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An Electric Braking Scheme for a BLDC Motor Driven Electric Vehicle

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Abstract

This paper proposes an electric braking scheme for a brushless DC motor driven electric vehicle. This electric braking scheme is developed by combining various regenerative braking methods and plugging. At first, the speed profile and battery current profiles of each braking methods are studied during braking. It is observed that the speed reduction by plugging is very fast and by single and two switch method is slow, while regeneration occurs only in single and two switch methods. Based on these results, a new braking scheme is developed by combining these braking methods and it is switched among them based on the brake force applied by the driver. Simulation results are presented to validate the proposed technique.

Keywords: BLDC Motor, Electric Vehicle, Electric Braking, Regenerative Braking

1. Introduction

The usage of Electric Vehicles (EVs) is rising nowadays due to increase in fuel cost and environmental pollution. These vehicles use either AC or DC drive as thrusters for propulsion. Battery is the main source of energy in these vehicles, and it is connected to the drive through suitable power electronic converter[1–2]. At present scenario, brushless DC (BLDC) motors are widely used in EVs due to its high power density, better torque-speed characteristics, high efficiency, less maintenance and noiseless operation[3–4]. An overview of BLDC drive for EVs focussing on machine topologies, drive operations and control strategies are provided[5].

Energy conservation is a crucial part in EVs since the driving range of the vehicle depends only on the energy available in the battery. This motivates the energy conservation in battery through proper battery management system[6]. On the other hand, regenerative braking is an option to increase the battery energy by charging the battery while braking. During braking, back electromotive force (back-EMF) of the motor is used tocharge the batteryand hence the speed decelerates[7–8]. Various regenerative braking methods for BLDC motor driven electric vehicle are described in literature[9–14].

In[9–10], regenerative braking using boost converter is studied in which the converter boosts the back-EMF to the desired level to charge the battery. The boost converter is connected externally to the BLDC motor drive which creates an additional hardware. The ultra-capacitor connected in series or parallel with the battery is another technique used for regenerative braking. During braking, the ultra-capacitor is charged first and later on used to recharge the battery using dc-dc converters[11,12]. The ultra capacitor is expensive and moreover it requires sensors to check whether it is fully charged or not.

A novel electronic gearshift with ultra capacitors is proposed in[13,14] for regenerative braking. This technique uses stack of batteries, ultra capacitors and multiple winding type motor. The electronic gear switches different serial and parallel combinations of batteries, ultra capacitor and motor windings based on the speed for the effective energy recovery. This technique requires more number of relays, high power switches and moreover complex switching logic has to be developed for effective energy recovery.

In order to overcome the above drawbacks, regenerative braking using the existing BLDC motor driver (inverter)is proposed in[15–16]. The regenerative braking using thissingle stage converter is achieved by

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applying gate pulses in a proper sequence. Moreover this technique doesn't require any additional hardware or components to reach the purpose. Different regenerative braking methods named as single switch and two switch based on the number of switches being triggered are achieved in this converter which acts as boost converter[17–19]. Another braking method called plugging which consumes power rather regeneration is also achieved[20].

In this paper, initially the speed and current profiles of single switch, two switch and plugging are studied using simulation. Based on the speed and current profiles of each braking methods, a new electric braking scheme is developed by combining the single switch, two switch and plugging methods based on brake force applied on the brake pedal.

The rest of the paper is organized as follows. The working principle of BLDC motor is explained in section 2 while the different electric braking schemes are studied in section 3. The speed profile and battery current profile of each braking schemes are compared in section 4. The proposed braking scheme along with its simulation results are presented in section 5 followed by conclusions in section 6.

2. BLDC Motor

BLDC motors are principally an inside out permanent magnet DC motor in which the current commutation is performed by an inverter circuit instead of commutator and brushes. Therefore, the maintenance required for the BLDC motor is less and it is efficient than DC motor. The motor has high energy permanent magnets on rotor and three phase windings (armature winding) in the stator and are connected to the DC source through the three phase inverter.

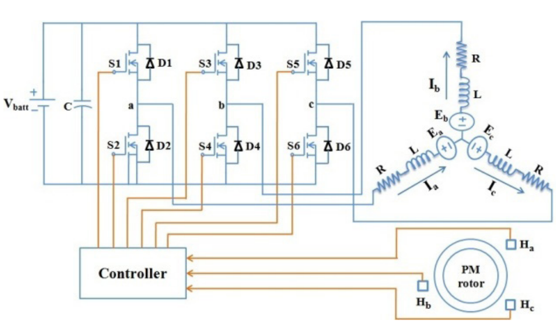

Figure 1. Equivalent circuit of BLDC Motor.

The equivalent circuit of BLDC motor with the inverter circuit is shown in Figure 1. The resistance of stator winding of each phase is represented as R, inductance as L, back-EMF as E_a, E_b and E_c and current through the winding as I_a, I_b and I_c. S1–S6 are power switches, D1–D6 are freewheeling diodes, C is the DC link capacitor to maintain DC voltage of the inverter. The hall signals H_a, H_b and H_c from the hall sensors provides the position of rotor magnets, communicates to the controller. The inverters are triggered based on these positions by the controller to operate the motor.

Table 1. Switching sequence of inverter

State	Rotor position			Switches	
	H_a	H_b	H_c	PWM	ON/OFF
I	1	0	1	S1	S4
II	1	0	0	S1	S6
III	1	1	0	S3	S6
IV	0	1	0	S3	S2
V	0	1	1	S5	S2
VI	0	0	1	S5	S4

The sequence in which the inverter is triggered with respect to the rotor magnet position is shown in Table 1. The top side switches S1, S3 and S5 are operated in Pulse Width Modulation (PWM) mode and bottom side switches S2, S4 and S6 are operated in ON/OFF mode. The commutation cycle as seen in Figure 3 has totally six states and at any state, two switches are triggered, one from top and another from bottom side.

3. Various Electric Braking Schemes

In this section, we briefly describe various electric braking schemes obtained by changing the switching sequence of the inverter which includes plugging and regenerative braking methods.

3.1 Plugging

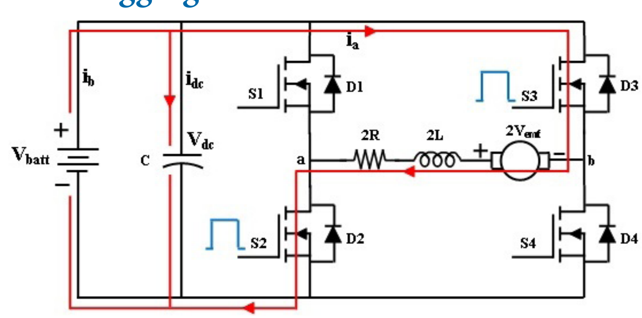

Figure 2. Equivalent circuit for plugging.

Plugging is a concept used to stop the DC motor by reversing the supply voltage. In BLDC motor, plugging is achieved by reversing the supply voltage in each commutation state using the inverter switches[20]. The supply voltage and the back-EMF are added together to form a large armature current in the reverse direction to develop high braking torque instantly. Due to plugging, motor comes to zero speed in a very short time. This braking technique is suitable for emergency braking and further it consumes energy from battery to stop the vehicle. The operation during state I of switching pattern is shown in Figure 2 and the switching diagram is shown in Figure 3. In the State I, when switches S3 and S2 are triggered, the battery supply voltage (V_{batt}) and back-EMF (V_{emf}) are added to form a high armature current. As a result a high braking torque is developed to stop the motor instantly. However, no energy can be recovered.

By applying Kirchhoff's voltage law, the equation of armature current (I_a) is written as:

$$I_a = -\frac{V_{batt} + 2V_{emf}}{2R} \tag{1}$$

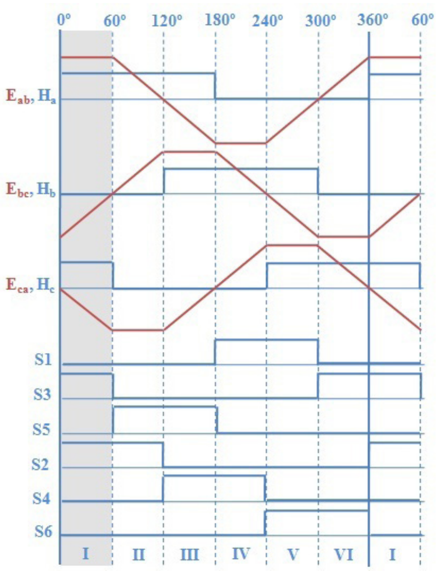

Figure 3. Switching diagram for plugging.

3.2 Two Switch Regenerative Method

In two switch method, two switches (i.e. one from top side and other from bottom side) are operated in PWM switching mode at each commutation state[18,19]. Figure 4 shows the equivalent circuit during the State I and Figure 5 shows the switching sequence of the complete commutation cycle. In the state I as shown in Figure 4, when the switches S3 and S2 are turned on, the back-EMF and battery voltage are connected in series to charge the armature inductor(L). Conversely, when the power switches S3 and S2 are turned off, the charge stored in the armature inductor (L) is returned to the battery through the freewheeling diode D4 and D1. As a result, energy regeneration and electric braking are achieved simultaneously.

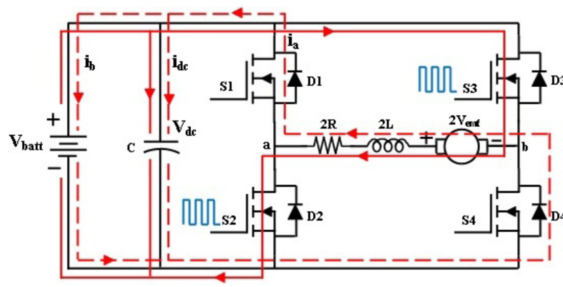

Figure 4. Equivalent circuit for two switch regenerative method.

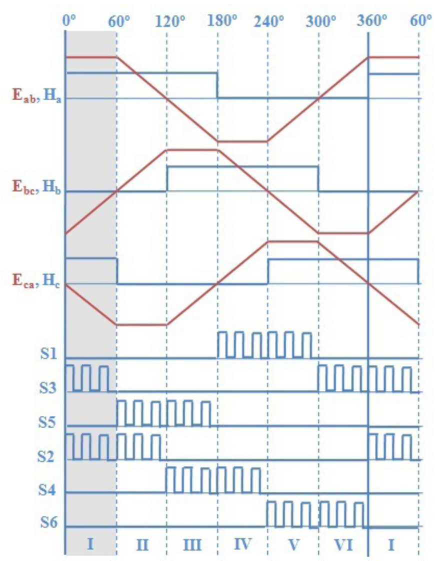

Figure 5. Switching diagram for two switch regenerative method.

The changes in the inductor current I_a during turn on time (t_{on}) and turn off time (t_{off}) are $\Delta I_{a(on)}$ and $\Delta I_{a(off)}$ respectively. The values of $\Delta I_{a(on)}$ and $\Delta I_{a(off)}$ is given by:

$$\Delta I_{a(on)} = \frac{V_{batt} + 2V_{emf}}{2L} \Delta t_{on}$$

$$= \frac{V_{batt} + E_{ab}}{2L}\Delta t_{on} \quad (2)$$

where, $\mathbf{E_{ab}} = \mathbf{2V_{emf}}$ is the line to line back-EMF during the State I.

$$\Delta I_{a(off)} = \frac{2V_{emf} - V_{batt}}{2L}\Delta t_{off}$$

$$= \frac{E_{ab} - V_{batt}}{2L}\Delta t_{off} \quad (3)$$

In steady state, the net change in inductor current over one switching cycle is zero. Therefore

$$\Delta I_{a(on)} + \Delta I_{a(off)} = 0 \quad (4)$$

Substituting (2) and (3) into (4), we obtain

$$\left(\frac{V_{batt} + E_{ab}}{2L}\right)\Delta t_{on} + \left(\frac{E_{ab} - V_{batt}}{2L}\right)\Delta t_{off} = 0 \quad (5)$$

On rearranging (5), we obtain

$$\frac{\Delta t_{off}}{\Delta t_{on}} = \frac{V_{batt} + E_{ab}}{V_{batt} - E_{ab}} \quad (6)$$

In this method, battery energy is spent during switch ON period, and energy is regenerated during switch OFF period and it is returned to the battery. Therefore, the amount of energy regenerated to the amount of battery energy consumed is related to the switching period and is written as:

$$\frac{\Delta t_{off}}{\Delta t_{on}} = \frac{W_r}{W_t} = \frac{V_{batt} + E_{ab}}{V_{batt} - E_{ab}}$$

$$= 1 + \frac{2E_{ab}}{V_{batt} - E_{ab}} \quad (7)$$

where, W_r is the regenerative energy fed back to the battery when switches are OFF and W_t is the energy delivered from the battery when the switches are ON.

3.3 Single Switch Regenerative Method

In single switch regenerative method, only one switch from bottom side is operated in PWM switching mode at each commutation state[17]. Figure 6 shows the equivalent circuit during the State I and Figure 7 shows the switching sequence of the complete commutation cycle. In the State I, as shown in Figure 6, when the switch S2 is turned ON, the back-EMF charges the armature inductor. On the contrary, when the switch S2 is turned off, the energy stored in the inductor is returned to the battery through the free wheeling diode D4 and D1. Therefore, energy regeneration and electric braking are achieved at the same time. Since back-EMF alone charges the armature inductor, the braking torque will be lesser compared to the two switch regenerative method.

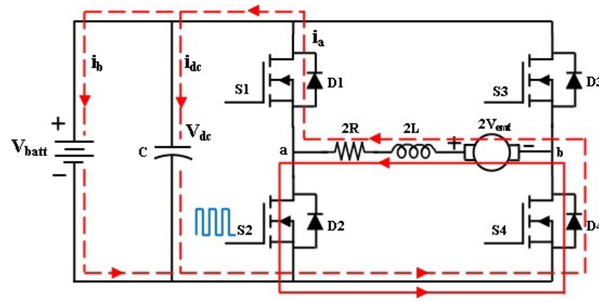

Figure 6. Equivalent circuit for single switch regenerative method.

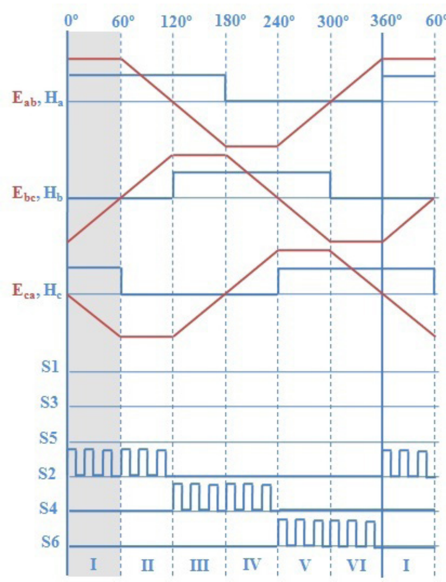

Figure 7. Switching diagram for single switch regenerative method.

The changes in the inductor current I_a during t_{on} and t_{off} states are

$$\Delta I_{a(on)} = \frac{E_{ab}}{2L}\Delta t_{on} \quad (8)$$

$$\Delta I_{a(off)} = \frac{E_{ab} - V_{batt}}{2L}\Delta t_{off} \quad (9)$$

During steady state, the net change in inductor current is zero over one switching cycle. Substituting (8) and (9) in (4) we get:

$$\left(\frac{E_{ab}}{2L}\right)\Delta t_{on} + \left(\frac{E_{ab} - V_{batt}}{2L}\right)\Delta t_{off} = 0 \quad (10)$$

After rearranging we can re-write above equation as

$$\Delta t_{off} = \Delta t_{on} * \frac{E_{ab}}{V_{batt} - E_{ab}} \quad (11)$$

From equation (11), we can say that the regenerative portion increases proportionally with back-EMF (E_{ab}).

4. Comparison of Speed Profile and Battery Current

In this section, the speed profile and battery current of the three braking methods are compared. A BLDC motor of 48 V input with a no-load speed of 430 rpm is considered. Initially the motor is allowed to rotate at its no load speed and at third second, a brake signal is applied. The speed and the current profile of each method are plotted from Figures 8–13. It can be noted that, the speed profiles of these techniques differ from each other. In the plugging case, the speed reduction is very quick. The speed reduction by two switch method is lesser than plugging but faster than single switch method.The sequence of motor stoppingare in the order of plugging, two switch and single switch, while regeneration occurs only in two switch and single switch method. The regeneration areas are indicated by circles. Two switch current profile has positive value because during ON time it draws current from the battery. But in single switch, the profile is always negative. These results motivates to design a braking scheme which changes the switching sequence of inverter based on brake force applied by the driver.

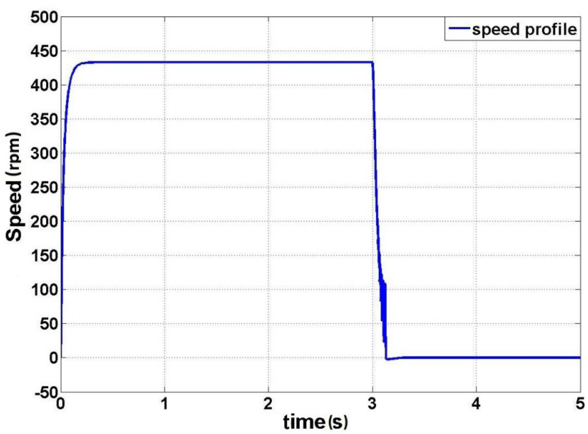

Figure 8. Speed profile for plugging.

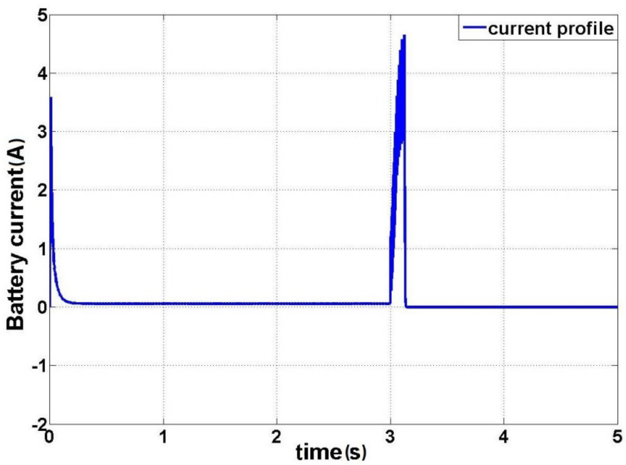

Figure 9. Battery current profile for plugging.

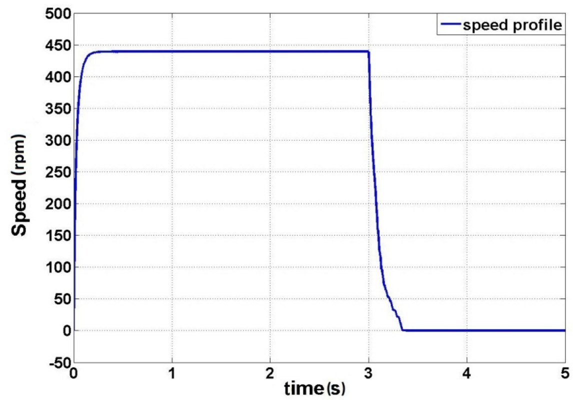

Figure 10. Speed profile for two switch method.

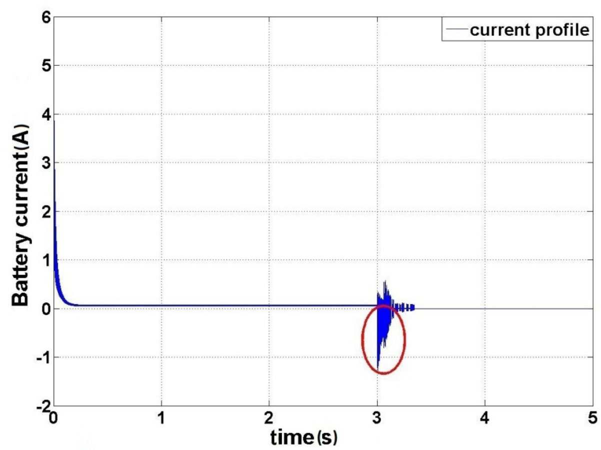

Figure 11. Battery current profile for two switch method.

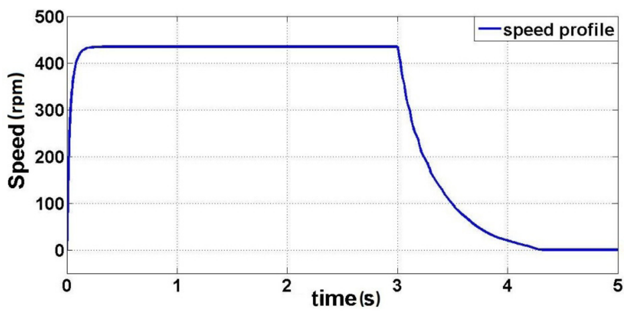

Figure 12. Speed profile for single switch method.

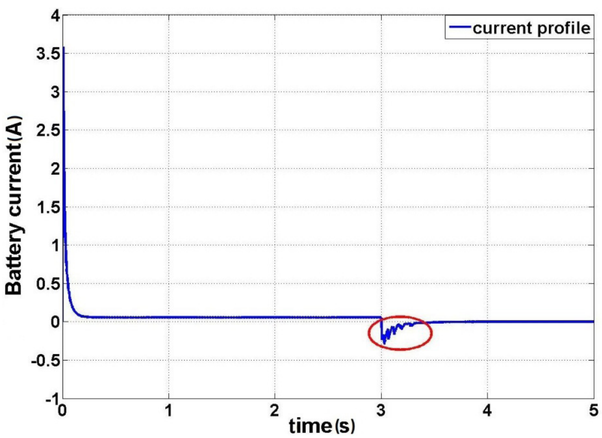

Figure 13. Battery current profile for single switch method.

5. Proposed Braking Scheme

Based on the analysis from section 4, the main idea in the proposed scheme is to select the braking methods from all the three techniques based on the brake force. If the brake force is large, assumed to be an emergency braking and hence plugging technique is enabled. If the brake force is in between pre-defined threshold values, two switch method is enabled. If the brake force is small, then single switch method is enabled. The block diagram of the scheme with acceleration and brake command is represented in Figure 14. The controller activates the suitable braking method based on the brake force applied. The activation of braking methods based on the brake force is given in the following condition.

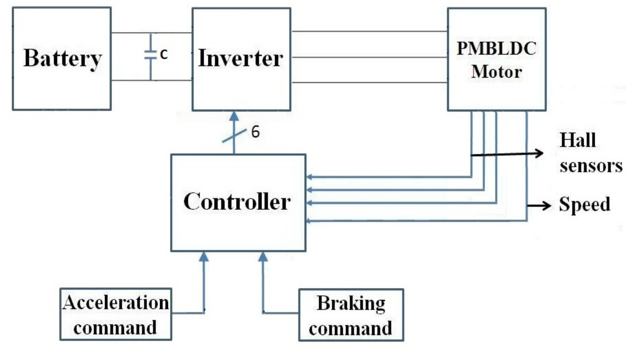

Figure 14. Block diagram of the proposed scheme.

if 30 N $\geq$ Brake force $>$ 20 N , S2 & S3 to be turned on with $T_{on} = T$

if 20 N $\geq$ Brake force $>$ 10 N, then S2 & S3 to be turned on with $T_{on} = DT$

if 10 N $\geq$ Brake force $>$ 0 N,then S2 only to be turned on with $T_{on} = DT$

where, D is the duty cycle and T is switching time period.

The proposed method is tested with an assumed drive cycle consisting of several accelerations and braking instants shown in Figures 15 and 16. The braking signal consists of various brake forces which helps in studying the strategy. The speed, battery current and the battery power are shown in Figures 17–19. The motor is driven at its maximum speed of 430 rpm and tested with a brake force of 10 N, 20 N and 30 N. In Figure 16, initially for a brake force of 20 N, it can be seen that the two switch method is activated. The activation of two switch method is confirmed from the battery current waveform having both positive and negative values. Secondly for the brake force of 10 N, single switch method is activated and the current value is negative. Again for the brake force of 30 N, plugging is activated and the current value is only positive. Similarly, the same scenario occurs for remaining drive cycle. From the speed profile, it can be noted that out of the same braking period, speed reduction by plugging method is 90 rpm, which is very fast compared to two switch method. The speed reduction by two switch method is 110 rpm. The speed reduction by the single switch method is 210 rpm and it is very slowin comparision to two switch method. Thus it can be observed that the speed is reduced based on the brake force applied. Moreover, a considerable amount of energy is also recovered.

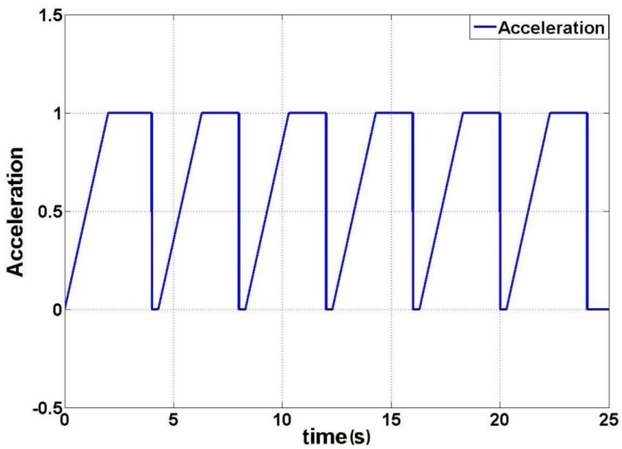

Figure 15. Acceleration signal.

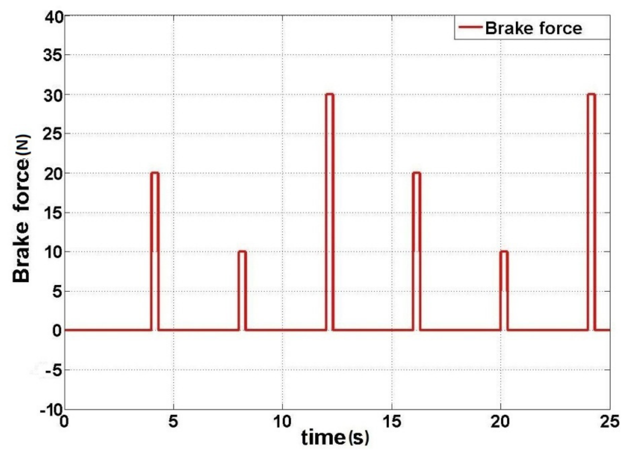

Figure 16. Brake signal.

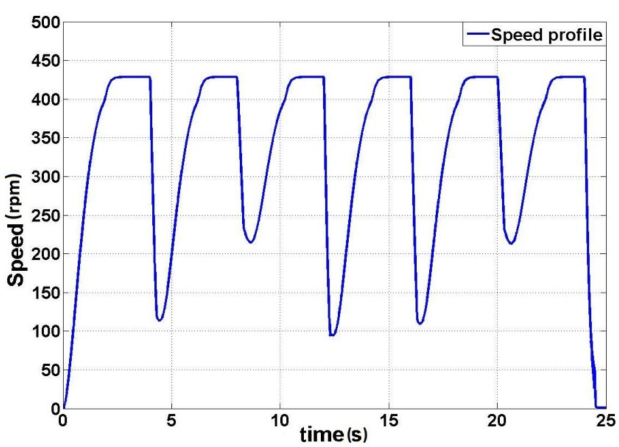

Figure 17. Speed profile.

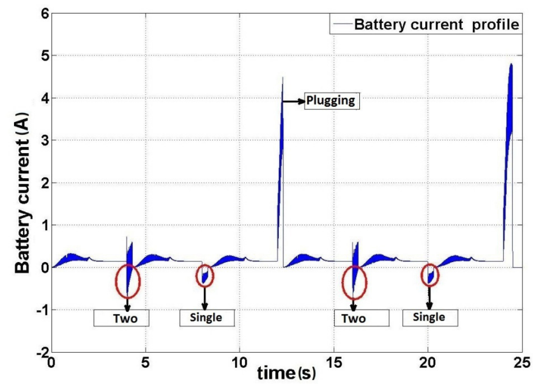

Figure 18. Battery current profile.

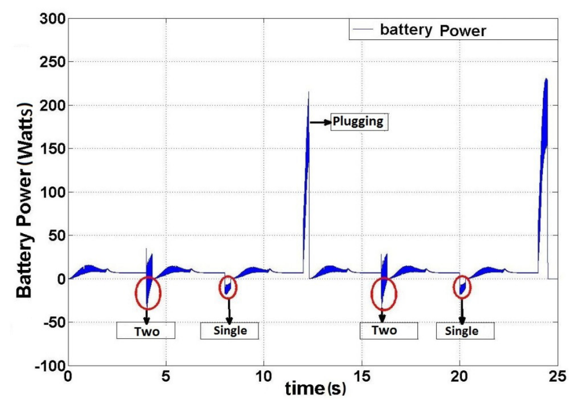

Figure 19. Battery power profile.

6. Conclusions

A new electric braking scheme for a BLDC driven electric vehicleis proposed which works based on the brake force applied on the brake pedal. The speed and battery current profiles for braking methods such as single switch, two switch and plugging are analysedusing simulation. The results show that the plugging has the fast speed reduction capability and no regeneration and moreover single and two switch braking methods has better regeneration capability and less speed reduction. Based on these conclusions, a new braking scheme is developed by combining all the three barking methods which switches between each other based on the applied brake force. The effectiveness of the proposed method is validated by simulation. The results shows that this scheme is well suited for electric braking since it is based on brake force applied by the driver which mimics the actual mechanical braking.

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