MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

An Experimental Verification of Regenerative Braking Characteristics of Dc Motor

By

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October 2021.

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DEDICATION

This thesis is dedicated to my beloved parents and all well-wishers, helping me to accomplish this work.

ACKNOWLEDGEMENTS

Every honour and every victory on earth is due to the Great Almighty, descended from Him and must be ascribed to Him. I would like to express my heartiest gratitude to my supervisor, Prof. Dr. Md. Ashraful Hoque for his keen supervision, inspiration and motivation for doing this thesis. He is the person who played the instrumental role behind this work, and his motivation in every possible stage is the key to the completion of this thesis. I am also indebted to Dr. Md. Shahid Ullah, Professor of the Electrical and Electronic Engineering Department, rendered the administrative support and his valuable suggestions.

My sincere gratitude to Dr. Kazi Khairul Islam, Dean, Department Of EEE, Uttara University and Ex. Professor, IUT for his guideline during my research, which encouraged me to improve the work further. I want to thank other graduate students, faculty members and staffs of my department at the Islamic University of Technology.

I would also like to pay my solemn regards to my friends and colleagues who supported me generously and encouraged me enormously to complete this work.

Last but not least, I would like to thank my parents. Their optimism and encouragement have allowed me to overcome any obstacle that I face. Their unconditional support made it possible for me to finish this thesis.

S.M. Baque Billah

Abstract

Nowadays, electric vehicles are becoming very popular due to easy operation, no fuel usage and smoother function. However, it requires enormous electric power to recharge the battery, which is the primary source of energy for the vehicle. In addition, the existing braking system of conventional transport, mainly the lightweight electric vehicles (EVs), wastes some of the energy in the form of heat during the braking periods. Hence, energy-saving and prolonging mileage are significant for battery-operated electric vehicles (BEV). For saving energy in BEV's the key parts are regenerative braking performances. In this research, a novel regenerative braking mechanism is proposed and developed for lightweight electric vehicles having DC motors. The proposed method is effective for Permanent magnet DC (PMDC) and Brushless DC (BLDC) motors. Based on the proposed method braking can be achieved by applying different armature voltage(For PMDC motor) or applying different Stator voltage (for BLDC motor) from a multi-cell battery system without using an additional DC-DC boost converter with a complex switching technique or ultra-capacitor. Two separate experimental setups(prototype model of BEV) for PMDC and BLDC motors have been used to evaluate the performance of the proposed braking system. Multiple flywheel attachment mechanisms with the motor shaft are also used to simulate the braking performance at different loading conditions.

Furthermore, different characteristics such as braking current, time and back emf performances by varying terminal voltage and load are noted. Based on the gathered data, energy regeneration is calculated**.** Simulated results prove that the proposed regenerative braking process is feasible and efficient. Also, this research provides the most straightforward approach for regenerative braking for PMDC and BLDC motors to improve the mileage of lightweight electric vehicles (EVs).

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List of Abbreviation & Symbols

Abbreviation & Symbols	Description
EVs	Electric Vehicles
BLDC	Brushless DC
PMDC	Permanent Magnate DC
FLC	fuzzy logic controller
BEMF	Back Electromotive Force
SOC	State Of Charge
I_{ST}	Braking Current
t_{RB}	Regenerative Braking Time
t_{mh}	Mechanical Hard Braking Time
t_{mm}	Mechanical Medium Brake
N	Motor Speed
I_R	Rated Stator Current
T_R	Rated Torque
V_t	Motor Terminal Voltage

CHAPTER 1

Introduction

Recently due to global warming and rising cost of petrol battery-operated electric vehicles (BEV's) are getting accepted. It is believed that in near future electric vehicles (EVs) will replace the conventional fuel based vehicles and also dominate the market due to some aspects like zero carbon emission, less expensive and quiet maneuver. Fundamentally AC and DC motor are the core part of different types of EVs [1], including two-, three- and four-wheelers. For EVs automobile manufacturer prefers AC motor instead of DC motor because of its high efficiency [2]. But for simpler speed control methods and less expensive with respect to AC motor researches till see the potentiality of DC motor in EVs [3].

In Bangladesh Lightweight electric vehicles (EVs) like rickshaws are becoming trendier because of less physical effort and time to drive [4]. Moreover no dependency on fuel results quite low fare, which is very expedient for the traveler [5]. Most of the time EVs are driving on busy traffic where drivers have to start and stop frequently. This means lots of kinetic energy is lost as a heat for using conventional mechanical braking system and reduce battery backup time. As many researches show that during braking one third to one half of energy is lost [6]. Although in [7] a regenerative braking system using series wound brushed DC motor is designed where braking efficiency is around 26.34% which is less than 30%. Instead of series wound brushed DC motor PMDC motor has some advantages, such as does not have field winding. So excitation current is not needed in PMDC motor and the efficiency of these motors is generally higher than that of the wound-field motors. For that in [8] they use PMDC motor to design a scooter but can't achieve higher regenerative braking efficiency.

On the other side Due to higher efficiency, higher speed ranges, noiseless operation and better speed versus torque characteristics Brushless DC Motor is becoming an attractive choice for EVs [9]. But a major drawback of BLDC motor based EVs is consumption of significant amount of electricity to charge the battery which runs the motor [10]. So in the heavy traffic condition of a busy city, regenerative braking will be an effective way to extend the driving range as well as enhancement of viability and efficiency of DC motor based EVs [11].

1.1 Related Work

Electric vehicles have electric motors inside their structure and regenerative braking can be incorporated. In the regenerative braking operation the motor operates as a generator. The regenerative braking systems are applied in two and three wheeler vehicles [20].However, this scheme includes many of the additional hardwires [21]. The battery pack has significant role for getting distance and it should be used carefully. Therefore, it uses extra units for careful and efficient operations. In this regard, the super capacitor technology is used for effective energy 4 usage and it also extends the lifetime of the battery [22]. Generally, the super capacitor is connected in shunt with the battery bank. Recently, many analyses about regenerative braking are performed by different perspectives. One of the most common practices is to usea boost converter system to harness the braking energy.

In the boost converter based scheme, the back emf is increased and then the battery is charged. In particular, the back emf of a motor is always less than the battery voltage. Hence, it is obvious to boost the magnitude of the back emf to transfer the energy into the battery. To accomplish the charging operation, the boost converter is connected with the motor terminal and the higher voltage is obtained controlling the duty cycle of the switching pulses.

An ultracapacitor bank regenerative braking control system for an electric vehicle has been analyzed [23-25]. The system allows higher accelerations and decelerations of the vehicle with minimal loss of energy. In this method an IGBT Buck-Boost converter is used, which is connected to the ultra-capacitor bank at the Boost side, and to the main battery at the Buck side. The control system measures the battery voltage, the battery state-of-charge, the car speed, the instantaneous currents in both the terminals (load and ultra-capacitor), and the actual voltage of the ultra-capacitor. The level of actual voltage allows to know the amount of energy stored in the ultracapacitor. A microcontroller control is used to generate the PWM switching pattern of the

IGBTs. When the vehicle is accelerating, the battery voltage goes down, which is an indication for the control to take energy from the ultracapacitor. In the opposite situation where regenerative braking is concerned, the battery voltage goes up, and then the control needs to activate the Buck converter to store the kinetic energy of the vehicle inside the ultracapacitor. The measurement of the currents at both sides allows to keep the current levels inside maximum ratings. The battery state-of charge is used to change the voltage level of the ultracapacitor at particular values. If the battery is fully charged, the voltage level of the capacitors is kept at lower level that is below the partially discharged battery. The converter also has an IGBT controlled power resistor, which allows to drop energy in some extreme situations that cannot be accepted neither for the ultracapacitors nor for the battery pack.

The regenerative braking energy recovery control strategies for electric vehicle (EV) based on fuzzy logic control and FPGA control are proposed [26-28]. The sugeno fuzzy logic controller (FLC) is developed by analyzing the characteristic of the regenerative braking.Simulation experiments with different driving cycles were carried out, and the feasibility and effectiveness of the fuzzy logic control strategy are tested with the state of charge (SOC) and braking energy recovery.

However, these methods require auxiliary components that not only increase the cost and reduce the overall regenerative braking efficiency. Hence, there is a scope for further research to reduce the cost involved and braking efficiency.

1.2 Motivation

The regenerative brake is an energy recovery mechanism which creates braking torque to brake a EVs by energy conversion (kinetic to electrical energy) and charges the battery [4] [12] [13]. Basically regenerative energy is mainly limited by three constrains [14]. First, the regenerative torque depends on the max braking torque provided by the motor. The motor is desired of the high torque density and power density. Second, the regenerative power is limited by the charging power capability of the battery. Third the braking torque is limited by available tire-road friction.

From the above literature review regenerative braking is sometime realized by using the ultra-capacitor pack to absorb the instantaneous braking energy [15-18]. To detect the charging state of ultra-capacitors this method requires additional switches and sensors. Additional discharge circuits are also required for avoiding overcharge before the brake. Thus the whole system becomes complicated, moreover, due to the high price of ultra-capacitor pack; the cost of the controller becomes high for this approach [15]. In some cases, a bidirectional DC-DC power converter is used for boosting control in regenerative braking [15] [18]. Since the back electromotive force (BEMF) is much lower than the battery's terminal voltage, it needs to be boosted for charging the battery pack [35][36].

All those conventional approach increase the cost and the size of the system and cause extra power losses. So those systems are not suitable for low cost lightweight electric vehicles having PMDC or BLDC motor. Hence, in this research, the primary goal was to develop a flexible and cost-effective efficient regenerative braking system for DC motors of lightweight electric vehicle's considering various driving conditions in a country like Bangladesh.

1.3 Research Objective

The aim of this research is mainly to design and develop a cost effective simplest regenerative braking system for battery-operated electric vehicles (BEV) of two and three wheelers.

The main objectives of this research can be summarized as:

- To propose the design of a new method of regenerative braking system.
- To analyze the efficiency of the proposed system and compare it with the conventional system,
- To reduce the total complexity to make the system more efficient, robust and compact in size with simpler open loop control.

The successful implementation of this work can explore the possibility of regenerative braking for the battery driven motor operated vehicle and thus enhance the energy efficiency and stability of the vehicle system.

1.4 Outline of the Thesis

This thesis is divided into chapters for presenting a structured view of the developed work. In this introductory chapter the main purposes and motivations of the work are presented with the current state of the problem.

Since this thesis develops a regenerative braking system of low cost electric vehicle having Dc motor, Chapter 2 describe the proposed regenerative braking method and the related theoretical analysis based on PMDC and BLDC motor. Also this chapter elaborately explains the experimental setup electrical and mechanical construction that is used for the verification of proposed method.

Chapter 3 describes the key parameters that have to measure using the experimental setup. All the data measurement parts are described step by step in this chapter.

In Chapter 4 simulation and Analysis of the measured data are described. Also it shows the graphical comparison of the braking characteristic.

Chapter 5 describes the final results in a very constructive way to verify that the proposed systems are effective both for PMDC and BLDC motor base EVs.

Conclusion over the entire work that has been done is made in Chapter 5. This chapter also suggests the possible future opportunities and scopes of this study.

CHAPTER 2

Proposed System and Experimental Setup

2.1 Introduction

In this chapter, the proposed regenerative braking system for Dc motor will be discussed based on relevant theoretical concept. After that part, there will be an elaborate discussion about the experimental setup or prototype model that was used for the verification of the proposed braking method. Bothe proposed method and experimental setup was discussed with respect of permanent magnate DC (PMDC) motor and brushless DC (BLDC)motor. Finally, what kinds of perimeter we have to observe and why, was explained in this chapter.

2.2 The Proposed Regenerative Braking System

Regenerative braking of the DC motor can be achieved by applying different voltage across motor input terminal. This new method does not require complex switching technique based DC-DC converter but need to use only a low cost rotary mechanical switch and a battery bank from where rotary mechanical switch will select different voltage based on brake pedal position. Thus proposed braking system of DC motor is based on motor input terminal voltage control method. Figure 2.1 illustrates the concept of proposed braking method using rotary mechanical switch and a battery bank for EV's having DC motor.

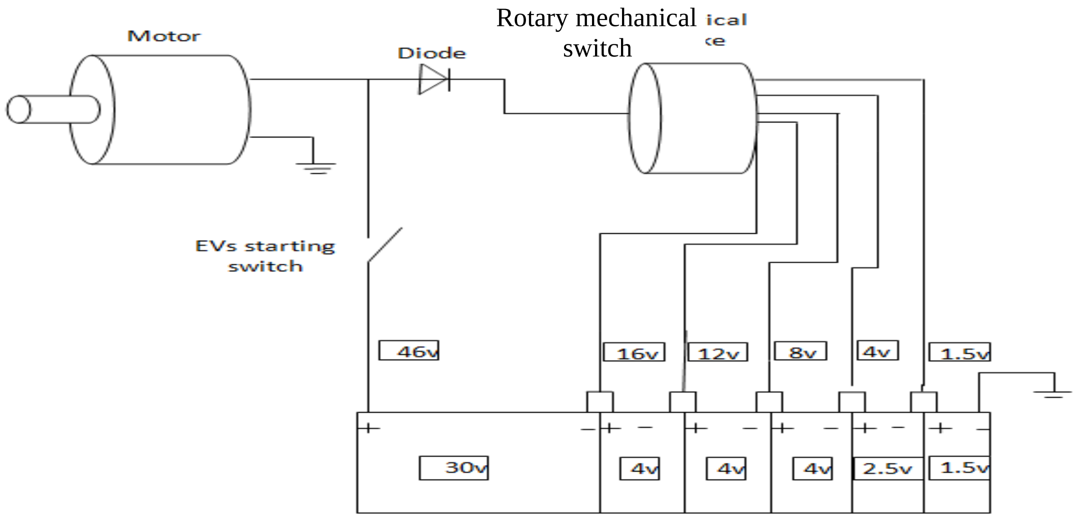


Fig. 2.1 The circuit diagram for proposed braking system

2.2.1 Theoretical Analysis of Proposed Braking System

The speed of dc motor is controlled using variable armature voltage and rotational speed is proportional to motor terminal voltage [29] [30]. High voltage will generate high rotational speed and low voltage will low speed. Two different armature voltages V_{a1} and V_{a2} will be considered. Those voltages will generate two different speeds N_1 and N_2 RPM simultaneously. If $V_{a1} > V_{a2}$ then $N_1 > N_2$ also. Now if a motor feed with V_{a1} voltage then its RPM will be N_1. During this running condition if the motor armature voltage V_{a1} is changed to V_{a2} using different Battery cell then motor will experience a braking torque T_b until its speed reduced to N_2. For this braking torque motor will works as a generator (Regenerative mode) and charge the battery cell (Which voltage is V_{a2}) until motor achieve the speed N_2. This braking torque T_b is proportional to difference of rotational speed $N_1 - N_2$ and the storage energy of battery during charging time is also proportional to $N_1 - N_2$. Basically here the extra rotational or kinetic energy is converted into electrical energy and return back to the system. Using this technique, a simple and effective regenerative braking system can be developed which is proposed in this research.

If mathematically express the above discussion then we will have,

$$N_1 \propto V_{a1} \tag{2.1}$$

$$N_2 \propto V_{a2} \tag{2.2}$$

And

$$T_{b2} \propto N_1 - N_2 \tag{2.3}$$

At equation (2.3) T_{b2} is the braking torque at V_{a2}voltage when motor armature voltage shifted from V_{a1} to V_{a2} where $V_{a2} < V_{a1}$.

From equations (2.1) and (2.2) it is clear that

$$N_1 - N_2 \propto V_{a1} - V_{a2} \tag{2.4}$$

Using equations (2.3) and (2.4)

$$T_{b2} \propto V_{a1} - V_{a2} \tag{2.5}$$

Equation (2.5) indicates that, at motor higher armature voltage difference will create higher braking torque. Now let $V_{ra}$is a rated motor armature voltage. For braking if reflect on three (3) different voltages like V_{a1}, V_{a2} and V_{a3} where

$$V_{ra} > V_{a1} > V_{a2} > V_{a3} \tag{2.6}$$

Then braking torques will act like

$$T_{b3} > T_{b2} > T_{b1} \tag{2.7}$$

In equation (2.7) T_{b1} is the braking torque when motor armature voltage shifted from V_{ra} to V_{a1} and similarly T_{b2} , T_{b3} for V_{ra} voltage to V_{a2} and V_{a3} voltage respectively .Higher braking torque means higher deceleration of vehicles and lower the braking time required to stop the vehicle. So if t_1, t_2 and t_3 are the braking time during regenerative braking for V_{a1}, V_{a2} and V_{a3} armature voltage respectively then from equation (2.7) it is cleared that

$$t_1 > t_2 > t_3 \tag{2.8}$$

During generator action of motor, as generated voltage of armature is directly proportional to motor rotational speed .so motor armature voltage V_{ra} will represent the characteristics of motor rotational speed.

2.3 Regenerative Braking of PMDC motor Based on Proposed method

Based on proposed method, by applying different armature voltage regenerative braking can be achieved for PMDC motor. The PMDC motor is similar to an ordinary D.C. shunt motor except that its field is created by permanent magnets instead of salient-pole wound-field structure.

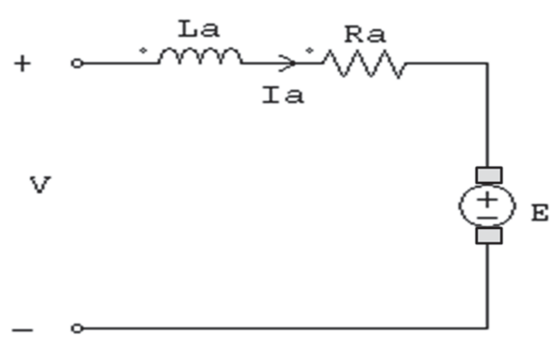


Fig. 2.2 Circuit diagram of Permanent magnet DC motor.

Figure 2.2 shows the equivalent circuit of PMDC motor. The common basic two equations of PMDC motor are [30]

$$E = K \times \emptyset \times \omega \tag{2.9}$$

$$T = K \times \emptyset \times I_A \tag{2.10}$$

I_A = armature current (amps)

$\emptyset$ = field flux per pole (Weber)

E = Back E.M.F voltage (volts)

ω = angular speed of dc motor (rad/sec)

K = constant that relates to construction of dc motor

T = induced torque (N.m)

R_a= armature resistance (Ω)

L_a = armature inductance (H)

Armature current is given by

$$I_A = \frac{\mathrm{V-E}}{\mathrm{Ra}} \tag{2.11}$$

In equation (2.11) V = motor armature voltage.

Now rotational speed of PMDC is proportional to motor armature voltage and Speed is controlled by applying variable armature voltage [30]. Let us consider two different armature voltages V_1 and V_2 . Those voltages will generate two different speeds N_1 and N_2 RPM and two back E.M.F voltages E_1 and E_2 simultaneously. If $V_1 > V_2$ then also $N_1 > N_2$ and from equation (2.9) $E_1 > E_2$. Now if a motor feed with V_1 voltage then its speed will be N_1 RPM. During this running condition if we change the motor armature voltage V_1 to V_2 using different Battery cell then $E_1 > V_2$ and based on equation (2.11) $I_A < 0$ that means motor will work as a generator (Regenerative mode) and charge the battery cell (Which voltage is V_2) until motor achieve the speed N_2 and back E.M.F E_2. Now based on equations (2.10) and (2.11) $T < 0$ which indicates motor will experience a braking torque

T during this regenerative mode and comparative to difference of rotational speed. This extra rotational or kinetic energy is converted into electrical energy and return back to the battery system. Based on this different armature voltage technique an effective regenerative braking system of PMDC motor can be developed [32].

Now it's essential to identify some key parameters of braking and their conditions for experimental verification of proposed method. In this research armature current I_a, braking torque T_b and braking time t are considered. Now based on section II let V_a is a rated armature voltage and Ira, Tra and Era are the rated armature current, Torque and Back E.M.F respectively for this PMDC motor .For regenerative braking if focus is on three different voltages like V_1, V_2 and V_3 where

$$V_a > V_1 > V_2 > V_3 \tag{2.12}$$

Then back E.M.F $E_{ra} > V_1 > V_2 > V_3$ and based on equations (2.10) and (2.11) armature current and braking torques will be negative and act like

$$I_{a1} > I_{a2} > I_{a3} \tag{2.13}$$

$$T_3 > T_2 > T_1 \tag{2.14}$$

In equations (2.13) and (2.14) I_{a1}, T_1 is the braking current and torque when motor armature voltage shifted from V_a to V_1 and similarly I_{a2}, T_2 and I_{a3}, T_3 for Va voltage to V_2 and V_3 voltage respectively .Higher braking torque will create higher deceleration of vehicles and required lower braking time to stop the vehicle. So if V_1, V_2 and V_3 armature voltage require t_1, t_2 and t_3 braking time respectively during regenerative braking then from equation (2.14) it is cleared that

$$t_1 > t_2 > t_3 \tag{2.15}$$

2.3.1 Experimental Setup for Proposed Braking of PMDC Motor

An experimental setup is used to verify this proposed technique. This is actually a simulator of electric vehicles driven by PMDC motor. Setup consists of a PMDC motor, one flywheel, battery bank, mechanical braking system, electrical brake (rotary mechanical switch), DC volt meter and DC ammeter.

2.3.1.1 PMDC Motor

Figure2.3 shows the PMDC motor used in this research. Originally is a DC geared motor but we remove the gear box and did some modification in such a way to made in computable to attached with the flywheel considering the mechanical frame we have used to attached the motor and flywheel. shaft The specification of this motor are as follows.

Rated Voltage: 48V

Rated Current: 23.0A

Rated Speed: 1800RPM

Fig. 2.3: PMDC Motor

2.3.1.2 Flywheel

To harness the energy from the braking system, the weight is attached as flywheel. The weight of the flywheel is 2Kg. This is used to store kinetic energy which will be returned to the supply as electrical energy by the regenerative braking system.

Fig. 2.4: Flywheel used for the setup.

2.3.1.3 Battery bank and Mechanical Brake

Battery bank (Multi cell batteries) allows us to select different armature voltage through electrical brake (rotary mechanical switch) and calculation of energy regeneration.

For mechanical brake, a conventional braking pad system is attached on the brake holder. This mechanical braking system is used in this research to take mechanical braking characteristics data. This will allow us to compare the proposed regenerative braking with the mechanical braking of the experimental setup. Figure 2.3 shows the battery bank and Mechanical Brake pad system that is used.

Fig. 2.5: Battery Bank (Multi cell batteries) and Mechanical Brake pad system.

2.3.1.4 Rotary Mechanical Switch

The rotary mechanical switch that means the electrical brake consists of a brake pedal, selector pin and contact leads. Battery bank is directly connected with contact leads of electrical brake. Based on the brake pedal position, the electrical brake will select different voltage from the battery bank and feed it to the motor armature.

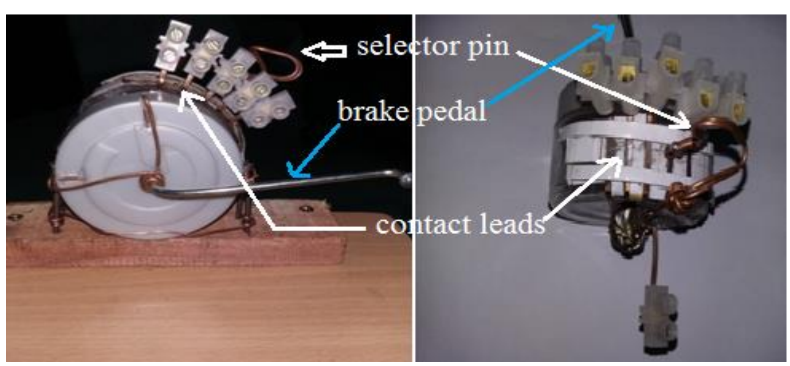


Fig. 2.6: Electrical brake of EVs (rotary mechanical switch).

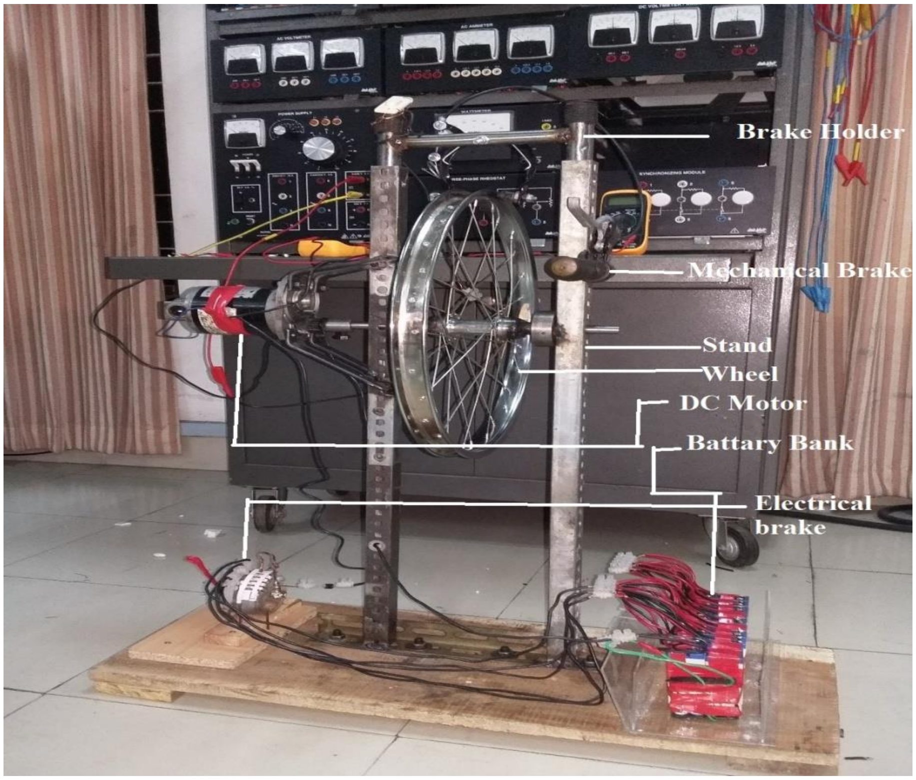


Fig. 2.7 Experimental Setup of PMDC motor based Proposed Braking.

Figure 2.6 and Figure 2.7 shows the construction of the newly designed electric brake and the actual structures of the experimental setup, respectively. The circuit diagram of this experimental setup is the same as that was illustrated in figure 2.1.

2.4 Regenerative Braking of BLDC motor Based on Proposed method

Based on proposed method, regenerative braking of BLDC motor can be achieved by applying different stator voltage [33]. The BLDC motor retains the characteristics of a PMDC motor [35] only commutation is done electronically. Figure1 shows the equivalent circuit of Y –connected 3-phase BLDC motor.

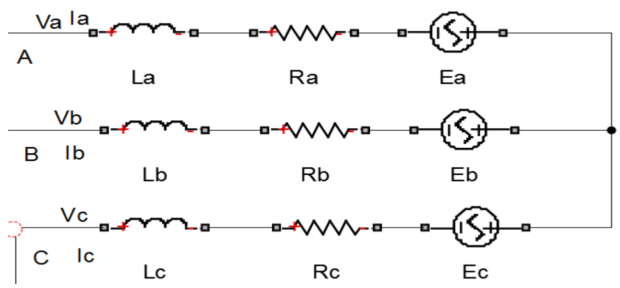


Fig.2.8 Circuit diagram of Brushless DC (BLDC) motor.

The common basic equations of BLDC motor for different terminals are [16]

$$V_a = I_a.R_a + L_a\frac{dI_a}{dt} + E_a \tag{2.16}$$

$$V_b = I_b.R_b + L_b\frac{dI_b}{dt} + E_b \tag{2.17}$$

$$V_c = I_c.R_c + L_c\frac{dI_c}{dt} + E_c \tag{2.18}$$

In Steady-state condition equation (2.16) will be (for simplicity considering only phase a)

$$V_a = I_a.R_a + E_a$$

$$I_a = \frac{Va - E_a}{Ra} \tag{2.19}$$

The back EMF voltages are functions of the rotor mechanical speed and motor torque are functions of stator phase current. So their equations are

$$E_a = K_e \times \emptyset \times \omega \tag{2.20}$$

$$T_a = K_t \times \emptyset \times I_a \tag{2.21}$$

R_a, R_b, R_c= Each Phase Stator resistance (In ohms)

L_a, L_b, L_c =Each Phase Stator inductance (in henry)

I_a, I_b, I_c = Each Phase Stator phase current (in ampere)

V_a , V_b , V_c = Each Phase Stator phase voltage (in volts)

E_a, E_b, E_c = Each Phase Back EMF voltage (in volts)

K_e= Constant of Back EMF

T_a = Motor developed Torque in N-m

K_t= Torque Constant

ω = Rotor speed

$\emptyset$ = flux per pole (Weber)

Back E.M.F of BLDC is proportional to motor armature or rotor Speed. Let consider motor is running at rated speed N RPM and create a back E.M.F voltages E. During this running condition if motor stator terminal feed with a voltage V_t from battery cell where $V_t < E$. then based on equation (2.19) $I_A < 0$ that means motor will works as a generator (Regenerative mode) and charge the battery cell (Which voltage is V_t) until motor achieve a speed N_f and back E.M.F E_f where $E_f = V_t$. Now based on equations (2.19) and (2.21) $T < 0$ which indicates motor will experience a braking torque during this regenerative mode and from equation (2.20) its comparative to difference of rotational speed N and N_f. This extra rotational or kinetic energy is converted into electrical energy and return back to the battery system. So an effective regenerative braking system of BLDC motor can be developed based on different stator terminal voltage technique which is proposed in this research.

Let V_{rs} is a rated stator voltage and I_{rs}, T_{rs} and E_{rs} are the rated stator current, Torque and Back E.M.F respectively for this BLDC motor. For regenerative braking if stator voltage at A, B, C phase shifted from V_{rs} to V_{b1} and V_{rs} to V_{b2} , V_{b3} respectively where $E_{rs} > V_{b1} > V_{b2} > V_{b3}$ then based on equation (2.19) lower stator voltage will create higher braking current and based on equation (2.21) higher braking current will create higher braking torque. On the other hands higher braking torque will create higher deceleration and required lower braking time to stop the vehicles. So during regenerative braking lower braking time can be achieved by applying lower stator voltage. Finally, theoretical relationship of braking current, torque and required braking time at different braking condition are same as equations (2.13), (2.14) and (2.15) respectively.

2.4.1 Experimental Setup for Proposed Braking of BLDC motor

To verify this proposed technique an experimental setup is used. This setup consists of a BLDC motor, one fixed flywheel of 36kg, three moveable flywheels of 15kg each, Multi cell Battery system, rotary mechanical switch, a Motor driver, a 3phase diode rectifier, DC volt meter and a DC ammeter. Actually this test setup is a simulator of electric vehicles driven by PMDC motor.

2.4.1.1 Multi cell Battery system (Battery bank)

Multi-cell battery system (Battery bank) allow applying a different voltage to BLDC motor terminal through rotary mechanical switch (electrical brake) and calculation of energy regeneration that can be restored. The main battery bank consists of 4 cells, each cell having 12 volts to provide 48V to the system for motor starting and 12V and 24V during braking. Also, a secondary battery bank composition of 6V, 4V and 1.5V battery cells was used to apply extra-low voltage to the motor terminal during braking.

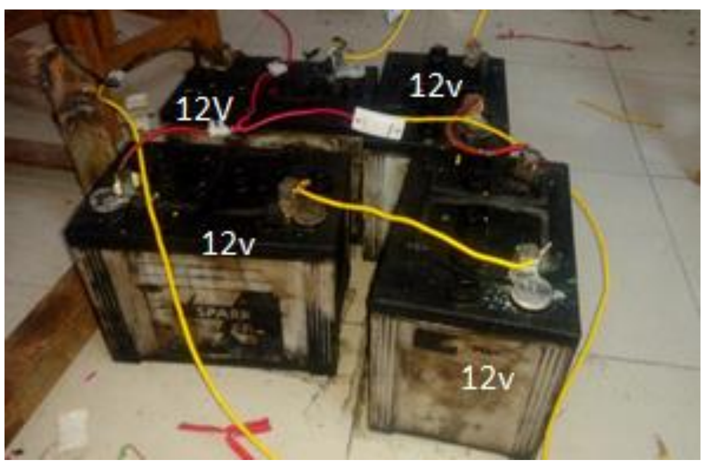


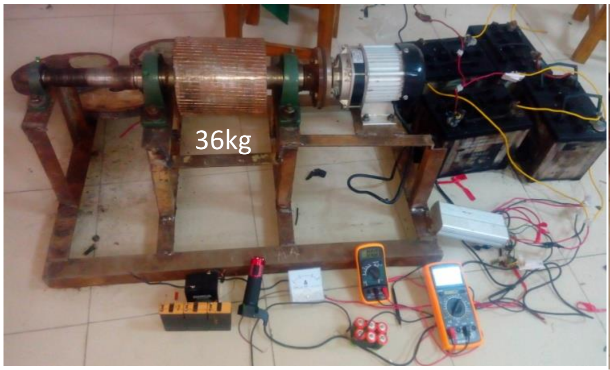
Fig.2.9 Main battery bank.

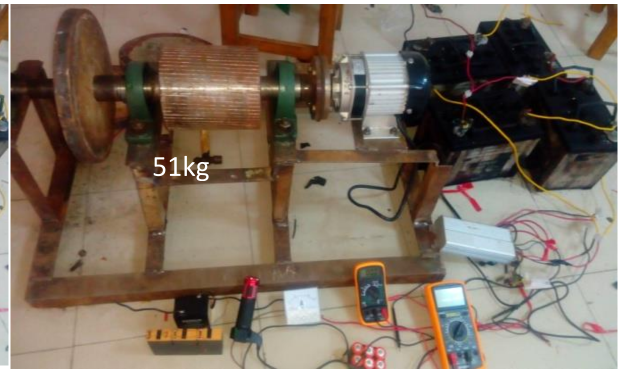
Fig.2.10 Secondary battery bank.

This various voltage level availability on the experimental setup allows us to analyze the proposed regenerative braking characteristics to identify the practical braking voltage needed for the desired braking. Figure 2.9 and figure 2.10 shows the battery setup used in this research.

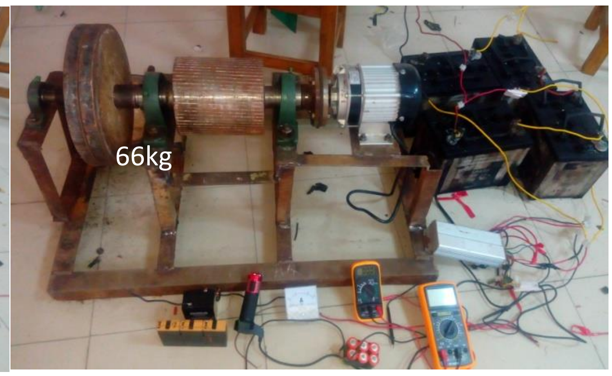
2.4.1.2 Flywheel and Mechanical Frame

To harness the energy from the braking system, the weight is attached as flywheel. In this experimental setup total 4 flywheels are used. one fixed flywheel of 36kg, three removable flywheels of 15kg each. This experimental setup was designed such a way that we can analyze the braking characteristics by changing the loading condition. The mechanical iron frame support BLDC motor shaft to couple with a shaft having 36kg fixed flywheel through two clamps. Left side of the 36kg flywheel shaft is extended enough to hold three 15kg flywheel all together. Most left side of the iron frame there is an arrangement to attach another iron column attached with a 3rd clamp to reinforce the shaft during the extra load or flywheel needed to be attached with the shaft. This load changing mechanism and 3 removable flywheels allow us to do the experiment of proposed braking with 4 different mechanical loading conditions. The possible mechanical loadings are 36kg, 51kg, 66kg and 81kg. Figure 2.11 ‘a’ ‘b’ ‘c’ and ‘d’ clearly shows the discussed mechanical construction and flywheel combination used in this research.





(a) (b)



(c) (d)

Fig. 2.11 Mechanical Construction of BLDC Motor Based Experimental Setup.

2.4.1.3 BLDC Motor

The ratings of the motor used in this research are 500 W and 48 V. Figure 2.8 show the BLDC motor that is used in this research.

Fig. 2.12 BLDC Motor.

2.4.1.4 Motor Driver

In the Figure 2.13 the BLDC motor driver unit is shown. It is basically a three phase inverter with necessary signal conditioning units. Different wirings are available for proper operation and connections. This unit is also directly connected with the battery. Additionally, the output of the driver goes to the motor.

Fig. 2.13 BLDC Motor Driver.

Finally, the construction and use of rotary mechanical switch (Electrical Brake) proposed in this research are the same as discussed in section 2.3.1.3. Also, a 3phase diode rectifier circuit is used in this research as the BLDC motor generates 3-phase back E.M.F during the regenerative braking mode. It is necessary to rectify the back E.M.F to transfer electrical energy from the motor to the battery. The actual constructions and the circuit diagram of the proposed experimental setup are illustrated in figure 2.14 and figure 2.15 respectively.

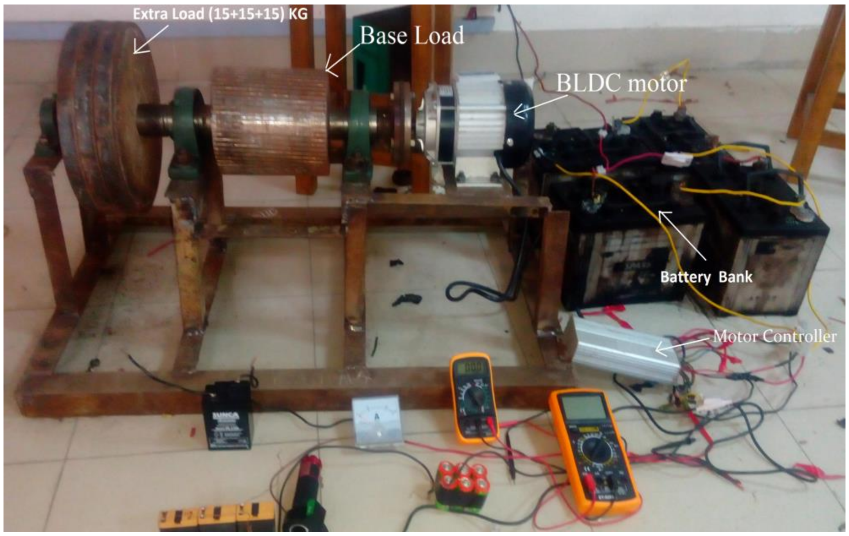


Fig.2.14 Experimental Setup for Proposed Braking of BLDC motor.

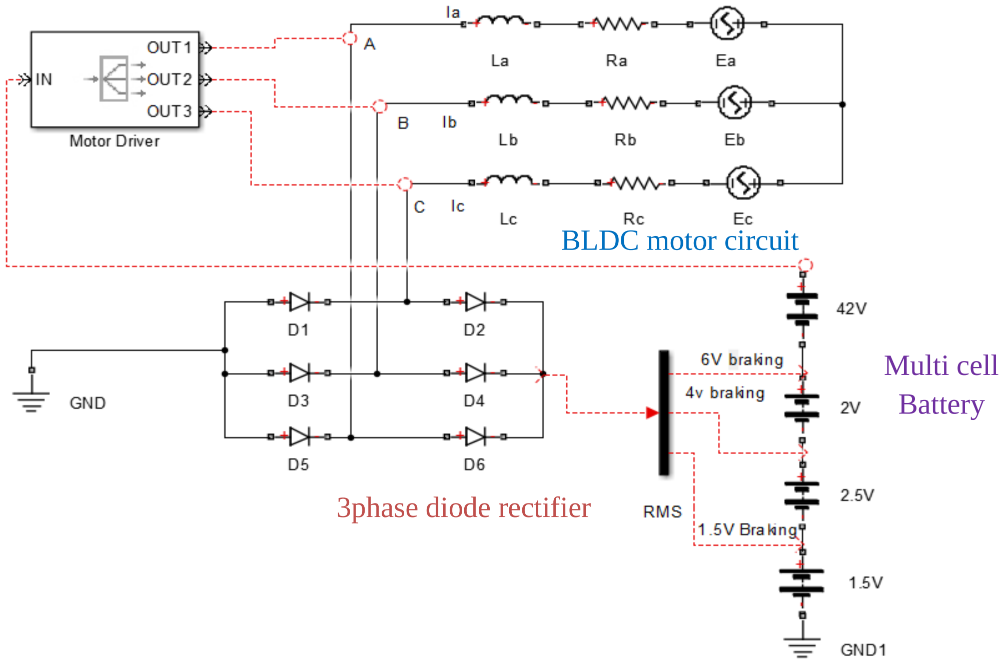


Fig. 2.15 Circuit diagram of Experimental setup of Brushless DC (BLDC) motor.

2.5 Key Parameters for Experimental Verification of Proposed Braking

For experimental verification of the proposed braking method, it's essential to identify some key parameters. After analyzing the proposed regenerative braking for BLDC motor and for PMDC motor, stator or armature current, back EMF, braking torque and required time for braking are considered as key parameters of braking characteristics. So using the experimental setup, those parameters are measured during regenerative braking at the different terminal voltage and loading conditions.

CHAPTER 3

Experimental Braking Characteristics Data of Proposed System

3.1 Braking Characteristics Data of PMDC Motor

Three different armature voltages V_1=8V, V_2=4V, and V_3=1.5V, are taken to feed the PMDC motor during braking for experimental verification when the motor is running at rated armature voltage V_a= 48 V.

3.1.1 Current consumption of PMDC motor based setup

Whenever a motor is started initially, it takes a high current, which eventually lowers down by armature reaction. Then, it takes current according to its steady-state condition. This high amount of current which is needed initially for a motor during starting is called starting current. High starting current means high starting power loss. For a particular vehicle starting power loss is a big concern. In data table 3.1 represent this characteristic.

Table 3.1: Current consumption of Experimental setup

Armature Current (A)	Time (S)
5.15	0.09
3.33	0.50
1.8	1.00
1.4	1.50
1.1	2.00
0.85	2.50
0.76	3.00
0.71	3.50
0.70	4.00

3.1.2 Mechanical Brake of PMDC Motor Based Setup

To analyze the effectiveness of the proposed braking, we need to compare it with the conventional mechanical braking system. Based on the experimental setup, we have considered two types of brake for mechanical brake analysis: medium brake and hard brake. To determine the mechanical brake characteristics, we have observed the back EMF and time as back EMF represents the deceleration of the flywheel. The data table for voltage against time for the medium brake and the hard brake is given in table 3.2 and 3.3.

Table 3.2: Back EMF Voltage during Mechanical braking (Medium)

Back EMF (V)	Time (S)
26.5	0.50
24.00	1.00
21.50	1.50
17.00	2.00
12.00	2.50
7.50	3.00
3.00	3.50
1.00	4.00

Table 3.3: Back EMF Voltage during Mechanical braking (Hard)

Back EMF (V)	Time (S)
28.5	0.15
14.3	0.30
2.2	0.45

3.1.3 Regenerative Braking Data of PMDC motor

Based on chapter two's discussion, armature currents and back EMF voltages are the essential perimeters that need to be observed during regenerative braking. Based on the proposed method, different voltages such as 1.5V, 4V, 8V, 12V, 16V are applied to the motor terminal to see the braking characteristics.

The experimental data of armature current and back EMF voltage during 4V, 8V, 12V, 16V, and 1.5V regenerative braking with respect to observation time are shown in table 3.4, 3.5, 3.6, 3.7 and 3.8.

Table 3.4: Current and voltage during 4V regenerative braking

Armature Current (A)	Back EMF (V)	Time (S)
-6.20	19.3	0.30
-3.19	8.00	0.55
-3.19	8.00	0.88
-0.54	6.30	1.05
-0.08	5.6	1.30
0	4.8	1.55
0	4.8	1.80
0	3.9	2.05

Table 3.5: Current and voltage during 8V regenerative braking

Armature Current (A)	Back EMF (V)	Time (S)
-3.86	27.8	0.17
-3.86	14.1	0.42
-2.52	14.1	0.67
-0.56	11.8	0.92
-0.98	10.6	1.17
0	9.7	1.92
0	7.8	1.67

Table 3.6: Current and voltage during 12V regenerative braking

Armature Current (A)	Back EMF (V)	Time (S)
-1.99	18.7	0.57
-0.56	16.6	0.82
-0.56	16.6	1.07
-0.19	15.3	1.32
-0.05	14.2	1.57
0	13.2	1.82
0	12.3	2.07

Table 3.7: Current and voltage during 16V regenerative braking

Armature Current (A)	Back EMF (V)	Time (S)
-1.50	28.6	0.22
-0.98	22.6	0.47
-0.49	20.8	0.72
-0.21	19.3	0.97
-0.06	18.3	1.22
0	17.1	1.47
0	16.0	1.72

Table 3.8: Current and voltage during 1.5V regenerative braking

Armature Current (A)	Back EMF (V)	Time (S)
-8.89	15.1	0.21
-2.01	3.8	0.46
-0.21	0.52	0.71

3.2 Braking Characteristics Data of BLDC Motor

In the BLDC motor base experimental setup, three different stator terminal voltages 6V, 4V, and 1.5V, are taken to feed the BLDC motor to practically examine the braking current and braking time when the motor is running at a rated speed at a rated stator voltage of 48V.

3.2.1 Current consumption of BLDC motor based setup

The starting power loss is a big concern for electric vehicles for stop-and-go driving in urban areas. Because during starting motor will consume a high amount of current but it reduced to rated current based on the loading condition during running. So by observing the current consumption patterns of the experimental setup, we can calculate the starting and running power consumption which is essential in this research to estimate the efficacy of the proposed regenerative braking system considering the stop-and-go driving pattern. Measured current consumption data of the Experimental setup applying different loading like 36Kg, 51Kg, 66Kg, and 81Kg are shown in Table 3.9(a), 3.9 (b), 3.9 (c), and 3.9 (d), respectively.

Table 3.9: Current consumption of BLDC motor at different loading conditions

a

Current consumption at 36Kg Load	
Time (S)	Running current (A)
0	11.72
1	2.78
2	2.77
3	2.72
4	2.72
5	2.72

b

Current consumption at 51Kg Load	
Time (S)	Running current (A)
0	17.39
1.05	9.37
2.1	2.69
3.15	2.76
4.21	2.76
4.29	2.76

c

Current consumption at 66Kg Load	
Time (S)	Running current (A)
0	19.98
1.4	4.21
2.8	2.9
4.2	2.81
5.2	2.81
6.2	2.81

d

Current consumption at 81Kg Load	
Time (S)	Running current (A)
0	24
1.6	17.89
3.38	3.34
5.07	2.89
6.76	2.89
7.76	2.89

3.2.2 Regenerative Braking Data of BLDC motor

Based on the proposed method, the regenerative Braking current of the BLDC motor-based setup is observed to calculate the energy regeneration during braking. Also, the Back EMF of the BLDC motor is observed to analyze the braking characteristics of the proposed method as the Back EMF represents the deacceleration of the flywheel. Experimental data of Braking Current and Back EMF at different loading conditions for 6V, 4V and 1.5V regenerative braking are presented in the following tables. Negative polarity indicates that current is returning back to the system during braking.

Table 3.10: Current and Voltage during 1.5V regenerative braking at 36Kg load

Time (S)	Armature Current (A)	Back EMF (V)
22.08	-35.0	11.6
22.69	-14.61	5.7
22.88	-4.61	5.6
22.99	-1.19	2.1
23.21	-0.29	1.7

Table 3.11: Current and Voltage during 1.5V regenerative braking at 51Kg load

Time (S)	Armature Current (A)	Back EMF (V)
14.86	-35	29.8
15.08	-32	15.4
15.61	-12.33	7.7
16	-3.82	3.6
17.08	-0.1	1.7

Table 3.12: Current and Voltage during 1.5V regenerative braking at 66Kg load

Time (S)	Armature Current (A)	Back EMF (V)
13.28	-35	31.4
14.12	-13	4.2
14.73	-1.15	2.8
15.17	-0.19	2.1
15.69	-0.15	1.8

Table 3.13: Current and Voltage during 1.5V regenerative braking at 81Kg load

Time (S)	Armature Current (A)	Back EMF (V)
43.32	-35	16.4
44.18	-22	6.6
44.49	-14.14	4.6
45.98	-0.49	1.9
46.29	-0.17	1.8

Table 3.14: Current and Voltage during 4 V regenerative braking at 36Kg load

Time (S)	Armature Current (A)	Back EMF (V)
15.22	-35	28.9
15.67	-13.33	12.7
15.89	-13.98	5.9
16.05	-1.48	5.8
16.62	-0.01	4.4

Table 3.15: Current and Voltage during 4V regenerative braking at 51Kg load

Time (S)	Armature Current (A)	Back EMF (V)
11.92	-35	30.1
12.57	-15.31	13.9
13.09	-5.28	6.3
13.97	-0.32	4.8
14.22	-0.03	4.6

Table 3.16: Current and Voltage during 4V regenerative braking at 66Kg load

Time (S)	Armature Current (A)	Back EMF (V)
12.39	-34	22.2
13.08	-15.1	11
13.46	-7.88	8.4
14.15	-1.58	6
15.19	-0.23	4.7

Table 3.17: Current and Voltage during 4V regenerative braking at 81Kg load

Time (S)	Armature Current (A)	Back EMF (V)
14.09	-34	23.4
15.28	-19.88	8.7
15.74	-5.59	7.4
16.88	-3.08	6.5
17.39	-0.19	5

Table 3.18: Current and Voltage during 6V regenerative braking at 36Kg load

Time (S)	Armature Current (A)	Back EMF (V)
36.70	-22	24.8
36.88	-18	25
37.09	-8.11	10.7
37.39	-0.85	7
38.19	-0.01	6.5

Table 3.19: Current and Voltage during 6V regenerative braking at 51Kg load

Time (S)	Armature Current (A)	Back EMF (V)
2.36	-35	30.7
2.79	-15.18	11.4
3.18	-5.57	8.8
3.99	-1.82	7.5
4.99	-0.03	6.8

Table 3.20: Current and Voltage during 6V regenerative braking at 66Kg load

Time (S)	Armature Current (A)	Back EMF (V)
12.39	-34	22.2
13.08	-15.1	11
13.46	-7.88	8.4
14.15	-1.58	6
15.19	-0.23	4.7

Table 3.21: Current and Voltage during 6V regenerative braking at 81Kg load

Time (S)	Armature Current (A)	Back EMF (V)
52.00	-35	21.5
52.88	-14.84	14.4
53.55	-5.5	9.4
54.54	-1.98	7.9
55.54	-0.21	7

CHAPTER 4

Simulation and Analysis of Proposed Braking Characteristics

4.1 Simulation and Analysis of PMDC motor Braking Characteristics

In this section equations (2.13), (2.14) and (2.15) are observed based on propose technique using the Experimental numerical data measured and simulation output. For identification of proposed braking condition mechanical braking characteristics of experimental setup are also observed.

4.1.1 Mechanical Braking characteristics

In mechanical braking system t_{mh}= 0.85s are considered as mechanical hard braking time for Experimental setup of PMDC motor. Same way t_{mm}=4.0s are considered as mechanical medium brake. That means the PMDC motor will decelerate within 0.85s during hard brake and 4.0s during medium brake. Motor generated armature voltage is observed to fine the mechanical brake characteristics because flywheel is directly connected with PMDC motor. Fig. 4.1 shows the mechanical hard and medium brake characteristics.

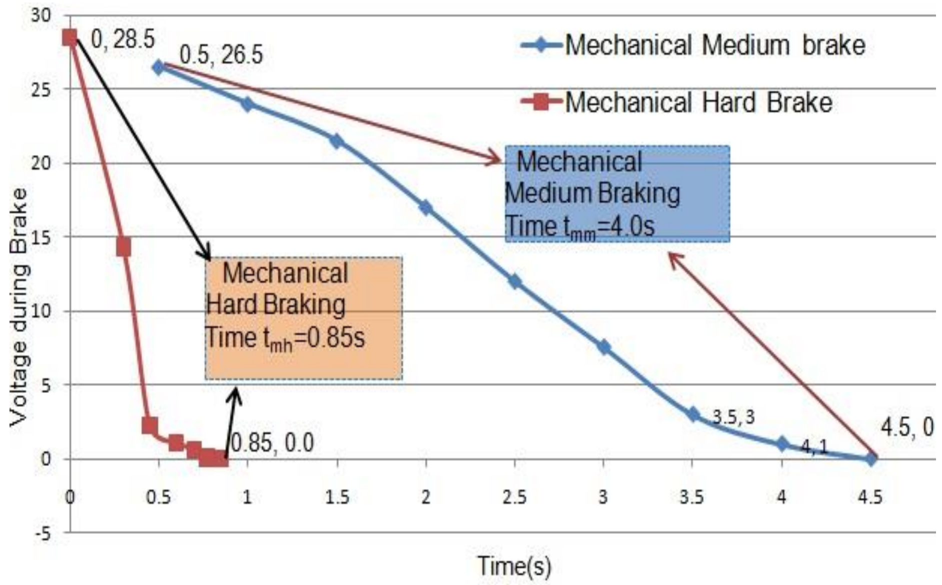


Fig. 4.1 Mechanical Brake Characteristics of Experimental Setup.

4.1.2 Proposed Regenerative Braking Characteristics

Regenerative braking of PMDC motor based on proposed method is presented in fig. 4.2. All figure is simulated based on numerical value taken from experimental setup. From fig. 4.2 it's clear that regenerative braking time during 8 volt armature voltage t_{rb8}=4.75s. Similarly, the estimated braking time for 4V and 1.5V armature voltage are t_{rb4}=2.75s and $t_{rb1.5}$=1.15s respectively. In fig.4.2 4V and 1.5V regenerative braking characteristics of PMDC motor are also presented.

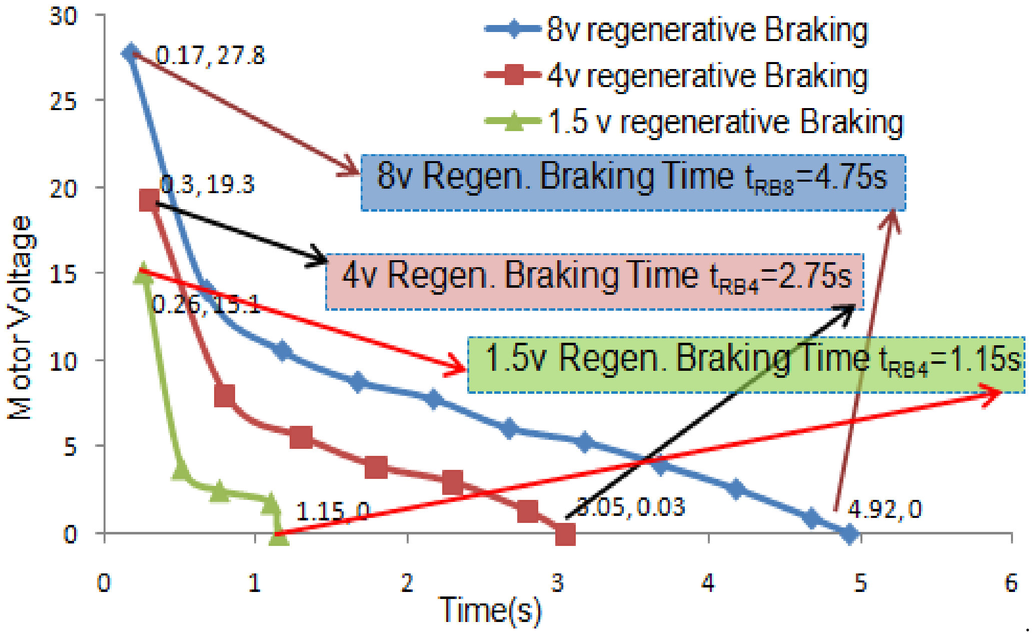


Fig. 4.2 Proposed Regenerative Braking Characteristics of PMDC Motor.

4.1.3 Comparison of mechanical and proposed braking

To justify the state of proposed regenerative braking, it's compared with mechanical braking system of experimental setup. Comparison shows that 1.5V armature voltage braking is comparative to mechanical hard brake and 8V braking with mechanical medium brake. Fig.4.3 and Fig.4.4 clearly shows those interpretations.

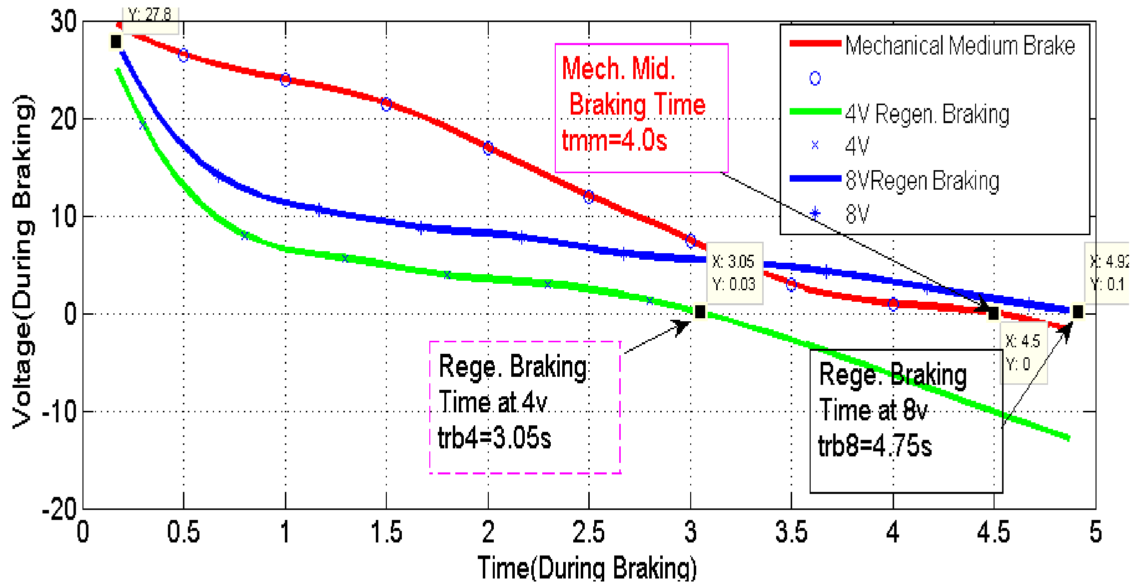


Fig. 4.3 Comparison with medium brake.

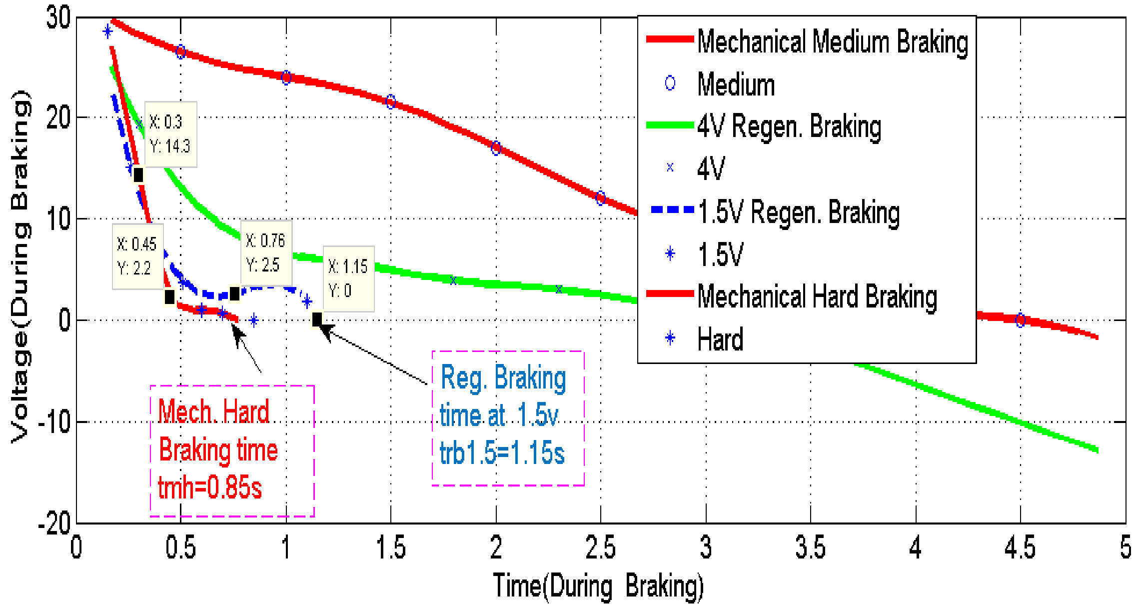


Fig. 4.4 Comparison with hard brake.

4.1.4 Current Consumption Characteristics of Experimental setup

Armature current consumption of PMDC motor is observed and numerical values are taken during normal running condition. This helps to characterize the current consumption of experimental setup and calculation of energy utilization. Here current consumption with respect to time is divided into two parts. One transient period where experimental setup takes high current with higher rate of change and another saturation period where current is low but constant. Fig.4.5 shows these observations.

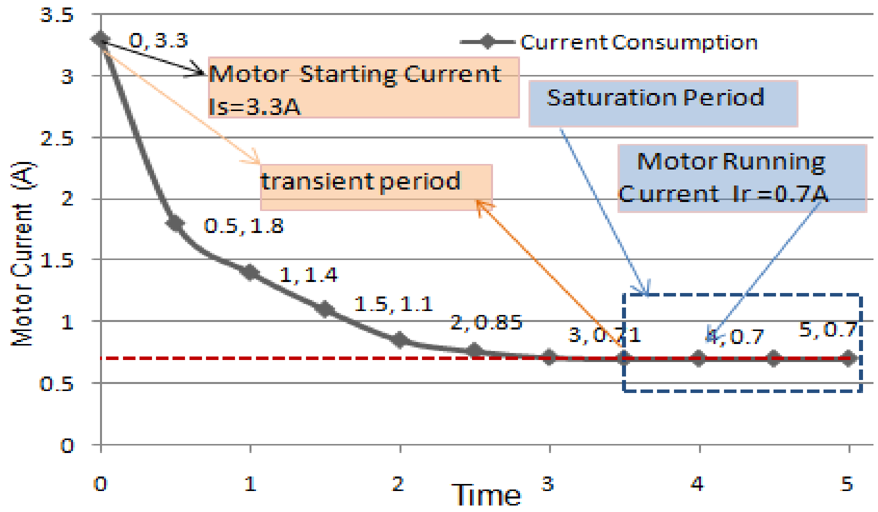


Fig. 4.5 Current Consumption Characteristics of Experimental setup.

4.1.5 Regenerative Braking Current Characteristics of PMDC Motor

Based on proposed method regenerative Braking or battery charging current of PMDC motor is also observed. Simulated numerical data are presented in fig. 4.6. In fig.4.6 braking current I_{st8} =-3.86A, I_{st4} =-6.2A and $I_{st1.5}$=-8.89A where I_{st8}, I_{st4} and $I_{st1.5}$ are braking current during 8V, 4V and 1.5V regenerative braking respectively. Negative polarity indicates that current will return back to the system during braking.

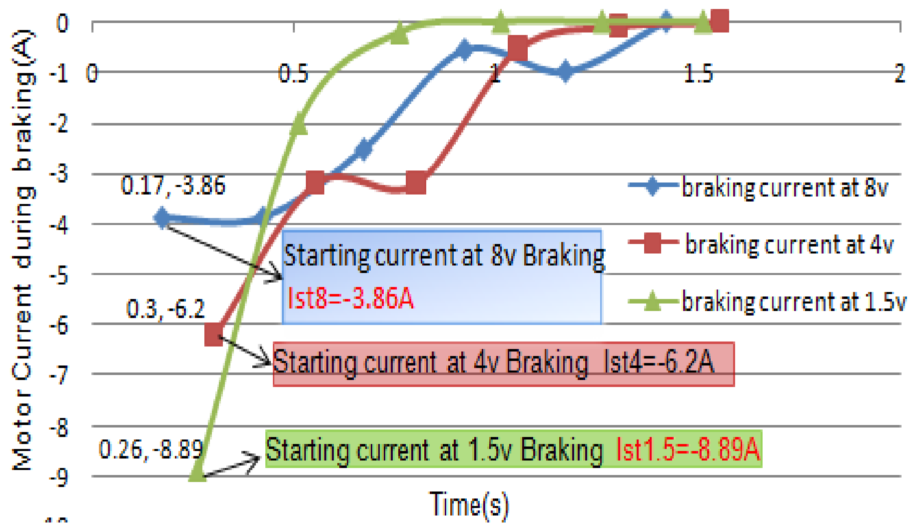


Fig. 4.6 Regenerative Braking current at 1.5V braking.

4.2 Simulation and Experimental Results of BLDC motor

This section contains the detail analysis of the proposed braking systems of BLDC motor. All the key parameters of braking characteristics like braking current, torque and required braking time at different braking conditions are analyzed using the measured experimental numerical data to verify that, practical braking system implemented based on proposed method satisfy the equations (2.13), (2.14) and (2.15) which was claimed after theoretical analysis of the proposed method. For clear understanding and visualization of the analysis different relationship graphs are simulated using the experimental data. Finally, the energy regeneration is calculated and compared with other braking system.

4.2.1 Regenerative Braking Current Characteristics of BLDC Motor

Based on proposed method regenerative Braking current or battery charging current of BLDC motor is also observed. Experimental numerical data are presented in fig.4.7. In fig.4.7 braking current I_{st6} = -22A, I_{st4} = -31.5A and $I_{st1.5}$= -35A where I_{st6}, I_{st4} and $I_{st1.5}$ are braking current during 6V, 4Vand 1.5V regenerative braking respectively. Negative polarity indicates that current will return back to the system during braking.

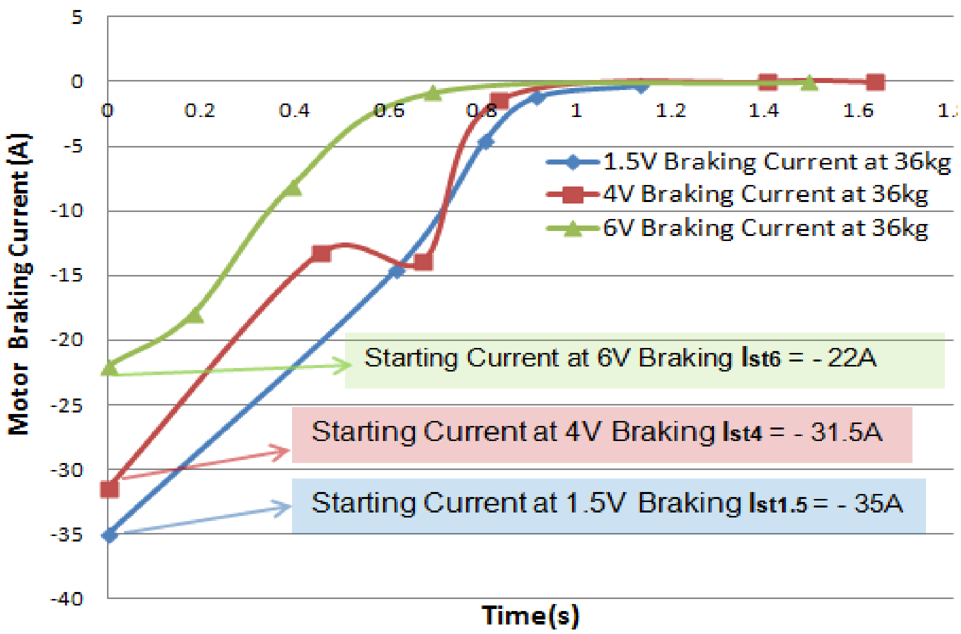


Fig. 4.7 Regenerative Braking current at 36Kg load

4.2.2 Proposed Regenerative Braking Characteristics

Regenerative braking characteristics can be represented by braking time required to stop the vehicles. Braking time of BLDC motor based on proposed method is presented in fig.4.8. All figures are simulated based on numerical value taken from experimental setup. From fig.4.8 it's clear that regenerative braking time during 6 volt stator voltage t_{rb6}=1.81s.

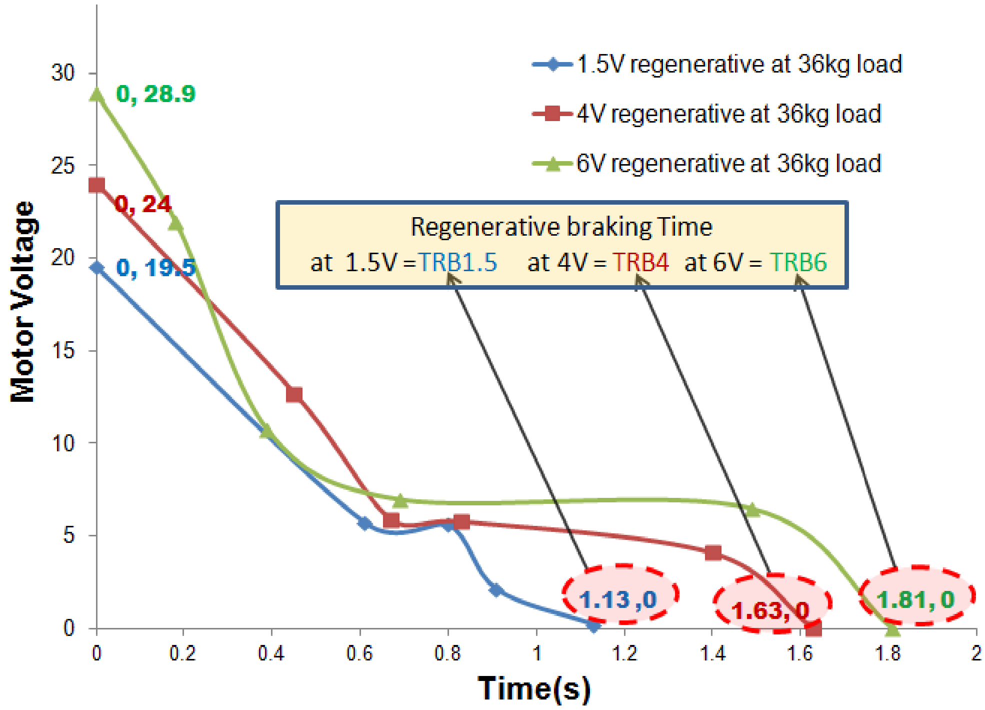


Fig. 4.8 Proposed Regenerative Braking Characteristics of BLDC Motor.

Similarly, the braking time for 4v and 1.5v stator voltage are t_{rb4}=1.63s and $t_{rb1.5}$=1.13s respectively. Based on the experimental data it can conclude that lower the applied stator voltage lowers the braking time. So different braking level like high, low and medium brake can be achieve through proposed regenerative braking system. Fig.4.8 clearly shows those interpretations. Braking condition for different loading is also observed. Experimentally 36Kg, 51Kg, 66Kg and 81Kg load are used to verify the loading effect on regenerative braking time for the same braking voltage.Fig.4.9 shows those observations.

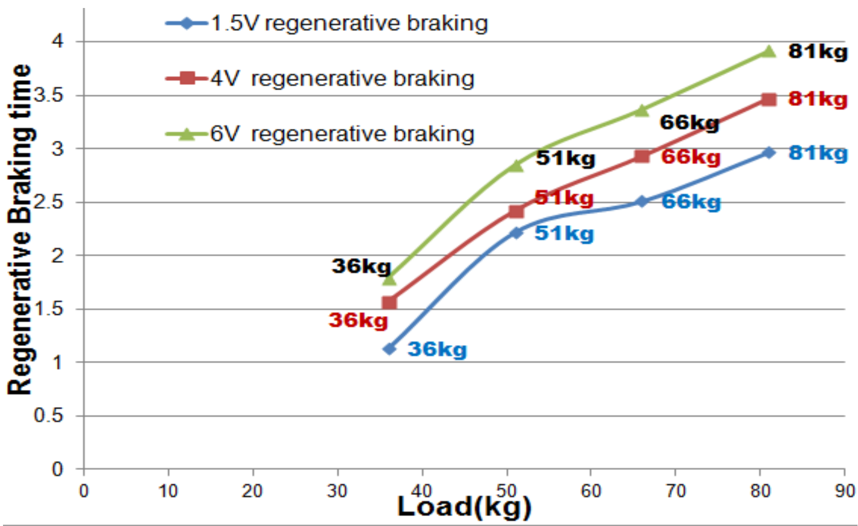


Fig. 4.9 Regenerative Braking time for different loading condition.

4.2.3 Current Consumption Characteristics of Experimental setup

Stator current consumption of BLDC motor for different loading conditions is observed and numerical values are taken during normal running condition. This observation helps to characterize the current consumption of experimental setup and calculation of energy utilization. Here current consumption is divided into two parts. One transient period where experimental setup takes high current with higher rate of change and another saturation period where current is low but constant. Fig.4.10 shows these observations.

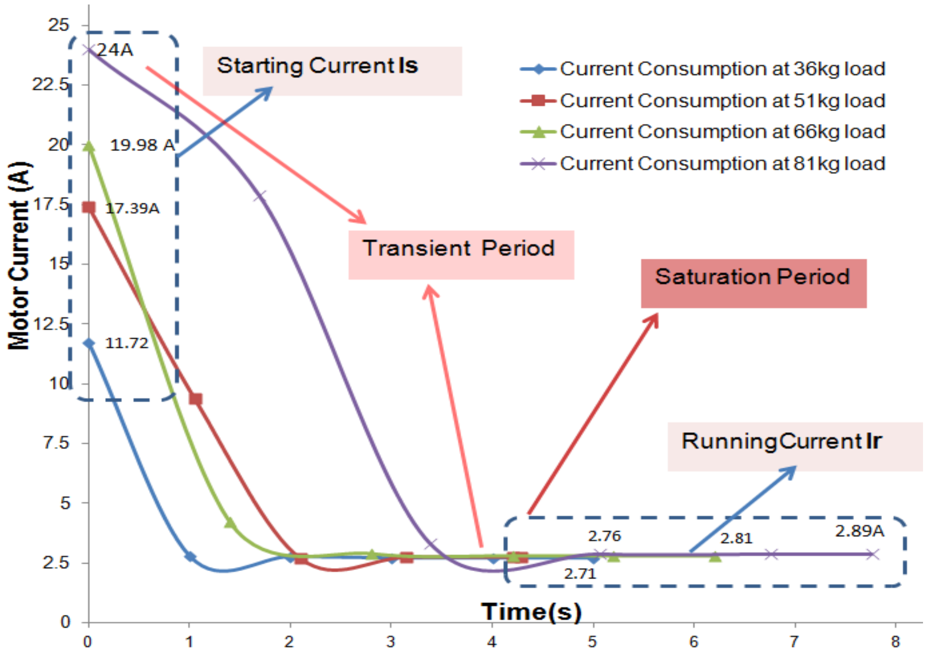


Fig. 4.10 Current Consumption Characteristics of Experimental setup for different load

CHAPTER 5

Result and Discussion

5.1 Result of PMDC Motor Based Proposed Braking System

In this section armature current I_a, braking torque T_b and braking time $t_,$ are defined as a key parameters following the equations (2.13), (2.16) and (2.15) respectively to prove that proposed method is feasible. From simulated figures fig.4.2 and fig.4.6 it's clear that proposed method is feasible because its follows the equation (2.15) for the regenerative braking time and equation (2.14) for braking current respectively.

That means $t_{rb8} > t_{rb4} > t_{rb1.5}$ and $I_{st8} < I_{st4} < I_{st1.5}$

Based on equation (2.10) and values of braking current, it's clear that proposed regenerative braking system also follows equation (2.13) for regenerative braking torque of PMDC motor.

Now for efficiency estimation, 1.5v regenerative braking are considered because most of the times vehicles use hard breaks. From the experimental data the calculated energy recovery during 1.5v braking is:

Power of regenerative Braking, $P_{RB1.5}$: 66.54W (average)

Energy of regenerative braking, $E_{RB1.5}$: 94.49J (average)

Same way after analyzing numerical data of current utilization of experimental setup the calculated powers consumed by the experimental setup are:

Power at transient period, P_t: 34.94W (average)

Power at saturation period, P_s: 21.49W (average)

Total Power, $P_T = P_t + P_s$= 56.43W (average)

Total Energy Used, $E_T =$ 220.64J (average)

From calculation it is very much clear that if a vehicle having proposed braking system using PMDC motor and does hard brake to stop and again starts to achieve rated velocity, throughout this situation vehicle will consume 220.64J energy and 94.49J energy will return back to the Battery.Fig.5.1 will clarify the energy consumption and regeneration of proposed braking for stop and go driving pattern in urban area. So the Efficiency of this proposed method is η = 42. 8254%. That means driving range based on proposed method will increase around 42.825% or 42.825% further than without regenerative braking and also around 16.485% more than the proposed regenerative braking system of series-wound brushed DC motors where efficiency is 26.34% [7]. So proposed system is efficient then the system proposed in [7].

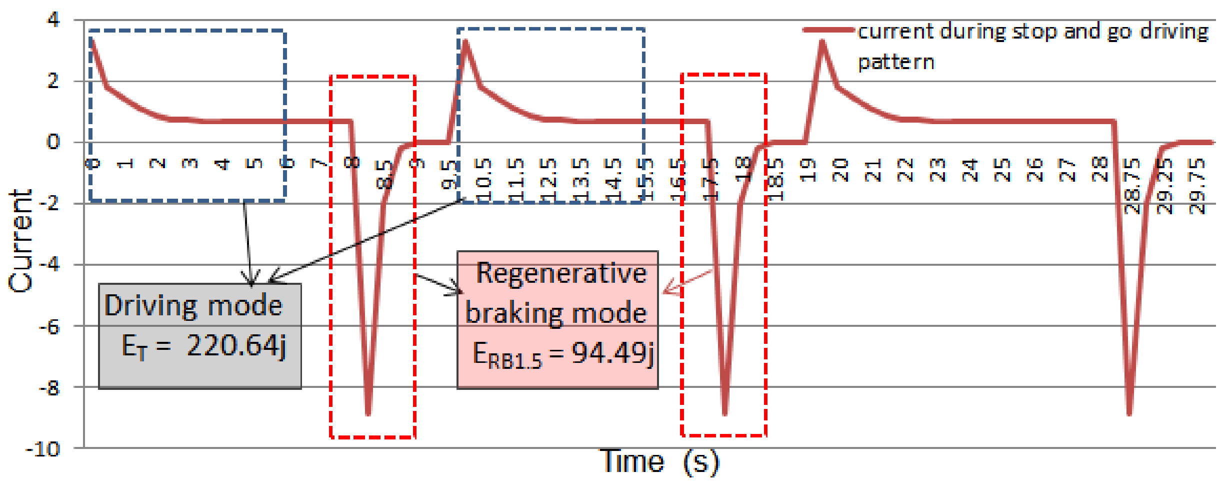


Fig. 5.1 Energy Consumption and Regeneration During stop and go driving pattern

5.2 Result of BLDC motor braking system

In this section experimental data of regenerative braking current and braking time for BLDC motor are analyzed from different aspect. Analysis proves that proposed regenerative braking method is feasible and effective then ultra-capacitor and boost converter based conventional braking system of BLDC motor.

For simplicity, 1.5V regenerative braking with 36kg load is considered for efficiency estimation. From the experimental data the calculated energy recovery during 1.5V regenerative braking with 36Kg load is:

Power of regenerative Braking, P_{RB} : 173.25 W (average)

Energy of regenerative braking, E_{RB}: 195.77 J (average)

Same way energy consumption of experimental setup with 36Kg load is calculated by analyzing the current consumption characteristics at 36Kg load. Table 5.1. shows this calculation.

Table 5.1: power and energy consumption of experimental setup at 36Kg load

Period	Average Power (W)	Average Energy (J)
During Transient period	211.28	422.569
During Saturation period	127.099	254.198
Total	338.379	678.767

From calculation, it is very much clear that if a vehicle with 36kg load has a proposed braking system using BLDC motor and do brake to stop and again start to achieve rated velocity, throughout this situation, the vehicle will consume 678.767J energy and 195.77J energy will return to the Battery. Fig.5.2 will clarify the energy consumption and regeneration of proposed braking for the stop-and-go driving pattern in urban areas. So the efficiency of this proposed method is 28.842%. That means the driving range will increase around 28.842% based on the proposed method. The proposed method is also comparative to the method proposed in [19] where efficiency is 20% and more efficient than the technique proposed in [36] having efficiency of 9.5%.

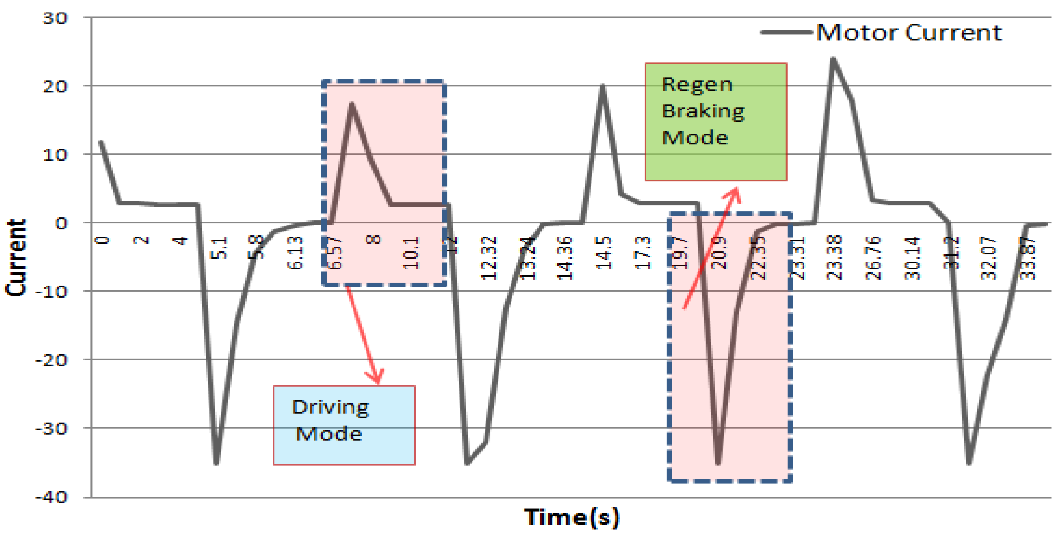


Fig. 5.2 Energy Consumption and Regeneration During stop and go driving pattern with different load

CHAPTER 6

Conclusion

6.1 Conclusion

In this thesis a cost effective regenerative braking system for DC motor based light weight electric vehicles (EVs) is developed. Currently most of light weight EVs does not include regenerative braking. In the first chapter the motivation and overview have been discussed to illustrate the reason of the thesis. A clear and broader discussion is given to point out the drawback of the conventional braking system. To include the conventional braking system in light weight EVs will increases the cost and the size of the overall system as conventional regenerative braking system use boost converter. Hence, a flexible technique, avoiding the use of boost converter is proposed and experimentally verified.

This research basically focused on two type of DC motor, one PMDC another BLDC. Firstly PMDC motor based simple but effective method of regenerative braking has proposed. Data has collected from experimental setup where the braking system allows us to do the brake based on proposed method. After simulation and analysis of experimental data, it's clear that the proposed method can enhance mileage by around 42.825% and also regenerative braking based on motor armature voltage control is more effective and efficient than the conventional method used for series-wound DC motor based regenerative braking system of EVs.

Secondly this research has also analyzed BLDC motor based regenerative braking using the proposed method. Simulated and analyzed result of experimental data shows that, proposed method can enhance mileage around 28.842% for BLDC motor based EVs. This research also proves that regenerative braking based on Stator voltage control is more effective and efficient than Ultra-capacitor and boost converter based braking systems. Finally, the proposed regenerative braking will make the light weight EVs convenient in Bangladesh by decreasing electricity consumption for charging the battery from supply as system allows charging the battery on the go while running on the road.

6.2 Future work and scopes

The regenerative braking system is experimentally verified in the laboratory. Moreover, the necessary data are gathered at some fixed loaded condition, while real scenario will be different as the loads will be variable at different cases. Additionally, this analysis is done for the motor used in electric rickshaw. However, in future, the analysis of regenerative braking of different higher rated vehicle can be carried out based on the proposed research work. Also, further research will focus more on designing the rotary selector switch proposed here instead of the converter and the battery lifetime or health condition for the proposed regenerative braking system. Particularly, it can be made commercially available to harness the braking energies to a greater extent. Hence, the exploration of this work at commercial aspect will be a lucrative area of research.

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