Regenerative braking system using pulse width modulation technique on brushed DC motor

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Abstract. In automobiles, large amount of energy loss due to braking takes place without any recycling. A brake is required to control the motion of an automobile. The conventional braking system uses friction of brake shoes and drums for conversion of kinetic energy developed by the vehicle into heat energy. In conventional braking system the heat energy generated at contact surfaces is dissipated to surroundings. In regenerative braking system the speed of the vehicle is reduced by the motors. No surplus energy of the vehicle will be wasted as the unwanted heat, the overhead wires receive electricity from the motors which act as a generator. In this paper, a novel technique of pulse width modulation on brushed DC motor is used for evaluating the availability of braking energy recovery. The vehicle receives power from the electrical energy taken from the battery is used by an electric motor that provides motive force to the wheels. To obtain more efficiency the regenerative braking should take place on the vehicle, so a model to control the speed of the motor has been simulated using circuit simulation software Proteus. The laboratory test has been performed on the built model before being mounted on the vehicle. The circuit is repeatedly tested for the desired wave functions and are absorbed on the oscilloscope. Results are presented for the amount of power generated during braking and variation of run speed of the vehicle with time for different rated speeds of the motor at different loads.

1. Introduction
Unconventional braking system is an evolved method where vehicle performance can be increased with decrease in the emission levels, regenerative braking system is one such system. Regenerative braking system is used to reduce speed of a vehicle by transmitting kinetic energy into a system that can store energy and can be used when required. The overall efficiency of the vehicle and braking system life can be improved with regenerative braking system as the parts of the system are less prone to wear. Progressing countries like India will benefit more if large amount of energy is restored through regenerative braking system. Many researchers are focussing on improving the reactivation of energy in electric and hybrid vehicles by using this system. Chicurel [1] made an experimental study on electrical bus by designing a regenerative braking system consisting of fixed displacement hydraulic pump/motor and hydro-pneumatic accumulator. He found that the driving range of electrical vehicles can be improved without additional cost by regenerative braking. Gao et al. [2] conducted an investigation on passenger cars with three different braking patterns. They found that significant amount of kinetic energy can be recovered from electrical and hybrid vehicles with minor modification in existing braking system especially during heavy traffic. Panagiotidis et al. [3] developed a regenerating braking model for parallel hybrid electrical vehicle and simulated using Mat lab/Simulink. Their simulation studies showed a decrease in fuel consumption, exhaust emission and increase in driving
A regenerative braking algorithm for parallel hybrid electrical vehicle by considering the battery state of charge, vehicle velocity and motor capacity was proposed by Yeo and Kim [4]. They found an increase in braking system efficiency, mileage and battery life from their simulated results. Chuanwei et al. [5] conducted an experimental study to determine the kinetic energy recovery of an electrical vehicle (EV) with a constant regenerative current control. They observed an increase in performance of the vehicle with more energy recovery at less cost compared to other regenerative braking systems. A braking force distribution regenerative braking model based on optimal control theory for a hybrid electric vehicle was proposed by Luo et al. [6]. They found 10% increase in energy regeneration from the simulation results.

Peng et al. [7] proposed a control strategy by employing regenerative and hydraulic braking systems together on a hybrid electric vehicle. They used logical threshold control strategy and fuzzy logic control theory for dynamic control of hydraulic and regenerative braking torques respectively. They found from their experimental studies that the regenerative efficiency and braking performance has been improved with the proposed combined controlled braking strategy. Ayala et al. [8] proposed an energy storage system consists of flywheel, planetary gear set and brake for a hybrid electrical vehicle to reduce the size and cost of batteries. They found decrease in exhaust emissions and fuel consumption compared to a conventional hybrid vehicle by conducting tests on a laboratory scale model of the system. Ahn et al. [9] modelled an electro-mechanical regenerative braking system for hybrid electric vehicle and simulated the model using Matlab and Simulink. The simulated results for different operating conditions showed reduction in fuel consumption and an increase in braking efficiency. Yang et al. [10] proposed a regenerative braking system for an electrical vehicle using a brushless DC motor by changing the inverter switching sequence. The driving range of electrical vehicle was increased by 16.2%. Chen et al. [11] designed and instigated an unconventional braking system using a full-bridge inverter without any power switches for light electric vehicles. Their results revealed an enhancement in acceleration, braking efficiency and also braking reliability. Caratti et al. [12] made a theoretical investigation on power train configurations of hybrid electrical vehicles for efficient recovery of kinetic energy by using Matlab software. Their results showed an increase in braking efficiency, decrease in fuel consumption and exhaust pollution. Ko et al. [13] carried out theoretical and experimental study on auto transmission hybrid electrical vehicles by implementing regenerative braking cooperative control algorithm between friction braking and regenerating braking systems. They found an increase in energy recovery with the proposed cooperative algorithm. Long et al. [14] proposed a sliding mode robust controller to extend the driving range of battery powered regenerative braking electric vehicles. The driving range was improved by about 17% compared to conventional integral controller. Nian et al. [15] designed and simulated a regenerative braking system using brushless DC motor, conventional proportional integral derivative controller and the fuzzy logic control distribution of braking force. An increase in driving range of vehicle, braking efficiency and overall efficiency was observed from the simulated results. Also the practical implementation of the proposed method was verified.

Jin et al. [16] proposed an alternative braking system for an electric vehicle driven by in-wheel motors, with super capacitor and batteries as the energy storage unit. The simulation results showed an improvement in the life of the batteries and the rate of energy regeneration. Lv et al. [17] discussed the methodologies for measuring the contribution made by regenerative brake to vehicle energy efficiency. They proposed two different evaluation parameters based on vehicle’s driving range and energy consumption. Sliwinski [18] proposed a kinetic energy recovery storage device using torsion springs as an additional energy storage to the electrical energy from the vehicle braking. The time required to store the kinetic energy for the proposed device is very less and it is harmless to store the energy. They concluded that the fuel consumption and toxic emissions reduces with the proposed system. Nasiri et al. [19] proposed a dual energy storage system driven by brushless DC motor by utilizing complementary features of batteries and super capacitors to improve the vehicle acceleration. Brushless DC motor acts as a generator during regenerative braking. The energy recovered can be utilized for improving the acceleration of the vehicle. Sandilya et al. [20] made a theoretical study to recover dynamic energy of vehicle by using brushless DC motor. They implemented pulse width modulation
technique to control the inverter. PID controller was used for better changeover between mechanical and electrical braking. Their simulated results obtained using Mat lab showed an increase in kinetic energy recovery with good braking efficiency. Recently Godfrey and Sankaranarayanan [21] proposed an electric braking system based on stopping time and energy recovery by combining various regenerative methods and plugging for an electrical vehicle operating with brushless DC motor. It is observed from their theoretical and experimental studies that the kinetic energy recovery is better for single and three switch methods and stopping time was less for plugging. From the literature review it is found that no work has been reported on the recovery of brake energy of a light electrical vehicle using pulse width modulation technique on brushed DC motor. Hence in the present work a circuit is developed on the breadboard with hardware components to find the amount of power generated in regenerative braking mode to improve the efficiency of the vehicle. The circuit is repeatedly tested for the desired wave functions using the regulated power supply equipped with an auto transformer. The tests are performed on a light electric vehicle to find the amount of power generated at various motor speeds and at different loads.

2. Experimental setup

2.1. Description of experimental setup

The experimental setup consists of a DC motor 0.5HP, 220V, 1500 rpm whose speed has to be controlled in closed loop control using controller and insulated-gate bipolar transistor (IGBT) drive. Firing circuit is based on 555 integrated circuit and power circuit is based on two quadrant chopper. Automatically variable DC supply is provided to set the speed of the DC motor. A speed sensor is attached to the motor shaft. A tachometer is constructed internally to read the motor speed in rpm. A pulley is attached to the shaft of the DC motor for mechanical loading arrangement. An ammeter is provided to read motor current. And a voltmeter is used to read voltage across the DC motor. A DC voltage from three phase rectifier supply controlled from controller through the IGBT based two quadrant chopper. The DC supply is given to the chopper. The field supply is by the permanent magnet stator winding. The speed sensor must be connected from motor assembly to the instrument by the socket provided in the front panel of the control circuit. The speed sensor senses the speed of the motor and generates rectangular signal whose frequency is proportional to the rpm. The signal conditioner converts frequency into voltage corresponding to rpm. The digital panel meter displays the speed in rpm on the front panel of the instrument.

Figure 1. Layout of the experimental setup
2.2. Experimental procedure
The motor terminals of field and armature are connected to respective points in the power circuit and speed sensor to feedback terminals socket. The circuit connections made using three phase autotransformer and isolation transformer is shown in figure 1. The start/stop switch is kept at stop position and forward/reverse motion switch in forward motion position. Knob is used to set speed. A three pin power cord is used to connect rectifier to the mains supply. The auto transformer was kept at minimum position and switch on the three phase power input. Switch on the power circuit through MCB. Then switch on the firing unit. Adjust the transformer for suitable maximum voltage of 80%. Motor is loaded in the step of 0.25A load up to 1A. Speed was noted for different loads. Remove the load, keep the start/stop switch to stop position and reduce autotransformer voltage to a minimum value. Switch off the power circuit, firing circuit, three phase main supply, and field supply, and remove the connections. The above procedure can be repeated for the reverse rotation of the motor by keeping forward/reverse motion switch in reverse motion position.

2.3. Integration of experimental setup to test setup
The circuit simulated and tested is integrated with the test setup of electric bike as shown in Figure 2. The speed of the assembled motor is regulated for various speeds and then by using Double Pole Single Throw (DPST) switching system the motor terminals are transferred to the regenerative mode. The power regenerated for different speeds of motor at different loads are recorded.

![Figure 2. Test setup](image_url)

3. Results and Discussion
The circuit described in section 2.1 is simulated using electrical suite for circuit simulation called Proteus. The assembled circuit on the bread board has been tested for the voltage waveforms using the oscilloscope and controlled using the potentiometer. The power supply to the driver circuit is varied using the regulated power supply. A variable DC voltage is obtained from the fixed DC voltage by a DC chopper as they are more efficient, compact, and available at low cost. In chopper circuit an IGBT is used as a switch and voltage drop is neglected ranging from 0.5-2.5 volts. The duty cycle of the chopper circuit is varied to control the average output voltage. In the present work the width of the pulse is varied to get the required voltage output. The procedure given in section 2.2 is followed to obtain the results at different speeds and load conditions.
3.1. Effect of speed on power generation

Figure 3 shows the variation of power generation with run speed for set speeds of 400, 600, 800 and 1000 rpm without any load on the vehicle. The power generation in regeneration braking mode decreases with decrease in running speed due to back electromotive force generation in the motor. The power generation due to regenerative braking is more at higher run speeds. This is due to recovery of more kinetic energy available at higher speeds. The energy recovered can be used immediately or stored in battery until needed. The similar trend was observed by Nian et al. [15] using brushless DC motor with PID controller.

![Figure 3. Variation of power generation with time for different set speeds](image)

3.2. Variation of rated speed and power generation with brake time

![Figure 4. Variation of rated speeds with time for different set speeds](image)
Figure 4 shows the variation of speed of the vehicle with brake time for different set of speeds (400, 600, 800 and 1000 rpm) under no load conditions. It can be observed from the figure 4 that the vehicle came to stand still before 6 seconds after applying the brake. Hence there is no increase in stopping distance or time even when a continuous conventional brake is applied. So this novel technique used in the present work gives better performance and also directional control of the vehicle while braking. Also it is found from the Figure 5 that the power generation due to braking of electric vehicle (EV) is for a short period of time even before the motor comes to stop [10].

![Figure 5](image5.png)

**Figure 5.** Variation of power generation with time for different set speeds

### 3.3. Variation of power generation and speed for different loads

The tests were conducted at different loads of 1, 1.9 and 2.5 kg-f at the vehicle set speed of 1000 rpm as per the experimental procedure given in section 2.2 by loading the motor 0.5A, 0.75 A and 1 A load. Figure 6 shows the effect of vehicle speed on time for different loads. The running speed of the vehicle is reduced with increase in load and also the vehicle is motionless completely before 6 seconds irrespective of the load applied due to generation of back e.m.f.

![Figure 6](image6.png)

**Figure 6.** Variation of run speeds against braking time under different loads
The power recovered due to regeneration braking with pulse width modulation on brushed dc motor has increased with increase in load on the vehicle. The same can be found from the Figure 7, where the power generation is plotted against time for different load conditions.

![Figure 7. Variation of power generation against braking time under different loads](image)

4. Conclusions
Regenerative braking system of an electrical vehicle driven by brushed DC motor with pulse width modulation has been presented. The speed of the DC motor is successfully controlled by using a chopper circuit. The circuit is simulated using Proteus and the results are obtained for different rated speeds of the motor at different loads. The laboratory test has been performed on the built in model before being mounted on the vehicle. The regeneration of power is for a very short duration of time, a maximum of 4 seconds. The maximum power regenerated in the present work is 150 W at maximum load of 2.5 kg-f and vehicle set speed of 1000 rpm. It is observed from the results that with increase of load on the vehicle the amount of power generated also increases. Therefore it can be concluded that the proposed regenerative braking system has greater ability to recover energy, ensure better performance and better directional control of the vehicle in different situations.

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