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Full Length Article

A new electric braking system with energy regeneration for a BLDC motor driven electric vehicle

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ABSTRACT

A new electric braking system is proposed for a brushless DC (BLDC) motor driven electric vehicle (EV) in this paper based on stopping time and energy regeneration. This new braking system is developed by combining various regenerative methods and plugging. Other than the existing performance measures such as boost ratio, braking torque, and maximum conversion ratio; stopping time and energy recovery for various methods are studied for different running conditions. It is observed that the stopping time is less for plugging and increases in the order of two, three and single switch method. In addition, energy recovery is better for single and three switch method. Based on these performances, a new braking strategy is proposed which combine all the regenerative braking methods including plugging and switch among themselves based on the brake pedal depression. The effectiveness of the proposed method is shown using both simulation and experiment results.

1. Introduction

Electric vehicle (EV) is one of the alternatives to internal combustion engine powered vehicle due to pollution concern, cost and availability of the oil. These vehicles are propelled by electric motors of either AC or DC. DC motors are mainly used for propulsion since batteries are used as the main power source. In recent days, due to the advancement in power electronic converters, motors such as brushless DC (BLDC) motors, permanent magnet synchronous motors (PMSM) and switched reluctance motors are used [1,2]. Among these, BLDC motors are often used due to high efficiency, high power density, large starting torque, noiseless operation, low weight and smaller in size [3]. Recent vehicles are powered by hub type BLDC motors, motors in-build in the wheel, to avoid complex power train mechanism [4].

Range (driving range) of the EV, the distance traveled by the vehicle per charge, is an important parameter. Improving the range is the main objective for most of the EV manufacturer. The range can be improved by increasing the efficiency of the overall components including the motor, power converter, and battery. Regenerative braking is one of the methods to increase the range by charging the battery from the energy available during braking. During regenerative braking, the vehicle inertia together with power electronic converters makes the motor to act as the generator to send the energy back to the battery [5,6]. Studies are ensuring that the driving range can be improved by 8–25% using regenerative braking [7].

Regenerative braking is achieved through various methods in EVs. In [8–11], regenerative braking is achieved using additional DC-DC converter which boosts the back electromotive force (back-EMF) to the appropriate level to charge the battery. This method requires extra converter which increases the cost and weight of the system. In [12–15], regenerative braking is achieved using ultracapacitor connected either in series or parallel with batteries. The ultracapacitor stores the regenerative energy surge and sends it back to the battery with the help of additional converters. This method also increases the cost and weight of the overall system.

Regenerative braking is achieved using electronic gear shift technology [16,17] in which the electronic gear forms different serial and parallel connections of batteries, motor winding, and ultracapacitor based on vehicle speed to recover regenerative energy. This method requires specially designed motors with multiple windings, various battery connections, and multiple switches. Moreover, a complex switching topology has to be developed for implementation.

To overcome the disadvantages of various regenerative scheme discussed [8–17], an alternative method is proposed using the single stage converter which drives the BLDC motor. The single stage converter is able to perform regenerative braking by applying

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switching pulses in a proper sequence without any additional power converter. In this single stage converter, different types of braking methods based on different switching topology namely single switch, two switch and three switch are studied [18,19]. Based on the study, it is concluded that single switch and three switch are capable of producing required braking torque and better energy recovery in mid to high-speed range. Moreover, two switch is recommended for low speed or emergency braking case since it produces high braking torque. Regenerative braking using the single switch and two switch are also studied in [15,20–22]. Recently a fully electrical regenerative braking is proposed for very fast and precise braking torque control [23]. However, use of regenerative braking alone is not effective at low speeds and for emergency case [24,25].

In order to ensure effective braking at all speeds, this paper proposes a new electrical braking system for a BLDC driven EV based on various electric braking methods such as single, two, three switching topologies and plugging. The performance indices such as boost ratio, braking torque, and maximum voltage conversion ratio are studied for each braking method. In addition, stopping time and energy recovery are studied through simulation and experiment for different running conditions. Based on stopping time and energy recovery, a new braking strategy is developed to combine different regenerative method and plugging using brake pedal depression.

The paper is organized as follows. Section 2 describes the conventional electric braking methods and stopping time. In Section 3, the performance of the braking methods is studied by simulation and experimentation. Section 4 explains the implementation of a proposed braking system based on brake pedal depression and followed by the conclusion in Section 5.

2. Conventional electric braking methods and stopping time

2.1. Single stage electric braking methods

In single stage electric braking method, the braking and energy regeneration are achieved by the use of single stage bidirectional DC/AC converter which is used to drive the BLDC motor. The BLDC motor driven by a single stage bidirectional converter is shown in Fig. 1. R and L are the phase resistance and phase inductance respectively. E_a, E_b, E_c and I_a, I_b, I_c are back-EMF and armature currents respectively. S_1 *to* S_6 are switches and D_1 *to* D_6 are the freewheeling diodes and C is the DC link capacitor. A dedicated controller is used to switch the inverter in a particular fashion based on the rotor position received from hall sensors H_a, H_b and H_c. The switching sequences and the switches incorporated in achieving various braking methods such as single switch, two switch, three switch, and plugging are shown in Fig. 2. The performance parameters are given in Table 1.

In single switch braking method, only one switch out of switches S2, S4, S6 is operated in pulse width modulation (PWM) switching mode at each commutation state [15,20]. In two switch method, two switches out of switches S1-S6 are operated in PWM switching mode at each commutation state [21,22]. In three switch method, three switches S2, S4, S6 are operated in PWM switching mode at the same time in each commutation state [18,19]. The switching sequence of plugging is similar to that of two switch method, where a continuous signal is applied instead of PWM pulses [26]. The performance indices of these braking methods such as boost ratio, braking torque and maximum voltage conversion ratio [18,19] are presented in Table 2.

2.2. Stopping time calculation

In addition to the performance indices [18,19], the stopping time of each braking method is obtained in this paper.

The motor dynamics can be expressed as

$$J\frac{d\omega}{dt} + B\omega + T_l = T_e \tag{1}$$

On neglecting the friction coefficient and load torque, Eq. (1) can be simplified as

$$J\frac{d\omega}{dt} = T_e \tag{2}$$

While braking, the motor torque T_e becomes negative and is written as $T_e = -K_t i_a$. Therefore

$$J\frac{d\omega}{dt} = -K_t i_a \tag{3}$$

The equation of braking current for the single switch method at steady state is [27],

$$i_a = \frac{D(2V_{emf})}{R_b + 2R} \tag{4}$$

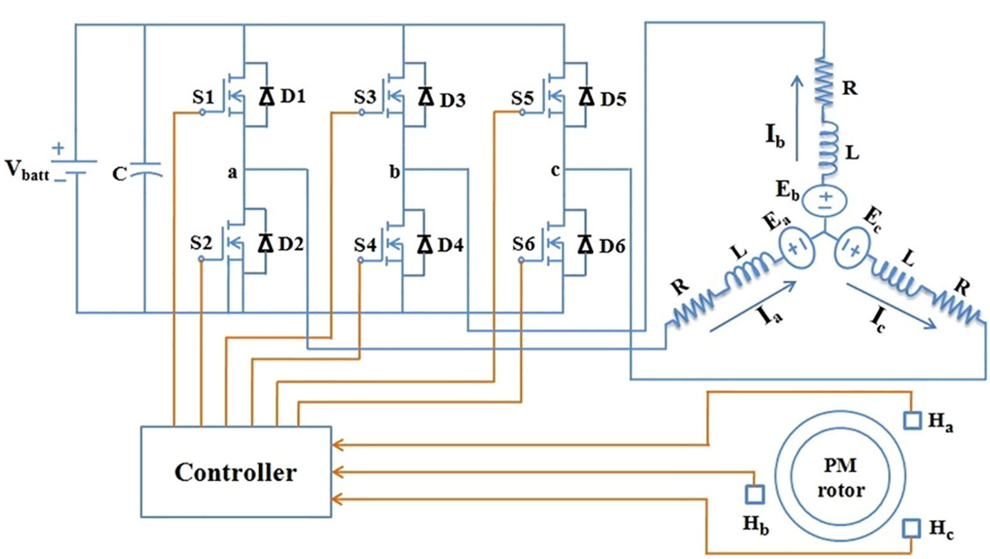

Fig. 1. Equivalent circuit of BLDC motor.

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