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A review on regenerative braking of electric vehicle

* Laxmi Ashok Patil
TSSM'S BSCOER, Pune
ME Electrical (Power System), Savitribai Phule Pune University, Pune, Maharashtra, India

Abstract
The Electric vehicles are upcoming interest in the market. The traditional braking topologies are nowadays used. These braking techniques have lot of wastage of energy during the braking in form of heat. Thus regenerative braking is the prime method to be focus as it is energy saving method. It increases efficiency of electric vehicle by saving of waste energy. In regenerative braking mode of electric vehicle the kinetic energy of wheels is converted into electricity and stored in batteries or capacitors. This method is improved by using flywheel, DC-DC converter, ultra capacitor as well as super capacitor. In this paper various types of controllers have been studied to improve energy saving of electric vehicles.

Key-words: BLDC motor, Regenerative braking, brake controller, flywheel, ultra capacitor

1. Introduction

Nowadays electric vehicles become popular as we know it is green vehicle producing zero emission to the air which is general cause of depletion of ozone layer. There are no toxic gases releases from vehicle to pollute the atmosphere. In recent years the Electric vehicle population starts increasing according to demand in the market. Besides, government is more serious for the production of electric vehicles. All the humanities are trying to save Mother Nature & natural resources such as crude oil & gases in the earth. In twentieth century, vehicular technology such as control technology and integrative technology have been developing aggressively. Somehow, the limitation of driving mileage still becomes an obstacle for the development of electric vehicles. This problem had been tackle by using regenerative braking; it has become one of the ways to improve the driving range as this method can increase an EV's driving range by 8-25% [1]. This technology had mostly replaced the traditional braking system in the vehicles 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.

This wasted energy actually can be converted to a useful energy especially for the hybrid and electric car. Therefore regenerative braking had been implemented in the car braking system to recapture this wasted energy. In addition, the total energy saves is dependent on the driving condition, normally it is more effective in city driving rather than highway whereas little braking occurs [2].

There are several advantages of regenerative braking taken over the traditional braking system such as:

- More control over braking
- More efficient and effective in stop-and-go driving conditions
- Prevents wear on mechanical brake systems
- Better fuel economy

In this work, the working principle and some braking controller for the regenerative braking have been reviewed.

2. Regenerative Braking System

Regenerative braking is a braking method that utilizes the mechanical energy from the motor by converting kinetic energy into electrical energy and fed back into the battery source. Theoretically, the regenerative braking system can convert a good fraction of its kinetic energy to charge up the battery, using the same principle as an alternator.

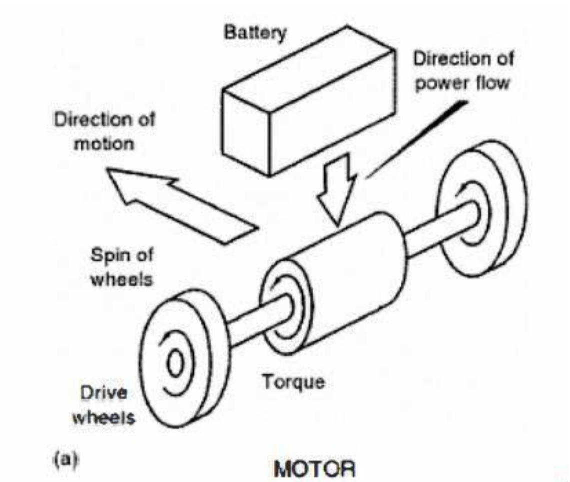

Fig 1: Normal forward driving condition

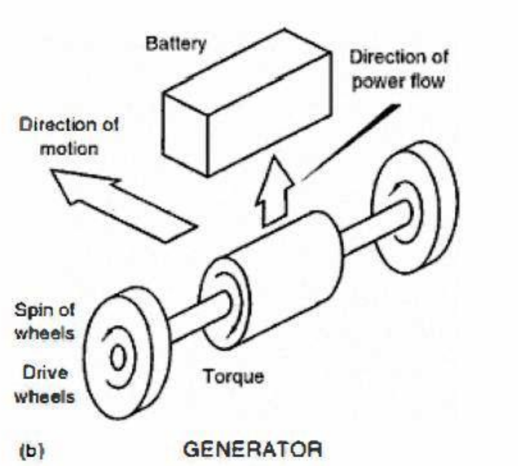

Fig 2: Regenerative action during braking

In regenerative braking mode, it uses the motor to slow down the car when the driver applies force to the brake pedal then the electric motor works in reverse direction thus slowing the car. While running backwards, the motor acts as the generator and recharge the batteries as shown in Fig.2. Meanwhile in Fig.1 shows the car in normal running condition whereas the motor turning forward and taken energy from the battery. By using regenerative braking, it vastly reduces the reliance on fuel, boosting fuel economy and lowering emissions. These types of brakes work effectively in driving environment such as stop-and-go driving situations especially in urban city.

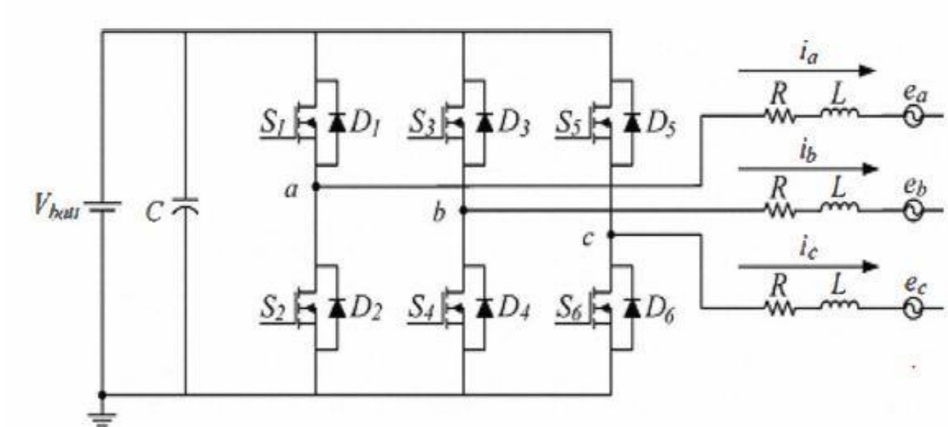

Fig 3: Three phase frequency dependent inverter

In the regenerative braking system, the braking controller is the heart of the system because it controls the overall process of the motor. The functions of the brake controller are monitor the speed of the wheel, calculate the torque, rotational force and generated electricity to be fed back into the batteries. During the braking operation, the brake controller directs the electricity produced by the motor into the batteries or capacitors.

In additional, the advanced algorithms in the motor controller give a complete control over the motor torque for both driving and regenerative braking. A torque command is derived from the position of the throttle pedal. The motor controller converts this torque command into the appropriate 3-phase voltage and current waveforms to produce the commanded torque to the motor in the most efficient way. The torque command can be positive or negative. When the torque serves to slow the vehicle then energy is returned to the battery, regenerative is achieved.

Regenerative braking system known as three phase frequency dependent inverter. It consisted of power electronic components such as N-channel power MOSFET, diode, resistor, capacitor and inductor.

Base on the Fig. 4:

- R and L are armature resistance and inductance
- ea, eb, and ec are the armature back EMFs of the phase a, b, and c.
- ia, ib, and ic are the armature currents of the phase a, b and c.

Meantime, Fig. 4 shows the switching sequences of the normal and energy- regenerative modes for the Brushless DC Motor (BLDC).

Base on Fig. 4:

- eab, ebc, eca are the line-to-line armature back EMFs.
- H1-H3 are the commutation signals (Hall sensor signals).
- S1-S6 are the switching signals of the six power switch.

During the normal mode, the high side switches S1, S3, and S5 are operated in pulse width modulation (PWM) switching mode; the low side switches S2, S4, and S6 are operated in normal high or low. To the contrary, all the switches are operated in PWM switching mode during the energy-regenerative mode.

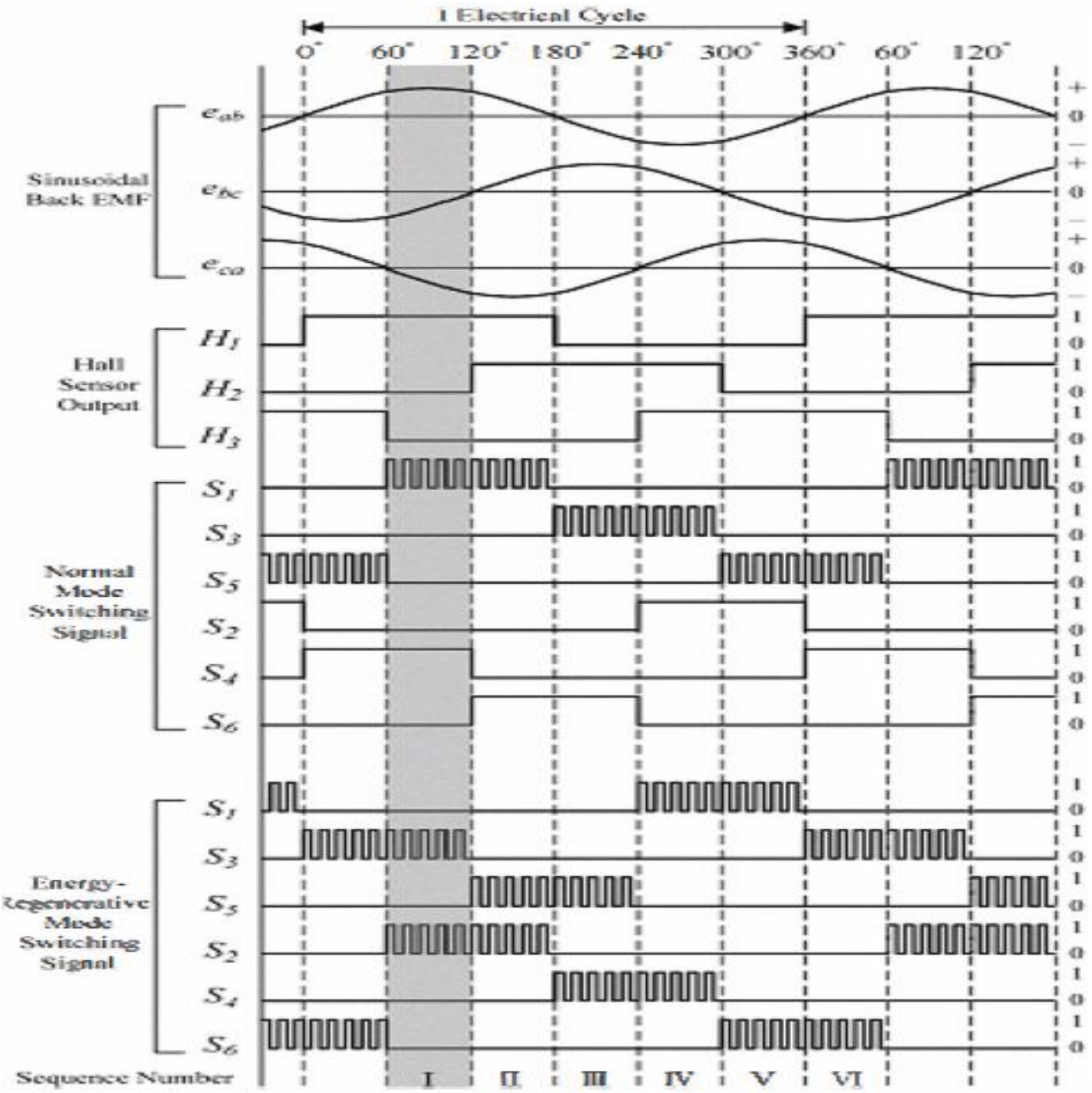

Fig 4: The characteristics of Hall sensor signals, back EMFs, and switching signal sequences of normal and energy-regenerative modes

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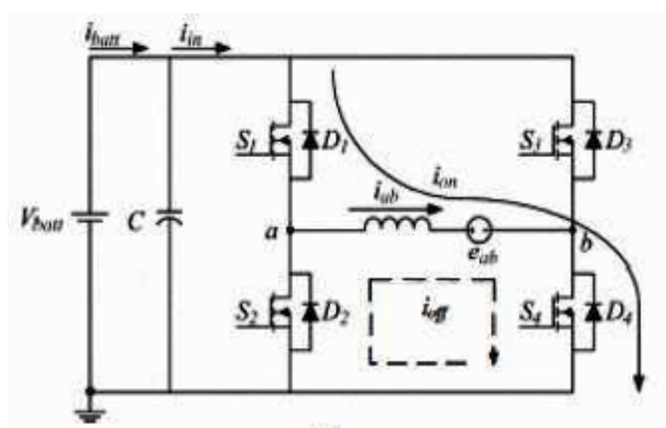

(a)

- **Normal Mode**

Fig. 5(a) is the equivalent circuit III normal driving mode under state I interval. During state I the conduction mode, it switches Sl and S4 on simultaneously. The inductor current iab would be increased by the energized current loop ion of the winding. When the magnetic field of the winding is increased due to iab increase, a reverse induction voltage eab has to resist the variation of the magnetic field according to Lenz's Law [1].

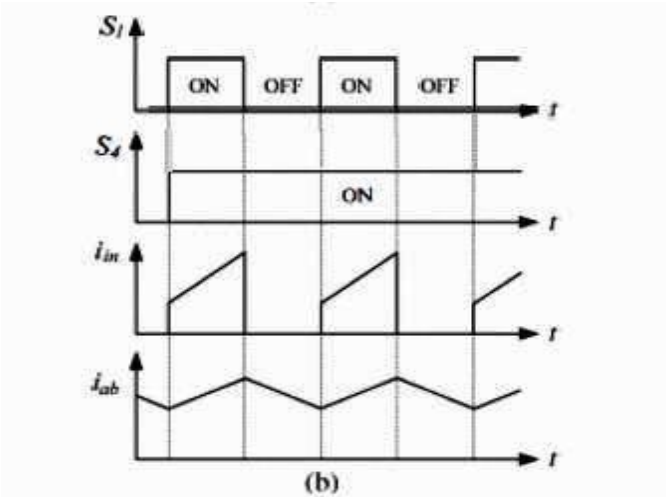

Fig 5: The state 1 under normal condition (a) Equivalent circuit (b) Waveform of input and phase current, switching signal SI and S4

This is represented by the armature back EMF of the motor. During freewheeling mode, the switch Sl is turned off, and S4 is still on, in such condition the inductor current will flow into the freewheeling diode D2 and the switch S4, which makes a discharging current path ioff. The corresponding sequences of S1, S4, input current iin and phase current iab are shown in Fig. 5(b).

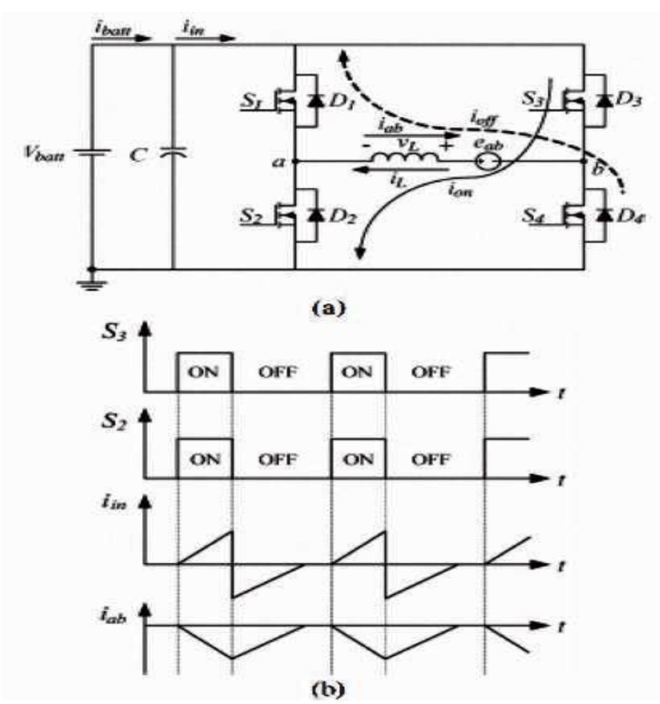

Fig 6: The state I under energy regenerative mode (a) Equivalent circuit (b) Waveform of input and phase current, switching signal of S, and S3

- **Energy-Regenerative Mode**

When the controller receives a brake signal; the motor operation changes from the normal mode into the energy regenerative mode. Thus, the operating principle of the energy regenerative mode for the duration of the state I is analyzed by the controller [1]. By switching S2 and S3 on, it change the switching sequence to the energy regenerative mode and the back EMF eab becomes a voltage source. During the turn-on period of S2 and S3, the winding will be energized. Therefore the voltage VL is equal to V batt + eab, and the current iin is equal to -iab or ion. On the other hand, during the turn-off period of S2 and S3, the current iin which flows through the freewheeling diodes D1 and D4 is equal to iab. It creates a current path ioff and this current fed to the battery.

3. Improvement in Regenerative Braking System

3.1 Implementation of Flywheel in Regenerative Braking System

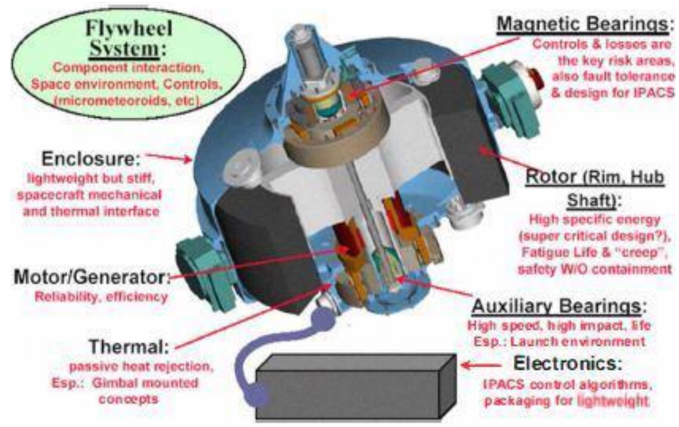

Fig 7: Flywheel system

A flywheel is an inertia energy storage device or known as electromechanical battery. It is use to absorb mechanical energy and serve as a storage reservoir. Flywheel is supported by magnet floating bear in vacuum and converts electric energy into kinetic energy and also kinetic energy into electric energy through the same motor/generator. Basically it store energy during the period when the supply of energy is more than the requirement and release it during the period when the requirement of energy is more than the supply.

In regenerative braking system, flywheel is used to smoothen out variations in the speed of a shaft caused by torque fluctuations. It functions when the source of the driving torque or load torque is fluctuating in nature. Flywheel design can be improve by increasing its angular velocity and delivers the stored energy by decreasing its velocity. The specific energy of flywheels increases proportionally as the weight of rotating material is reduced, when compared it terms of equal mechanical strength of the flywheel. There are some solid reasons for choosing Flywheels:

- It is a pure mechanical device without external power input.
- Flexibility in design and operation.
- No chemical reaction like chemical battery and zero emission so it is categorized as ecologically clean nature.
- Long cycle life and longer life span.
- High cycle efficiency of around 90%.
- Low effect on life cycle although in fast charging profile.
- Long maintenance period of more than 10 years therefore it is more reliable and low maintenance cost.

3.2 Implementation of Ultra capacitor and DC-DC Converter in Regenerative Braking

In the ultra-capacitor system, the 4 main components are the DC-DC converter based on the insulated gate bipolar transistors (IGBTs), smoothing aluminum inductor Ls, ultra capacitor bank and battery pack. The buck-boost converter is connected in parallel to the main of the batteries. During acceleration, the capacitor voltage is allowed to discharge from full charge to one-third of its nominal voltage. During deceleration, the energy is recovered back and charge up the ultra-capacitor. For the DC-DC converter which is the buck-boost circuit. The boost operation is used for acceleration while buck operation is use for deceleration which will help in charging up the capacitor.

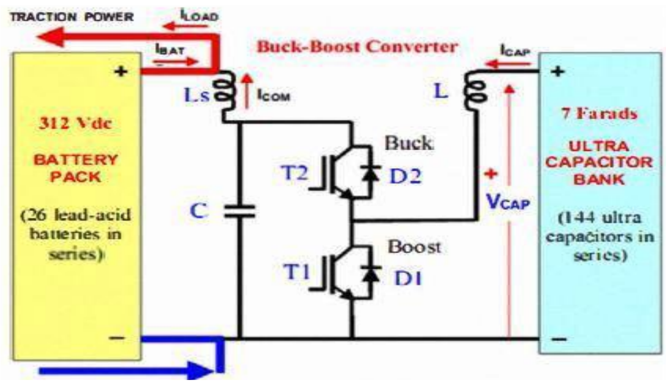

Fig 8: Ultra capacitor system

The operation of the circuit is basically divided into two states which are boost and buck. The boost state can be achieved by switching Tl ON and OFF at a controlled duty cycle. In this state, the amount of energy required from the capacitor will flow to the battery. When Tl is ON, energy is taken from the capacitor, and stored in the inductor L. When Tl is OFF, the energy stored in L is transferred into C through D2, and fed into the battery pack. While Ls is used to smoothen the current pulses going to battery pack [7].

During Buck operation, the energy of the battery is transfer to the ultra-capacitor. This operation is done by controlling the pulse width modulation operation on T2. When T2 is switched ON, the energy from the battery will flow to the ultra-capacitor while L stores part of this energy. When T2 is OFF, the remaining energy stored in L is transferred into the ultra-capacitor.

Ultra capacitor plays an important role in the system as this new technology has the abilities such as:

- Store 20 times more energy compare to electrolytic capacitor
- Charge and discharge thousands of times without performance degradation
- Improve the transient performance in EV
- Increase lifespan of the batteries
- Fast and sudden battery discharge during acceleration or breaking can be avoided
- Provide additional supply to the car to prolong its distance.

4. Results and Discussion

Regenerative braking is one of the important systems in electric vehicle because it has the ability to save the waste energy up to 8-5%. The regenerative braking system has been improved by the advanced power electronic component such as ultra-capacitor, DC-DC converter (Buck-Boost) and flywheel. The ultra-capacitor that helps in improving the transient state of the car during starting, provide a smoother charging characteristic for the battery and boost up the overall performance of the electric vehicle system. The Buck-Boost converter helps maintaining the power management in the regenerative braking system such as boosting the acceleration. Finally, the flywheel is used to enhance the power recovery process through the wheel of the car.

The regenerative braking is a tremendous concept that has been developed by Engineers. In the near future, regenerative braking techniques can be further developed by using different methods either by fuzzy controller or PID controller.

5. Refarence

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