Abstract: Regenerative braking can improve energy usage efficiency and can prolong the driving distance of electric vehicles (EVs). Traditional braking methodology causes a lot of energy wastage since it produces unwanted heat during braking. Thus, the invention of regenerative braking in electric vehicles has overcome these disadvantages. Moreover, it helps in save energy and provides higher efficiency for a vehicle. In this paper, BLDC motor control utilizes the traditional proportional–integral–derivative (PID) control, and the distribution of braking force adopts fuzzy logic control. Because the fuzzy reasoning is slower than PID control, the braking torque can be real-time controlled by PID control. In comparison to other solutions, the new solution has better performance in regard to realization, robustness, and efficiency. This paper presents the simulation results by analyzing the battery state of charge, braking force, and DC bus current under the environment of MATLAB and Simulink. The simulation results show that the fuzzy logic and PID control can realize the regenerative braking and can prolong the driving distance of EVs under the condition of ensuring braking quality. At last, it is verified that the proposed method is realizable for practical implementation.

1. Introduction

In recent years, electric vehicles (EVs) have received much attention as an alternative to traditional internal combustion engine (ICE) vehicles. The invention of electric vehicle (EV) is a miracle, as it also known as green vehicle as it produces zero emission to the air which means there are no toxic gasses release from the car that causes the ozone layer polluted. With the progress of battery and motor technology [1], the EVs become the most promising alternative to the ICE vehicles. Plug-in EVs use a battery system which can be recharged from standard power outlets. Since the performance characteristics of EVs have become comparable to, if not better than, those of traditional ICE vehicles, EVs present a realistic alternative. Regenerative braking can be used in EVs as a process for recycling the brake energy, which is impossible in the conventional internal combustion vehicles. Regenerative braking is the process of feeding energy from the drive motor back into the battery during the braking process, when the vehicle’s inertia forces the motor into generator mode.

In this mode, the battery is considered as a load, thereby providing a braking force to EVs [2]. It is shown that the use of regenerative braking of EVs can increase the driving range up to 15% with respect to EVs without the regenerative braking system (RBS). This technology had mostly replaced the traditional braking system in the cars because the traditional braking system always utilizes mechanical friction method to dissipate kinetic energy as heat energy in order to achieve the effect of stopping. Studies show that in urban driving, about one third to one half of the energy required for operation of a vehicle is consumed during braking. Base on the energy perspective, the kinetic energy is a surplus energy when the electric motor is in the braking state since it dissipated the energy as heat and causes a loss of the overall energy.

However, regenerative braking does not operate all times, e.g., when the battery is fully charged, braking needs to be effected by dissipating the energy in a resistive load. Therefore, the mechanical brake in the EV is still needed. A mechanical brake system is also very important for EVs’ safety and other operations [3]. Coordination of EV mechanical braking and regenerative braking is achieved by a single foot pedal: The first part of the foot pedal controls the regenerative braking, and the second part controls the mechanical brake. This is a seamless transition from regenerative braking to mechanical braking. It cannot be simply achieved by traditional ICE vehicles.

2. MOTOR AND CONTROL

2.1 BLDC Motors

In a BLDC motor permanent magnets are mounted on the rotor with the armature windings being hosed on the stator with a laminated steel core, as illustrated in Figure 1. Rotation is initiated and maintained by sequentially energizing opposite pairs of pole windings, which are said to form phases. Knowledge of rotor position is critical to correctly energizing the windings to sustain motion. The rotor position information is obtained either from Hall Effect sensors or from coil EMF measurements.
2.2 BLDC Motor Control

BLDC motor control is the main control of the electronic commutator (inverter), and the commutation is achieved by controlling the order of conduction on the inverter bridge arm. A typical H-bridge is shown in Fig. 2. A BLDC motor uses a dc power supply which is required to provide energy. If we want to control a BLDC motor, we must know the position of the rotor which determines the commutation. Hall Effect sensors are the most common sensor for predicting the rotor position. The BLDC voltage vector is divided into six sectors, which is just a one-to-one correspondence with the Hall signal six states, as illustrated in Fig. 3.

The basic drive circuit for a BLDC motor is shown in Fig. 2. Each motor lead is connected to high-side and low-side switches. The correlation between the sector and the switch states is noted by the drive circuit firing shown in Fig. 4. At the same time, each phase winding will produce a back EMF; the back EMF of their respective windings is also shown in Fig. 4. A number of switching devices can be used in the inverter circuit, but MOSFET and IGBT devices are the most common in high-power applications due to their low output impedances.

2.3 MOSFET Control of Regenerative

Regenerative braking can be achieved by the reversal of current in the motor-battery circuit during deceleration, taking advantage of the motor acting as a generator, redirecting the current flow into the supply battery. The same power circuit in Fig. 2 can be used with an appropriate switching strategy. One simple and efficient method is to independently switch the conjunction with pulse width modulation (PWM) to implement an effective braking control. However, with the low speed of the BLDC motor, the winding back EMF cannot reach the voltage across the battery. Moreover, the recovery of energy also cannot be achieved. Due to the presence of inductances in motor windings, these inductances in the motor can constitute the boost circuit. In order to achieve the recovery of energy, we have to raise the voltage on the dc bus through the inductor accumulator. We turn off all MOSFET on the high arms of H-bridge and control the low arms of H-bridge with PWM.

3. EV MODELING

The modeling of the EV has been done in MATLAB/ Simulink. The driver block makes a torque request which propagates through various powertrain system components and realizes vehicle motion. System-level simulators have been modeled by using empirical data that are based on measurements supplied by component manufacturers or extended from measurements obtained from literature sources.
3.1 Driver Subsystem

The driver block delivers the desired drive torque and the desired brake torque through the activation of the accelerator and brake pedal, respectively. If the driver wishes to accelerate the vehicle, he depresses the accelerator. Depending on the amount of depression of the accelerator pedal, a corresponding driver torque request is sent to the vehicle through various powertrain systems such as the battery and motor models. The regeneration starts only when the brake pedal is pressed. Once the brake pedal is depressed, in accordance with the position of the brake pedal, a corresponding proportion of brake torque is applied. Then, the brake torque due to the regenerative brake control strategy is divided into regenerative braking and friction braking.

3.2 EM

The power from the battery drives the electric machine (EM). The EM works as a motor to propel the vehicle when positive power is fed in and as a generator when negative power is fed in.

3.3 Brake Strategy Subsystem

The structure of the control strategy system is shown in Fig. 5. Through the pedal sensor, we can obtain the driver’s required braking force. According to the distribution regulations of braking force among front and rear wheels, the front braking force and the rear braking force can be calculated, respectively. According to the fuzzy logic controller, we can obtain the value of the regenerative braking force. Then, the front mechanical braking force, the regenerative braking force, and the rear braking force can be attained.

3.1.1 Fuzzy Control

Braking force distribution in EVs with regeneration is influenced by many factors, and many parameters are constantly changing, so recycling strategy is difficult to be expressed. The fuzzy logic control strategy for EV braking force distribution can be easily demonstrated by the influence of different factors. Therefore, the fuzzy control theory is applied to the EV braking force distribution. The fuzzy control strategy of the EV braking force distribution structure is shown in Fig. 5; the three inputs are the EV front-wheel braking force, speed, and battery charge state [state of charge (SOC)].

In the fuzzy control system, the input variables include the front braking force, the SOC, and the EV speed. The output variable is the ratio which is proportional to the regenerative braking force taking in the front braking force. Front braking force: the driver braking requirements are concerned with the driving safety. The value of the braking force represents the braking distance and time the driver requires. We prefer the concourse of speed to be low, middle, and high, and the universe of discourse is [0, 2000]. The membership functions are shown in Fig. 6(a).

SOC: when the battery’s SOC is less than 10%, the internal resistance of the battery is high, unsuitable charging in this case; the regenerative braking force should be a smaller proportion. When the SOC is between 10% and 90%, the battery can be charging with a large current; the ratio of the regenerative braking force should be correspondingly increased. When the SOC is greater than 90%, the charging current should be reduced to prevent the excessive charging of the battery; the value of the regenerative braking force should be lower. We prefer the set of SOC to be low, middle, and high, and the universe of discourse is [0, 1]. The membership functions are shown in Fig. 10(b).

Speed: vehicle speed plays an important role in ensuring the brake safety. To ensure the brake safety and to comply with the relevant legislation, the
Regenerative braking force should be a low proportion when the speed is low. The regenerative braking force can be increased to an appropriate level when the speed is intermediate. When speed is high, we can increase the ratio of the regenerative braking force to the biggest value. We prefer the set of speed to be low and high, and the universe of discourse is [0, 500]. The membership functions can be seen in Fig. 6(c). Output variables: the type of the fuzzy logic controller is Mamdani. Ratio = \{MF0, MF1, MF2, MF3, MF4, MF5, MF6, MF7, MF8, MF9, MF10\} = (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0). The membership functions can be seen in Fig. 6(d). Fuzzy control rules: the front braking force is \(L, M, \text{and } H\); SOC is \(L, M, \text{and } H\); and speed is \(L\) and \(H\). We prefer the rules shown in Table I.

### TABLE I

<table>
<thead>
<tr>
<th>Speed</th>
<th>(F_{\text{front}})</th>
<th>MF</th>
<th>Speed</th>
<th>SOC</th>
<th>(F_{\text{front}})</th>
<th>MF</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L)</td>
<td>(L)</td>
<td>2</td>
<td>(H)</td>
<td>(L)</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>(L)</td>
<td>(L)</td>
<td>1</td>
<td>(H)</td>
<td>(M)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>(L)</td>
<td>(H)</td>
<td>0</td>
<td>(H)</td>
<td>(H)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>(L)</td>
<td>(M)</td>
<td>4</td>
<td>(H)</td>
<td>(L)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>(L)</td>
<td>(M)</td>
<td>2</td>
<td>(H)</td>
<td>(M)</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>(L)</td>
<td>(H)</td>
<td>3</td>
<td>(H)</td>
<td>(H)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>(L)</td>
<td>(H)</td>
<td>3</td>
<td>(H)</td>
<td>(L)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>(L)</td>
<td>(H)</td>
<td>1</td>
<td>(H)</td>
<td>(M)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>(L)</td>
<td>(L)</td>
<td>2</td>
<td>(H)</td>
<td>(M)</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

3.1.2 Proportional–Integral–Derivative (PID) Control

With PID control used primarily to ensure a constant brake torque, different braking force values will give different PWMs. It is supposed that PID control can quickly adjust the desired PWM in order to maintain braking torque constantly. A constant electrical braking torque can be achieved during the fuzzy inference. When the fuzzy reasoning is slower than PID control, the braking torque can be real-time controlled by PID control [7].

3.1.3 Battery Subsystem

The power request from the driver block after translating through the brake control strategy subsystem reaches the battery subsystem. Here, the positive power discharges the battery, and the negative power charges the battery. The battery is set with an initial SOC of 90%. When the positive power is fed in, it enables the discharge block. In the discharge block depending on the SOC level, we obtain the maximum module voltage that can be supplied, from the plot of SOC versus voltage of the battery module. This module voltage is then multiplied with a number of cells in series to obtain the battery pack voltage. Then, from the power demand and the maximum possible voltage at that SOC, we calculate the current that can be supplied to the motor. This current is limited by the maximum amount of current that the motor can handle. When a negative power is fed in, the charge block becomes enabled. In the charge block depending on the SOC level and as explained previously, we calculate the maximum possible battery voltage and current that can be fed into the battery. This current is again limited by the maximum current capability of the generator. When the power request is zero, i.e., the vehicle comes to rest or when the braking power is too low to generate a significant current, the battery idle block is enabled. No current is withdrawn or put back during this phase.

4. SIMULATION RESULTS

“Figure 7. Braking force distribution”

“Figure 8. Simulink model of the 3-phase BLDC motor during the regenerative mode”
Under the environment of MATLAB and Simulink, the RBS is modeled, and the drive cycle is performed. The test is performed according to urban driving schedules. The simulation results and test are represented as follows.

5. CONCLUSION

This paper has presented the RBS of EVs which are driven by the BLDC motor. The performance of the EVs’ regenerative brake system has been realized by our control scheme which has been implemented both in the simulation and in the experiments. By combining fuzzy control and PID control methods which are both sophisticated methods, RBS can distribute the mechanical braking force and electrical braking force dynamically. PID control is a very popular method in electric car control, but it is difficult to obtain a precise brake current. Braking force is affected by many influences such as SOC, speed, brake strength, and so on.

In this paper, we have chosen the three most important factors: SOC, speed, and brake strength as the fuzzy control input variables. We have found that RBS can obtain appropriate brake current, which is used to produce brake torque. At the same time, we have adopted PID control to adjust the BLDC motor PWM duty to obtain the constant brake torque. PID control is faster than fuzzy control, so the two methods combined together can realize the smooth transitions. Similar results are obtained from the experimental studies. Therefore, it can be concluded that this RBS has the ability to recover energy and ensure the safety of braking in different situations.

REFERENCES


