Advanced Brake Energy Recovery Systems Based on Permanent Magnet Synchronous Motors

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Abstract. In today's society, energy saving and emission reduction have risen to the level of national strategy, new energy vehicles can achieve the effect of energy saving and emission reduction compared with traditional vehicles, but their lack of range and low penetration rate of charging piles and other issues to a certain extent limit its development. Brake energy recovery technology recovers part of the energy by reducing heat loss and improving the range. In this paper, the permanent magnet (PM) synchronous motor is chosen as the research object to explore the way of braking energy recovery system and the influencing factors. This paper first describes the structure, working principle, and operation mode of the PM synchronous motor. Secondly, under the premise of ensuring the safe operation of the car, to recover the lost energy to the maximum extent, the method and circuit principle of brake energy recovery are analyzed, and it is concluded that the factors affecting the brake energy recovery include driving conditions, motor configuration, energy storage device and vehicle structural parameters and so on.

Keywords: Energy saving; brake energy recovery technology; new energy vehicles; permanent magnet synchronous motor.

1. Introduction

Today's world is facing serious environmental and energy problems, for the automotive industry, the state has introduced a series of policies to encourage and support the development of the electric vehicle industry, but the electric vehicle range and charging have been criticized by the general public. Relevant studies show that 1/3~1/2 of the energy of an electric vehicle during driving is lost during braking, and it is of great significance to recover the energy during braking to address this issue [1]. According to the data, most of the electric vehicles manufactured in China use permanent magnet (PM) synchronous motors, and this study is based on the braking energy recovery of PM synchronous motors.

PM synchronous motor is to provide excitation with PMs, so that the motor structure is relatively simple, reducing the processing and assembly costs, and eliminating the problematic collector rings and brushes, improving the reliability of the operation, and because there is no need for excitation current, there is no excitation loss, improving the efficiency and power density of the motor. It has the advantages of a simple structure, small size, high efficiency, and high-power factor. Braking kinetic energy recovery achieves the purpose of energy recovery by making the electric motor rotate in the reverse direction during the braking process of the electric vehicle, so that the motor generates a negative electromagnetic torque to decelerate the electric vehicle, and the electric energy generated by the reverse current is stored in the battery.

The main research of this study is a review study of the braking energy recovery system based on a PM synchronous motor, by taking a PM synchronous motor as the research object, under the working condition of braking electric vehicle using a PM synchronous motor, the braking energy recovery method of PM synchronous motor is studied, as well as the factors affecting the braking energy recovery ability of PM synchronous motor.

2. Principle of Operation of PM Synchronous Motors

2.1. Structure of PM Synchronous Motors

A PM synchronous motor is mainly composed of a rotor, end cover, and stator. Among them, its stator is a three-phase symmetrical winding, usually using the Y-shaped connection, as shown in Fig. 1. The difference between PM synchronous motor and other motors is mainly in the rotor structure, there are high-quality PM poles placed at the rotor, according to its different places to be able to classify the PM synchronous motor into three categories: (1) convex mounted (2) embedded (3) embedded type [2].

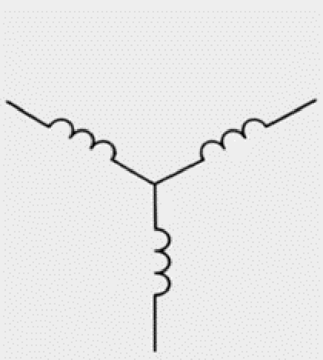

Fig. 1 Y-shaped connection [2].

PM synchronous motor in operation, for the first time by the inverter to complete the pulse width modulation of the three-phase current, flowing through its stator winding device, so that it will produce a certain strength of the rotating magnetic field, by the influence of the magnetic field, the rotor in the role of the magnetic field to produce rotating torque, the direction of the rotating magnetic field rotating in the same direction as the stator. When the output torque is greater than the friction torque and damping torque, the motor moves, accelerating until it is synchronized with the rotating pole speed [3].

2.2. Four-Quadrant Operation of PM Synchronous Motors

When the PM synchronous motor is applied to new energy vehicles, its working state can be split into four. So that the motor speed n is set to the horizontal coordinate and the output electromagnetic torque T is set to the vertical coordinate. Establish a right-angle coordinate system as shown in Fig. 2, with different quadrants in the coordinate system corresponding to their different operating states.

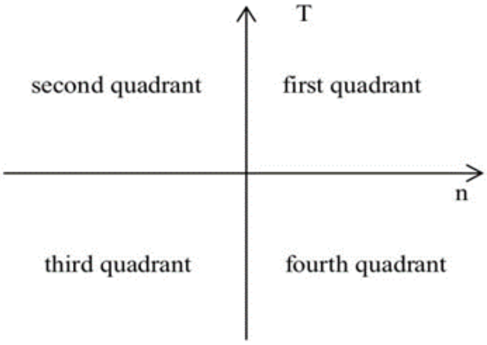

Fig. 2 Motor four-quadrant operation state [4].

When it is in the first quadrant, the rotational speed and output torque of the PM synchronous motor are tangent in the same direction and in the positive direction, at this time, the motor is rotating in the positive direction of the electric state, and at this time, the new energy vehicle is in the normal driving stage; The rotational speed of the PM synchronous motor in the second quadrant is still in the positive direction, but the output torque becomes negative in the opposite direction, at this time, the motor is rotating in the positive direction to generate electricity, and at this time, the new energy vehicle is in the braking state; The motor in the third quadrant, the rotational speed and output torque are in the opposite direction, at this time, the motor is reverse rotation electric state, the new energy vehicle is in reverse state; In the final fourth quadrant, the motor speed is reversed while the output torque is reversed positive, i.e., the motor is in the reverse rotation power generation state, and the new energy vehicle performs braking operation in the same state [4,5].

2.3. PM Synchronous Motor Energy Conversion Method

During braking, the PM synchronous motor of the new energy vehicle is in the state of power generation and electric state. During the process from normal driving to braking, i.e., the motor transforms from the electric state it is into the power generation state, due to the rotational inertia, the speed of the motor cannot be changed instantaneously and the rotor cannot be stopped immediately but kept rotating, which will cut its windings to induce an electric potential, which will then go through the conversion circuits involved to recharge the batteries on board, and ultimately realize the state of energy recovery.

3. Brake Energy Recovery Working Principle

3.1. Overview of Electric Vehicle Braking Methods and Energy Recovery

When an electric vehicle is braking, mechanical braking and motor braking work together, for mechanical braking, part of the kinetic energy of the car is converted into heat energy at the brake disc and emitted into the atmosphere, for motor braking, the electric motor of the electric vehicle provides a traction force opposite to the direction of the car's movement in the braking process, and through the transmission system, the motor produces a negative electromagnetic torque, which transforms the motor into a generator, and finally the recovered kinetic energy is converted into electrical energy and stored in the battery. charging, and finally converting the recovered kinetic energy into electrical energy to be stored in the battery. Comparing the two types of braking for electric vehicles, the energy lost to the atmosphere by mechanical braking is difficult to utilize, but motor braking can be a good way to recover the lost kinetic energy through the basic nature of the motor.

3.2. Forms of Brake Energy Conversion

In the braking principle, the energy recovered by the motor is stored and utilized. The energy consumed by the braking system is derived from the kinetic energy of the vehicle overcoming the energy consumed by the rolling resistance under braking and the energy consumed by the air resistance. The energy consumed by the braking system includes the kinetic energy consumed by the hydraulic braking forces of the front and rear axles, while the remaining energy is the energy recovered from the drive wheels. The energy recovered from the drive wheels is transferred and converted several times to electrical energy through the transmission system and the motor drive system, which contains the motor and controller, and stored in the energy storage device [6].

During braking, the kinetic energy is converted into electrical energy through the generator and stored in the energy storage in the form of chemical energy (Fig. 3). During driving or acceleration, the chemical energy in the energy storage is converted into kinetic energy of the vehicle in the form of electrical energy through the electric motor.

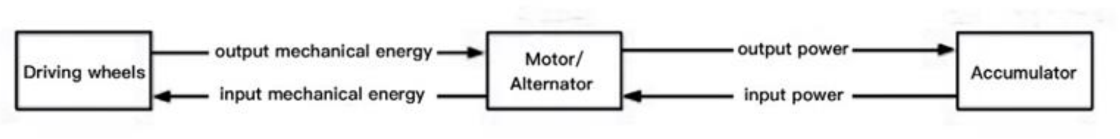

Fig. 3 Braking energy conversion forms [6].

3.3. Principle Analysis of Brake Energy Recovery Circuit

The schematic diagram of the regenerative braking system circuit is shown in Fig. 4. The circuit components include a motor M, an inductor L, a resistor R, two bipolar tubes V1 and V2, and a battery.

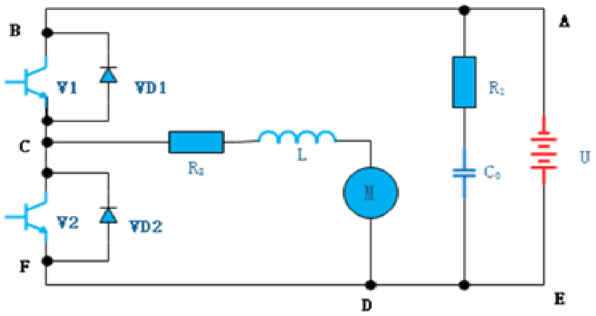

Fig. 4 Schematic diagram of regenerative braking system circuit [7].

When the car is driven, the motor works as an electric motor, in this state of the circuit, the body tube V1 is in the conduction state, the transistor V2 is disconnected, and the current circuit is shown in ABCDEA in Fig. 5, and the power is supplied to the motor by the battery at this time. When the braking of the car starts, the motor controller firstly controls the product body tube V1 and V2 to disconnect at the same time, at this time, the current of the current loop due to the existence of the inductive coil L will not suddenly drop to zero, but through the inductance L self-inductive effect of maintaining the current and flow through the diode VD2, to form the current loop DFC, as shown in Fig. 6, and in the current loop DFC, the current flows through the resistor R as well as inductance L and the current is dissipated in the form of heat energy. is finally dissipated in the form of heat energy.

After a while, when the motor acts as a generator to overcome the forward inertial rotation torque and generates a braking torque and a reverse-induced current, the body tube V2 in the electric circuit is switched on (V1 is still switched off), and a new current circuit CFD is formed, as shown in Fig. 7. However, at this time, the induced voltage generated by the motor is always less than the total voltage at both ends of the battery, and cannot charge the battery, so it is necessary to re-disconnect the pin body tube V2, the use of motor coils in the circuit is disconnected at the moment of the self-inductive phenomenon to increase the induced electromotive force of the motor terminals to achieve to the battery to charge the voltage 3, and then the inductance of the L maintains the reverse current will flow through the VD1, to form a current loop DCBAE and charges the battery (Fig. 8) [7].

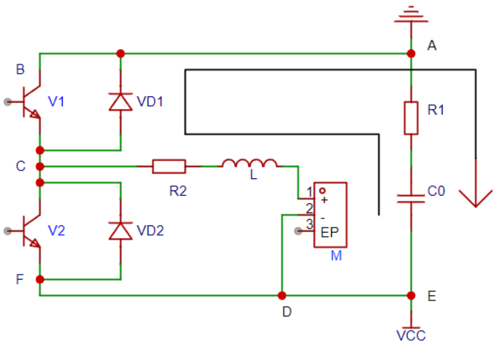

Fig. 5 Drive state [7].

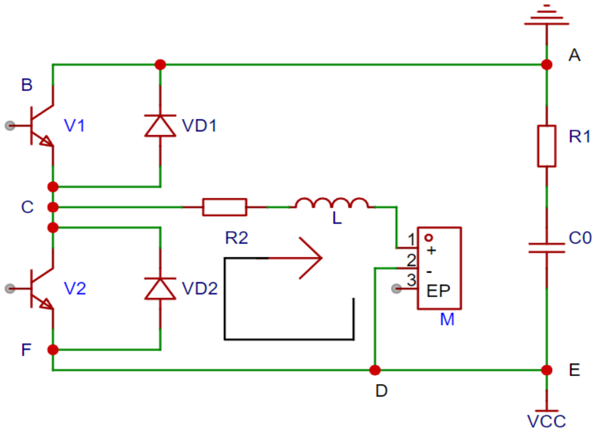

Fig. 6 Reflow stage [7].

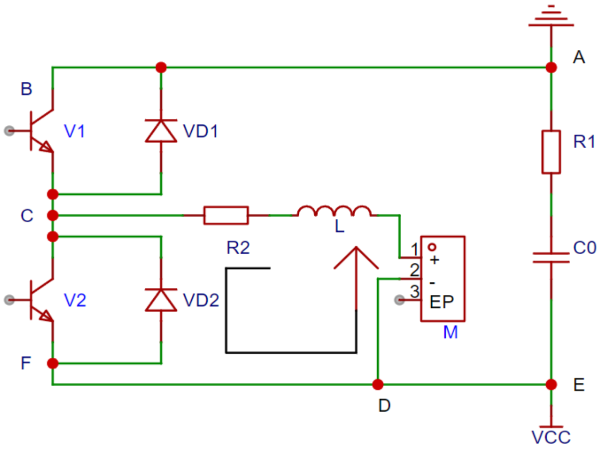

Fig. 7 Current reversal phase [7].

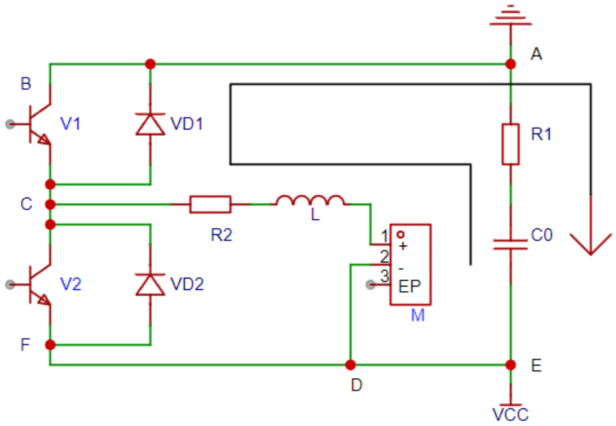

Fig. 8 Energy recovery phase [7]

4. Factors Affecting Brake Energy Recovery

4.1. Driving Conditions

The efficiency of braking energy recovery is greatly affected by the driving conditions of the vehicle. When the vehicle in traffic congestion in the city, limited by the traffic flow is large, the vehicle's low-speed driving, braking frequently, and braking intensity is small, more in line with the operating conditions of the motor brake, can recover a large number of braking process loss of energy. When the vehicle is traveling on highways and other roads with good conditions, the number of braking is very small, the vehicle driving conditions are stable, and the braking energy recovery effect is poor.

4.2. Motor Brake Strength

PM synchronous motor in the vehicle braking process, due to the motor reverse rotation generated by the torque cutting magnetic lines of inductance can be the basic nature of the battery charging, the intensity of the motor's reverse rotation of the braking energy recovery has a greater impact on the performance of the motor at different torques and speeds of the motor performance efficiency has a greater difference. To improve the efficiency of braking energy recovery, the participation time of the motor in the braking process should be increased, and the proportion of motor braking in the braking force of the vehicle should be increased appropriately, but it should also be noted that too high intensity of motor braking will bring about losses to the motor and the battery.

4.3. Accumulators

The battery is the energy storage element of the motor braking system, its performance and energy management strategy determine the working state of the battery, which is mainly reflected in the SOC (state of charge) and maximum charging power. Each type of battery has a fixed requirement on the operating range of SOC, and overcharging and over-discharging beyond the range will adversely affect the battery. For example, the lithium-ion battery SOC operating range is 30% to 70%, the section is called the active charging region. When the SOC of the battery is greater than 70%, the regenerative braking system no longer charges the battery. Because the entire braking process time is very short, the battery's SOC, temperature, and internal resistance can be considered to remain unchanged, so the open-circuit voltage of the battery remains unchanged. At the same time, to protect the battery, each battery has a maximum charging current limit. Throughout the braking process, the battery can maintain the maximum charging power for charging. The maximum charging power is

$$P = (U_{oc} + IR)I \tag{1}$$

where U_{oc}, I, and R are the battery open-circuit voltage, maximum charging current, and battery internal resistance, respectively. The generating power of the motor and the charging power of the battery together limit the size of the braking power, which further limits the maximum value of the braking force.

4.4. Hydraulic Braking System

Due to the limited ability of motor regenerative braking and considering that the electrical system is prone to malfunction, to ensure the safety of braking, the hydraulic braking system is essential for electric vehicles. However, the braking force is constantly changing with the vehicle speed, and accordingly, the friction braking force should also be changed to maintain the same braking strength as the traditional braking system. Therefore, the hydraulic braking system structure than the traditional braking system increases the hydraulic control unit, to accurately and stably control the pressure of the dynamic wheel cylinder, to ensure good braking efficiency. The ability of the hydraulic control unit to control the braking pressure indirectly affects the size of the regenerative braking force, the hydraulic control unit in this paper is idealized. To maximize the recovery of braking energy, the larger the proportion of regenerative braking force of the front axle, the more the front and rear axle brake force distribution curve deviates from the ideal brake force distribution line (i.e., I line). However, to ensure the basic braking efficiency of the car, the maximum regenerative braking force of the front axle cannot break through the ECE regulation line and f line (Fig. 9).

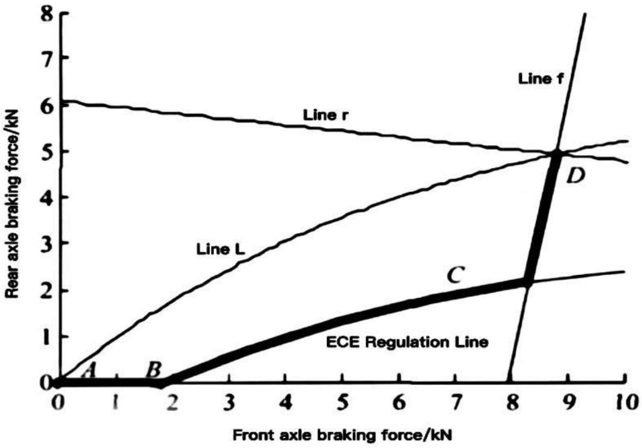

Fig. 9 Maximum regenerative braking force analysis of front axle [8].

The arrangement of brake lines affects the braking efficiency and the recovery of braking energy. At present, the most widely used in automobiles is X-type piping, braking the front and rear brakes braking force into a proportional relationship, which affects the friction braking force and regenerative braking force to a certain extent the degree of freedom of matching, the hydraulic pressure value at the wheel cylinder cannot be arbitrarily changed, but the use of such a way of the automotive braking system to minimize the changes. Another arrangement for the H-type arrangement, front and rear brake power independent control, friction braking force can be arbitrarily matched with the braking force, so that the electric mechanism power in the total braking force accounted for a higher proportion. For each wheel brake cylinder pressure can be adjusted independently of the braking system, and the front and rear brake braking force can be achieved independently controlled, which can be attributed to the H-type discussion. For electric vehicles with front axle electric drive, the braking force distribution along the curve AD in Fig. 9 can maximize the braking energy recovery. Based on the target braking intensity Z0 and the total braking force requirement F_{bd}, its maximum braking force at each braking intensity can be obtained. For the X-type brake line, the ratio of front and rear brake braking force β/(1-β), the maximum regenerative braking force F_{reg} can be expressed as:

$$F_{reg=}F_{bd,} \quad AB \tag{2}$$

$$F_{reg} = F_{bd} - \frac{Gz_0 - \frac{z_0+0.07}{0.85}(b+z_0h_g)G/L}{1-\beta} \quad BC \tag{3}$$

$$F_{reg} = F_{bd} - \frac{Gz_0 - \varphi(b+z_0h_{g)}G/L}{1-\beta} \quad CD \tag{4}$$

For H-brake lines, the maximum regenerative braking force F_{reg} can be expressed as:

$$F_{reg=}F_{bd,} \quad AB \tag{5}$$

$$F_{reg} = \frac{z_0+0.07}{0.85}\left(b + z_0h_g\right)G/L \quad BC \tag{6}$$

$$F_{reg} = \varphi(b + z_0h_{g)}G/L \quad CD \tag{7}$$

where G, b, h_g, L, β are the weight of the car, the distance from the center of mass to the rear axle, the height of the center of mass, the wheelbase of the car, and the actual front/rear braking force distribution ratio, respectively. According to the above formula, the maximum share of regenerative braking force in the total braking force δ can be obtained under the two types of brake line arrangement. When the braking intensity is very small, the two layout types can achieve pure regenerative braking; with the increase of braking intensity, the proportion of regenerative braking force decreases and tends to be stable, in which the H-type decreases slowly and stably at about 80%, and the X-type decreases very quickly and stably at about 40%; when the braking intensity increases to the f-line constraints, the H-type decreases to 60%, and the X-type rapidly decreases to 0. The X-type rapidly decreases to 0. In general, the H-type provides more space for braking energy recovery, while the X-type has only about half of the space of the H-type due to the β-value constraints on the degrees of freedom for matching the regenerative and friction braking forces [8].

4.5. Vehicle Structural Parameters

The basic parameters of the vehicle's structure have a great influence on the braking energy recovery efficiency, such as the overall mass, the height of the center of mass, and the air resistance coefficient. The overall mass and air resistance coefficient will directly affect the dynamic performance of the vehicle during driving. If the vehicle structure can be reasonably designed to effectively reduce the air resistance and friction resistance during driving, it will be conducive to the improvement of braking energy recovery efficiency. In addition to the above factors, the drive form and control strategy also have a certain impact on the braking energy recovery [9-12].

5. Conclusion

New energy vehicles have been emphasized by countries all over the world because they can solve the problems of environmental pollution and energy shortage caused by traditional automobiles, and they are an important development direction in the field of automobiles. However, the development of new energy vehicles has been slow due to range and charging issues. Brake energy recovery technology recovers some of the energy lost during braking to improve the vehicle's range by reducing heat fade and loss. In this paper, based on the PM synchronous motor, the theoretical study of the braking energy recovery system is carried out, and the specific work is as follows:

i) Introduces the basic structure, working principle, and operation mode of PM synchronous motor, and analyzes the way of energy conversion under different working conditions of the motor by describing the different operation modes of the motor in different situations of the automobile.

ii) Analyze the way of braking energy recovery by understanding the loss of energy in the braking process. Analyze the regenerative braking energy recovery circuits in different states of new energy vehicles to understand the principle of braking energy recovery circuits.

iii) In actual working conditions, the actual value of energy recovery is often much smaller than the theoretical analysis value, and it is necessary to comprehensively analyze and consider the factors affecting the effect of brake energy recovery, including driving conditions, electric motors, hydraulic braking systems, and body structure parameters.

Currently, the energy recovery efficiency of the brake energy recovery system is relatively low, and further enhancement of the brake energy recovery efficiency is within reach by improving the design of the braking system and with the application of new materials.

Author contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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