectifier filter circuit converts the three-phase alternating current produced by the permanent magnet motor to direct current, and then the direct current is delivered to the inverter. Power batteries control the output frequency of inverter through feedback signals; the inverter controls permanent magnet motor to rotate and produces three phase alternating current which is converted into direct current through rectifier circuit at last.

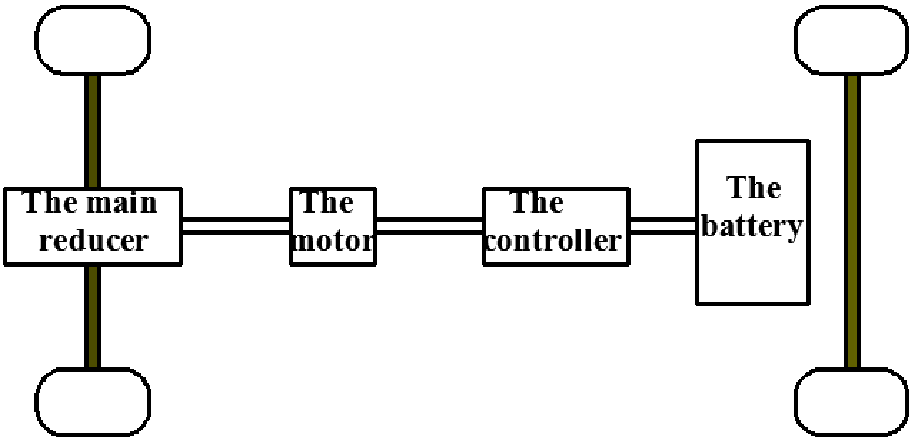

Figure 1. Front Wheel Drive Vehicle Regenerative Braking System Structure Diagram

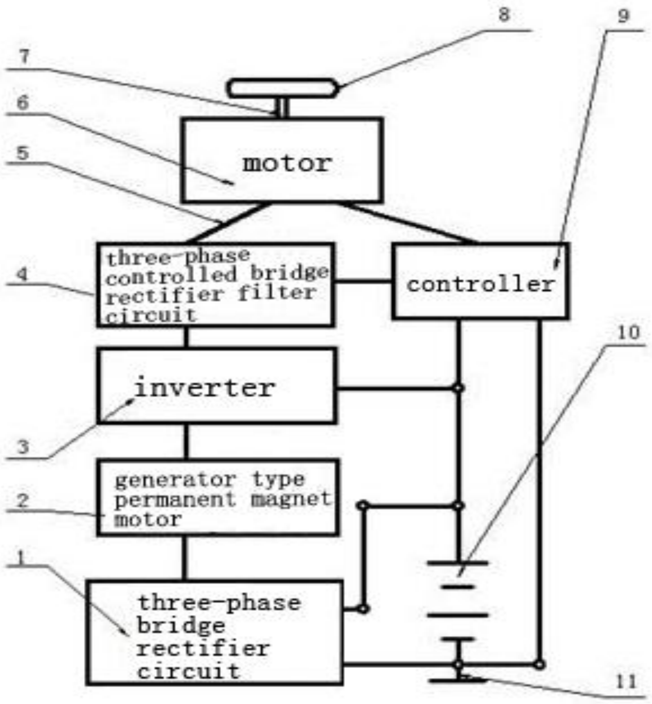

Figure 2. Energy Recovery System Working Schematic Diagram

1- three-phase bridge rectifier circuit; 2- power type permanent magnet motor; 3- inverter; 4- three-phase controlled bridge rectifier filter circuit; 5- three-phase line; 6-permanet magnet motor; 7-shaft; 8- vehicle driving wheels ; 9- controller; 10-power battery; 11-negative grounding end.

3. The Determination of Regenerative Braking System Energy Recovery

When braking, braking forces from wheels are needed reasonably distributed, preventing the lock and operation instability. Also we need to find the best coverage of the motor brake and mechanical brake and then recycle braking energy possibly.

3.1. The Restricting Conditions of Regenerative Braking Energy Recovery System

3.1.1. The Driving Motor: The role of motor is important as a component of energy conversion in the brake system. Most motors are decorated on the front of electric vehicle, this means that only the front wheel can produce regenerative braking force, rear wheels produce braking forces through mechanical friction. The output characteristics of the motor are as follows [8]

$$T = \begin{cases} 9549P_n / n_o & n \le n_o \\ 9549P_n / n & n > n_o \end{cases} \tag{1}$$

Among them: T is the motor torque; P_n is motor rated power; n is motor actual speed; n_0 is rated speed.

When the motor actual speed is less than rated speed, the output torque keeps constant, the power and speed are proportion relationship. When the actual speed is higher than rated speed, output torque decreases with the increased speed and the output power is constant. When vehicle in low speed running, its kinetic energy is low and it can't provide enough energy for driving motor to generate the braking torque, therefore, recycling braking ability will reduce with the lower speed.

3.1.2. The Capacity of Battery: The battery puts electric energy to the motor when driving, namely the battery in the discharging process; When braking, motor puts brake recycling energy to the battery and the battery is in charging. The main performances of battery reflect in maximum charging power and state of charge (SOC) the two aspects. Limited by the battery charging power, the recycling braking power is asked must not exceed the maximum charging power of the battery. Further more, the regenerative braking system can no longer charge for battery when its SOC is more than a certain value, or it will be adverse to battery. For example, the SOC of the Lithium-ion battery can't exceed 70% [9].

3.2 Vehicle Braking Dynamics and Limit Regulations

3.2.1 The Force Analysis of the Vehicle Braking: The braking force analysis in the process of vehicle braking is shown in Figure 3, the vehicle must overcome all kinds of resistance forces in braking. Assuming vehicle is on typical road surface and the equation is

$$\sum F = F_f + F_\omega + F_b \tag{2}$$

Among them: ΣF is the sum of the driving resistance, F_f is rolling resistance, F_ω is air resistance, F_b is ground braking force.

Expression F_f is

$$F_f = Gf \tag{3}$$

Among them: $G = mg$, m is the vehicle quality.

Expression F_ω is

$$F_\omega = \frac{1}{2} C_D A \rho V_r^2 \tag{4}$$

Among them: C_D is air resistance coefficient, A is the windward area, ρ is the air density, V_r is the relative velocity.

When $\rho = 1.2258 N \cdot S^2 \cdot m$, $F_\omega = \frac{C_D A}{21.15} V^2$

The force from ground F_b is

$$F_b = F_{bf} + F_{br} \tag{5}$$

Among them: F_{bf} is the front ground braking force, F_{br} is rear force.

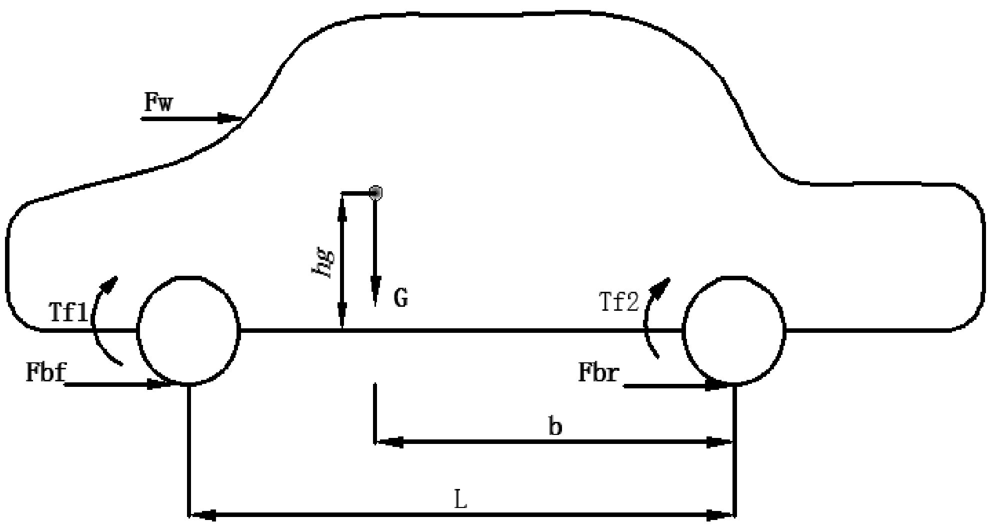

Figure 3. Electric Vehicle Force Diagram

3.2.2. The Determination of the Vehicle Total Braking Energy: The electric vehicle on the typical road surface brakes initially, the total kinetic energy concludes vehicle movement quality and vehicle rotation quality. The total braking energy is

$$E_1 = \frac{1}{2} m V_1^2 + \frac{1}{2} \Sigma I_\omega \omega^2 = \frac{1}{2}\left(1 + \Sigma \frac{I_\omega}{mr^2}\right) m V_1^2 \tag{6}$$

Among them: E_1 is total kinetic energy in initial braking, V_1 is velocity in initial braking, I_ω is rotational inertia, ω is angular velocity, r is wheel radius. Let $\delta = 1 + \Sigma \frac{I_\omega}{mr^2}$, δ is the vehicle rotation quality conversion coefficient, wheel is the only considered factor when calculating dynamic performance, usually $\delta = 1.04$, gets into (7)

$$E_1 = 0.52mV_1^2 \quad (7)$$

Similarly, total kinetic energy at braking end is

$$E_2 = 0.52mV_2^2 \quad (8)$$

Among them: V_2 is the velocity at the end of braking. Vehicle total braking energy E is in

$$E = 0.52m(V_1^2 - V_2^2) \quad (9)$$

3.2.3 The Determination of the Recycling Braking Energy: From figure4 [10], we can see the force distribution curve for front-wheel driving. The curve is composed of I line, abscissa axis, ECE regulation line and f line.

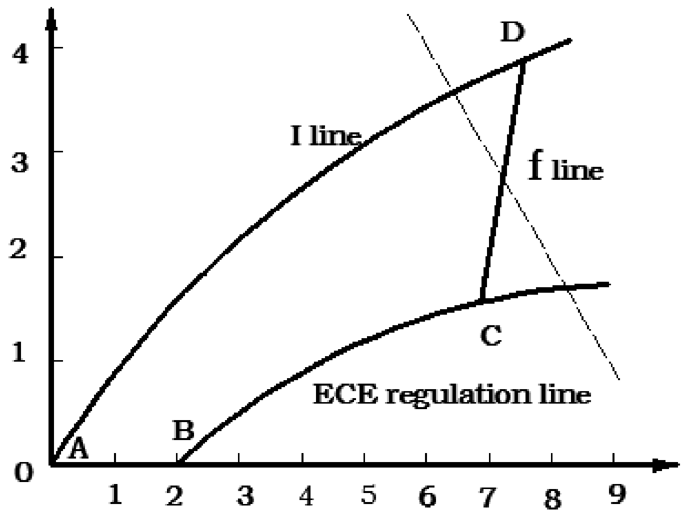

Figure 4. The Braking Force Distribution Diagram

According to the target braking intensity Z and ground braking force F_b

$$\begin{cases} F_{reg} = F_b & AB \\ F_{reg} = \dfrac{z+0.07}{0.85}\left(b + zh_g\right)G/L & BC \\ F_{reg} = \varphi\left(b + zh_g\right)G/L & CD \end{cases} \quad (10)$$

Among them: b is distance from center of mass to rear axle, h_g is mass center height, L is the wheel distance.

The power P_{reg} is

$$P_{reg} = F_{reg} \cdot V \quad (11)$$

The recycled energy E_0 is

$$E_0 = \int_{t_1}^{t_2} P_{reg} \cdot \eta_1 \cdot \eta_2 \cdot \eta_3 dt \quad (12)$$

Among them: t_1 is the motor braking initial time, t_2 is the motor braking end time, η_1 is transmission efficiency, η_2 is generator power generation efficiency, η_3 is battery efficiency.

3.2.4. The Determination of the Braking Energy Recovery Rate: The braking energy recovery rate η is in the process of braking

$$\eta = \frac{E_0}{E} \times 100\% \tag{13}$$

4. The Control Strategy of Regenerative Braking Energy Recovery

4.1 The System Control Strategy

The system control strategy means that basing on driver's braking intention and desired intensity, comprehensive considering vehicle speed, the battery charging capacity, maximum braking power of the motor, all efficiencies in braking, finally mechanical and regenerative braking reasonably. The specific control logic diagram is shown in Figure5 [11].

4.2 The Vehicle Wheel Braking Force Distribution

Vehicle wheels of braking force distribution point should be in the area which is composed by I line, abscissa axis, ECE regulation line and f line.

For braking intensity equation $z = b\varphi(L - \varphi h_g)$.

The total braking force distribution rules of the wheel rules is as follow:

1. When $z < 0.1$, the total braking force is provided by the front wheel separately.

2. When $0.1 \le z < 0.7$, the total braking forces are provided by whole wheel according to the distribution curve.

3. When $z \ge 0.7$, braking working time is very short, its braking effect is negligible comparing with mechanical braking, the total braking forces are provided by the front and the rear wheel friction braking.

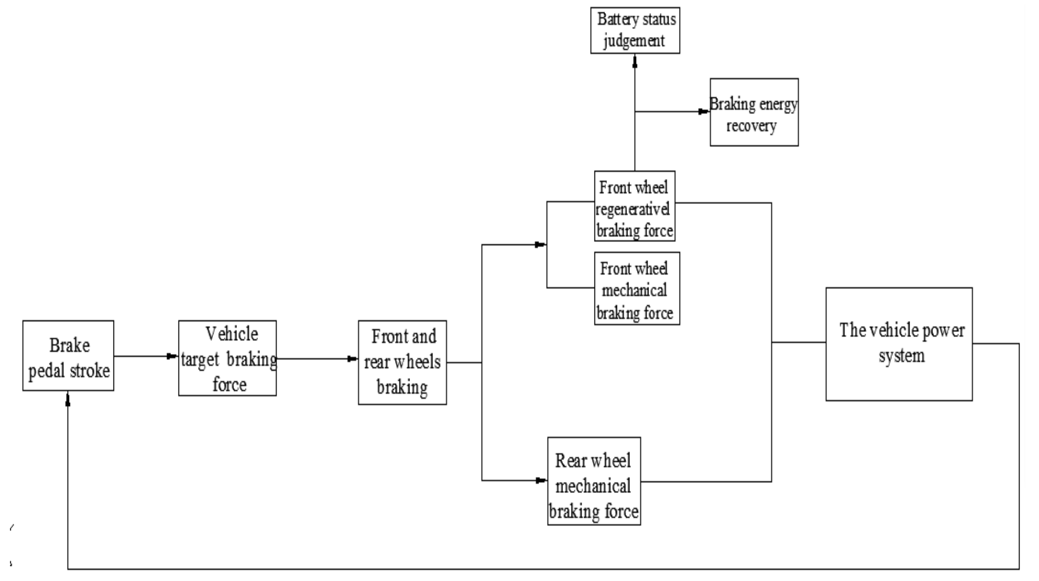

Figure 5. Regenerative Braking System Control Strategy Logic Diagram

5. The Modeling Simulation and Analysis based on ADVISOR

The simulation is established using Simulink according to system control strategy. In this paper, the electric vehicle uses double motor front wheel direct driving mode. From Table1, we can see the vehicle parameters.

5.1 The Energy Conversion Analysis of Electric Vehicle under Different Speeds

The paper analyzes the energy conversion at $V = 80km/h$ and $V = 10km/h$ the two moments [12].

The motor speed n is

$$n = (1 + 10\%) \cdot \frac{30 \cdot V}{3.6 \cdot \pi \cdot r} \quad (14)$$

The counter electromotive force E is

$$E = K_E \cdot \omega \quad (15)$$

Among them: K_E is the electromotive force constant, its value usually is 0.9.

The efficiency of E is

$$\eta_{反} = E / U \quad (16)$$

Among them: U is the lithium battery module voltage, its value is $96V$.

From Table 2, we can see values of electric vehicle at $V = 80km/h$ and $V = 10km/h$.

Table 1. The Main Parameters of Front Wheel Driving Electric Vehicle

The parameter name	The parameter value
vehicle mass(Kg)	1000
wheel radius(m)	0.34
rolling resistance coefficient	0.016
wind resistance coefficient	0..34
mechanical resistance coefficient	0.9
power generation efficiency	0.9-0.82
permanent magnet brushless DC morot rated power（kw）	5.5
lithium battery capacity(Ah)	150
lithium battery module voltage(V)	96

Table 2. The Parameter Values of Electric Vehicle Different Speed

The parameter	$V = 80km/h$	$V = 10km/h$
Motor rotation speed	$898\,r/\min$	$112\,r/\min$
Motor angular velocity	$94rad/s$	$11.7rad/s$
counter electromotive force	$84.6V$	$10.5V$
Motor efficiency	80%	10%
Rolling resistance	$188N$	$188N$
wind resistance	$167N$	$2.7N$
Total resistance	$355N$	$190.7N$
Output power	$10kw$	$1.4kw$
Driving torque	$102.6N \cdot m$	$55.1N \cdot m$

5.2 The Results of Simulation

The simulation is set up in Matlab environment, the simulation diagram about time-velocity, time-motor speed, time-motor torque, time-charging current and time-power are shown in Figure6 to Figure10. The results show recovery system efficiency is about $\eta = 60\%$.

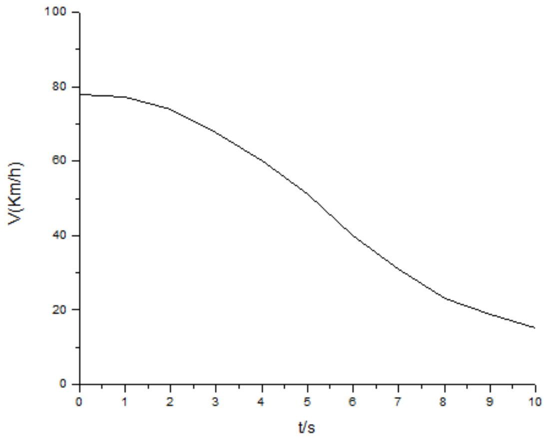

Fig . (6).Time-velocity relationship

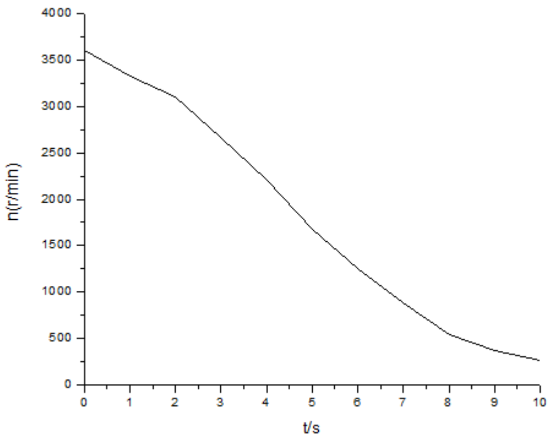

Figure 7. Time-motor Speed Diagram

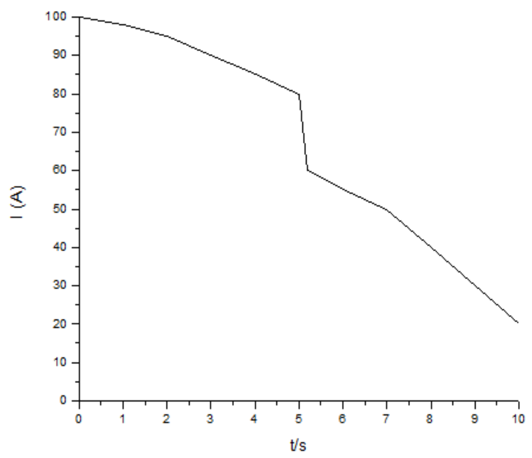

Figure 8. Time-motor Torque Diagram

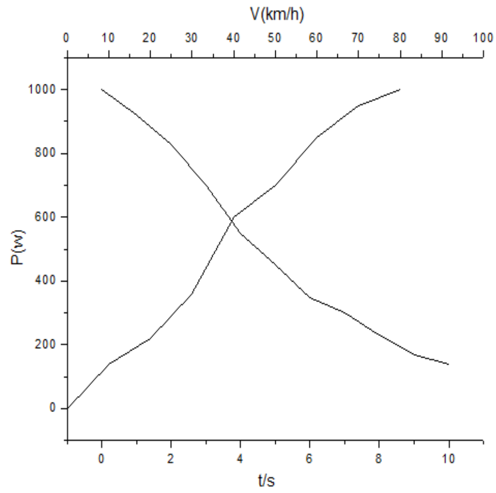

Figure 9. Time-charging Current Diagram

6. Conclusion

In this paper, the design of the electric vehicle energy recovery system converts the braking energy into electric energy which charges for the battery. By simulating in Matlab environment, we get the diagram about time-velocity, time-motor speed, time-motor torque, time-charging current and time-power. By rectifier filter, changing the frequency, driving motor generation, rectifier output, the recovery system efficiency is about $\eta = 60\%$ .The electric vehicle realizes the function of energy recovery, increases the driving mileage.

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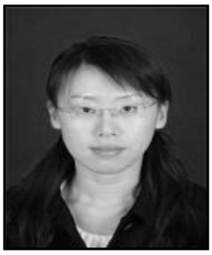

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