A STUDY OF REGENERATIVE BRAKING SYSTEM (RBS) INVOLVING MODIFIED BRAKE PEDAL FOR RETROFIT CONVERSION OF HYBRID ELECTRIC VEHICLE (HEV)

By

LEE KIEN YANG

FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
in Partial Fulfillment of the Requirements
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Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

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Dr. Nor Hisham b. Hamid
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

December 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Lee Kien Yang

ABSTRACT

Regenerative braking system has always been a very important feature in all hybrid and full electric vehicles since it helps to improve on fuel economy, as well as conserve energy efficiency. Unlike conventional vehicles which apply the friction brake system and contribute to the loss of the kinetic energy in the form of heat energy and friction, regenerative braking can conserve the energy lost during braking. Issue is addressed as to why this project is carried out. There is a lack of regenerative braking performance study for a bench-testing prototyping stage in retrofit conversion of hybrid electric vehicles. Also, the current solution to implement a regenerative braking system in existing vehicle part is costly. In this project, alternatives are first, explored to design brake pedal assembly to detect brake pedal movement for regenerative braking. In order to achieve this, a linear potentiometer is selected. This is followed with the design of a voltage follower circuit to produce stable output voltage to the motor controller. Then, configuration of the circuitry to the motor controller is learnt and set-up. Last part of the step covers the monitoring and experimentation of the performance for regenerative current by using the lab equipment. The bench-testing is done in free or zero-load condition. Results obtained showed a very little regenerative current being fed back into the battery when the brake pedal is exerted at its maximum, with respect to different motor speed run. Further work can be carried out to test the actual regenerative performance when the prototype is fully mounted into the vehicle.

ACKNOWLEDGEMENTS

The author understands that the success of this project would be impossible without the involvement and contributions from certain parties, organizations and individuals. Hence, the author would like to take this opportunity to express his deepest gratitude to them. First and foremost, the author would like to thank his supervisor, Dr. Nor Hisham b. Hamid for his continuous assistance, supervision and advise that he has given throughout the entire Final Year Project implementation. He has constantly provided guidance for every stage since the planning phase of the project until this dissertation has been completed.

Special thanks as well to the co-supervisor, Mr. Saiful Azrin b. Mohd Zulkifli for his guidance and patience in explaining thoroughly about the problems that were faced in the testing stage of the prototype. The author would also like to thank Dr. Nasreen Bt Badruddin, the FYP coordinator, for conducting several seminars and briefings to assist the FYP students as well as helping to arrange the schedule for Pre-SEDEX and Viva for students by inviting external examiners to evaluate the students. Besides that, the author wishes to express his outmost gratitude to his beloved family and colleagues (Azeem, Anas, Amin and Yuhendri) and for their support and encouragement throughout the duration of the project.

In conclusion, the author would like to thank all parties that have involved once again for contributing in this Final Year Project completion.

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LIST OF ABBREVIATIONS

The table below describes the significance of various abbreviations and acronyms used throughout this project report. Attached along is the page in which each of the abbreviation is defined or first introduced.

Abbreviations	Meaning	Page
EV	Electric Vehicle	1
HEV	Hybrid Electric Vehicle	1
ICE	Internal Combustion Engine	1
RBS	Regenerative Braking System	1

CHAPTER 1
INTRODUCTION

1.1 Background of Study

In the world of globalisation today, three main types of vehicles can be observed on the road, namely the conventional hydraulic vehicles, the hybrid electric vehicles (HEV) and also the full electric vehicles (EV). Conventional vehicles run on internal combustion engines powered by hydraulic pumps, while the hybrid electric vehicles run by utilizing both conventional internal combustion engines (ICE) propulsion system with an electric propulsion system. On the other hand, the full electric vehicles fully apply the electric propulsion for moving. By retrofitting conversion of hybrid electric vehicle, it simply means the addition or incorporation of electrical generation systems and components into the conventional hydraulic vehicles to enhance the energy efficiency and increase the output of the vehicles.

One of the key features in a hybrid electric vehicle is the regenerative braking system (RBS). It is actually a braking method that utilizes mechanical energy from the motor to change the kinetic energy to electrical energy which will be stored in the battery system. This help to conserve some of the kinetic energy that might be lost in the form of heat energy and friction into the environment. During RBS activation when the vehicle brakes or decelerates, the rotors being turned by the wheels of the HEV will experience opposing torque in the form of current. This slows the vehicle, and generated electrical is stored in the battery unit.

For the retrofit hybrid electric vehicle conversion, the focus is to maintain the current conventional friction brake of the vehicle, while incorporating the RBS feature to generate and store energy for vehicle's usage. Several methods have been proposed to implement and design the pedal brake with add-in RBS feature. Force from the pedal brake will be measured by a linear sensor, and the output voltage signal will be sent to a motor controller to justify how much torque speed should the rotor rotate.

From the controller, instructions are initialized to allow a feedback current flow in an alternative way into the battery storage.

1.2 Problem statement

In most of the hybrid and full electric vehicles nowadays, regenerative braking system often comes together as a whole with other related parts of the vehicles, being customized and programmed accordingly to fit into the energy management system. Therefore, there is a lack of regenerative braking performance study for a bench-testing prototyping stage in retrofit conversion of hybrid electric vehicles, more importantly for an academic form of study. On the other hand, the current solution to implement a regenerative braking system in existing vehicle part (brake pedal) is costly. This is due to high production from the automotive industries and the introduction of high technology or features into the regenerative braking system.

In a retrofit conversion hybrid electric vehicle, one of the problems faced is also to design a brake pedal assembly to collect data for regenerative braking system. In other words, a challenge exist to implement a newly regenerative braking system into the existing mechanical brake system - to retain the hydraulic brake for concurrent re-gen along with mechanical braking.

1.3 Objectives

The project mainly serves to study the regenerative braking system of a modified brake pedal assembly which is cheap in production and with minimal mechanical modification. Sub-objectives of the project are listed below:

i. To incorporate a linear sensor onto existing pedal brake to measure brake demand output.
ii. To construct a simple voltage follower circuit that outputs a stable voltage from the sensor into the motor controller input.
iii. To configure the connection between brake demand output and the motor controller.
iv. To monitor the regenerative performance of the bench-test prototype using the laboratory equipment.

1.4 Significance of the Project

Although the regenerative braking technology is considered a rather new technology, the fact that it is applied in most of the electric and hybrid electric vehicles cannot be denied. However, not all the vehicles apply and practice the same regenerative braking system type. The project serves as a platform to study and explore on alternative way to implement the regenerative braking system onto a conventional vehicle part using the available materials, as well as to study the performance.

It is therefore significant to be further studied and implemented for future reference. In the upcoming years, the automotive industries will be dominated by these electric vehicles, so there is a need to explore on regenerative braking system in various ways. With a better performance of regenerative braking system, not only it can save some energy lost to the environment, it can also help to make this world a cleaner place to live in.

1.5 Scope of Study

In this study, the main subjects under investigation in FYP 1:

i. Type of potentiometer/sensor to be used
ii. Configuration of the potentiometer to the existing pedal brake.
iii. Design of a voltage follower circuit to produce a stable output.

And the aspects being studied which are carried out in FYP 2:

i. Continued work progress from FYP 1
ii. Circuitry connection from brake demand output to motor controller.
iii. Monitoring and study of regenerative performance in bench-test prototyping using laboratory equipment.

1.6 Relevancy of the Project

The project is relevant to be carried out as part of the Electrical and Electronic course since it is basically related to energy regeneration field. The overall idea behind this project is to regenerate and save the energy lost from braking into the battery storage unit in hybrid electric vehicles. Throughout this project, the readers can benefit from the learning of regenerative braking system.

1.7 Feasibility of the Project

The project is carried out in two semesters and basically covers several parts. This includes research survey (literature reviews) for data collection, design of the brake pedal with the linear sensor on it, purchasing of the components needed, fabricating the pedal brake onto a bench-test and also monitoring the performance in terms of current feedback into the battery and rotational speed of the brushless motor for regenerative purposes via laboratory equipment.

CHAPTER 2
LITERATURE REVIEW

2.1 Regenerative Braking System

In conventional braking system, during the deceleration of stopping of vehicle, brake pad is exerted with force to produce friction with the friction rotors. Between the road surface and vehicles there exists an extra friction. With the presence of friction, energy is lost in the form of kinetic energy to heat energy. (www.howstuffswork.com)

On the other hand, in regenerative braking system, majority of the braking mechanism is done by the system. When the brake pedal is pressed, signal is sent to the controller which tells the electric motor to operate in a reverse mode. During reverse mode, the inertia load of the vehicle in motion will continue to spin the DC motor through gearing. In this case, the DC motor actually generates DC voltage which will drive current to be fed into the battery for storage. Often, in most of the hybrid electric vehicles, regenerative braking must come together with current hydraulic friction braking [4]. The reason behind this is that it acts a back-up system in cases where regenerative braking is not strong enough for the stopping power.

2.2 Layout Block and Working Principle

In the design of the overall regenerative braking system (RBS), there are several components involved. Initially, the pedal brake design is involved, followed by the controller, the electric motor drive and finally the battery storage. For the initial step, the pedal brake design is foremost, important for measuring displacement variation to be sent to a potentiometer/sensor. One of the criteria is that the brake must have the same physical position and contact as the conventional friction brake pedal for ergonomic purposes. Apart from that, the brake pedal must always maintain the current friction braking process, at the same time implementing the RBS feature as well [1]. Here, a suitable pedal assembly must be selected to fit into the conventional vehicle which will be converted to hybrid electric vehicle.

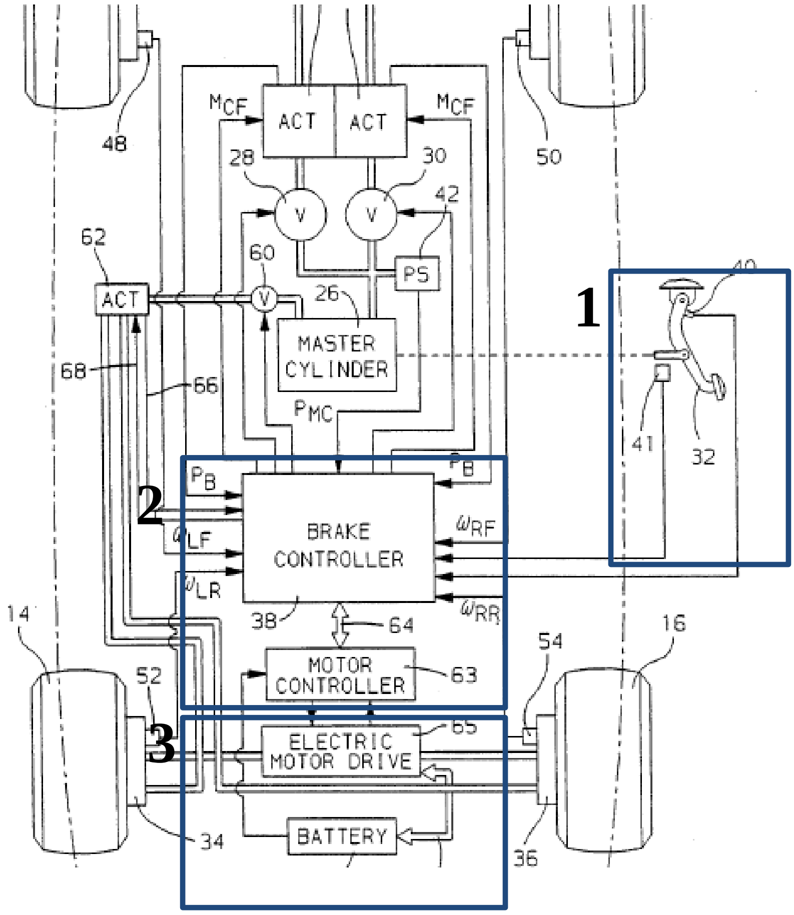


Figure 1: Regen-braking part in hybrid vehicles

A brake pedal system includes a brake pedal having a flexible arm with a first distal end adapted to be mounted to the structure of a vehicle and a second distal end having a foot pad. At least one sensor is mounted to the brake pedal and is adapted to sense the amount of deflection of the brake pedal and send a corresponding signal. A stop is adapted to be mounted within the vehicle at a distance from the brake pedal such that the brake pedal will contact the stop after flexing a pre-determined amount." (United States Patent 6571661).

There are several types of sensor to be chosen on, based on their feasibility to be implemented in the circuit. This includes angular, linear or rotational sensor. Angular and rotational sensors have the advantage of easy to be mounted on brake bracket, while the linear sensor is considerably economic in cost and commonly used in pedal brake design. The maximum output voltage of the sensor must not exceed 5V to avoid ECU overload [1]. From here, it is helpful to decide on the most economical cost of the sensor implemented to meet the project's specification and objective.

An electrical circuit to power a rotational sensor might be required to measure the angular displacement of brake pedal linkage [1]. Hence, a design of the small electric circuit consisting of various resistances and rotational sensor will also be needed. A voltage follower circuit, with the inclusion of an operational amplifier is basically needed in ensuring that the output voltage follows the input voltage. (http://www.talkingelectronics.com/projects/OP-AMP/OP-AMP-1.html)

In order to calculate and measure the displacement of the pedal, a potentiometer is also required in the pedal brake. This will output as voltage signal. The harder the pedal is pressed, more resistance of the potentiometer dropped which permits higher voltage flow to the Engine Control Unit (ECU) [1].

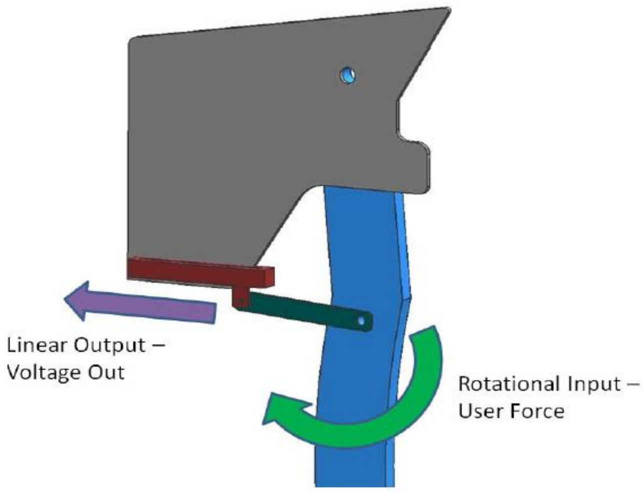


Figure 2: Potentiometer position on the pedal arm

After the pedal brake design, output voltage from the potentiometer will be inked to the brake controller to control the overall motor process initialization. The controller is very important in the system as it involves in monitoring the wheels 'speed and determine the exact amount of torque for electricity generation [2]. In this project, the recommended controller to be used involves the Kelly controller.

In a Kelly controller, there are three kinds of regenerative mode to be used. The first type is the "Releasing Throttle Starts Regen" mode which initiates the starting of regen when the throttle is released. The second type is the “Brake Switch Regen” which means the start of regen as soon as the brake switch is activated after the throttle is released. The last type is the “0-5V Signal Regen” which simply indicates that the level of regeneration can be adjusted by varying the signal. Therefore, a 0-5V brake sensor must be identified and installed.

From the controller, algorithms are generated via programming coding to control motor torque for regenerative braking purpose. The same principle applies for both the electric vehicle and hybrid vehicle. The only difference is that the same algorithm is required for driving mode and braking mode in electrical vehicle. Depending on the variable voltage input signal from 0-5V, the controller will respond by giving out variable levels of regenerative braking which will control the level of regen-current allowed to flow from the motor controller to the battery. (www.kellycontroller.com)

Derivation of the torque command from the pedal will be converted by the motor controller into a three phase voltage with current characteristic to move the motor in desired directions [2]. This three phase voltage-current waveforms is also known as the control circuit for regenerative braking in the motor part. In this case the motor used is the Brushless DC (BLDC) motor.

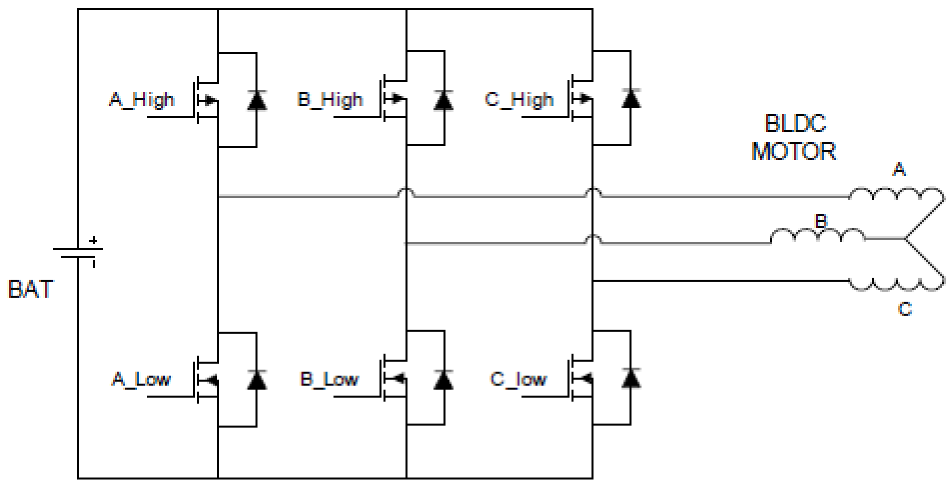


Figure 3: Power inverter circuit for 3 phase BLDC control

With the BLDC motor used in this project, a DC source voltage is required to be applied to the stator windings in orders to sustain rotation. Electronic switching with the use of inverter is applied here. Figure below illustrates the current flow from the three phase inverter circuit during normal motoring and regenerative braking [3].

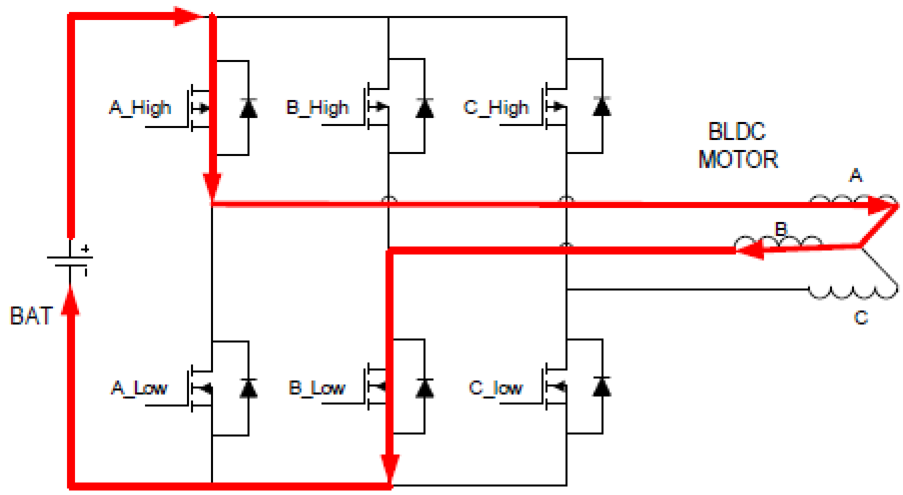


Figure 4: Current flow during motoring

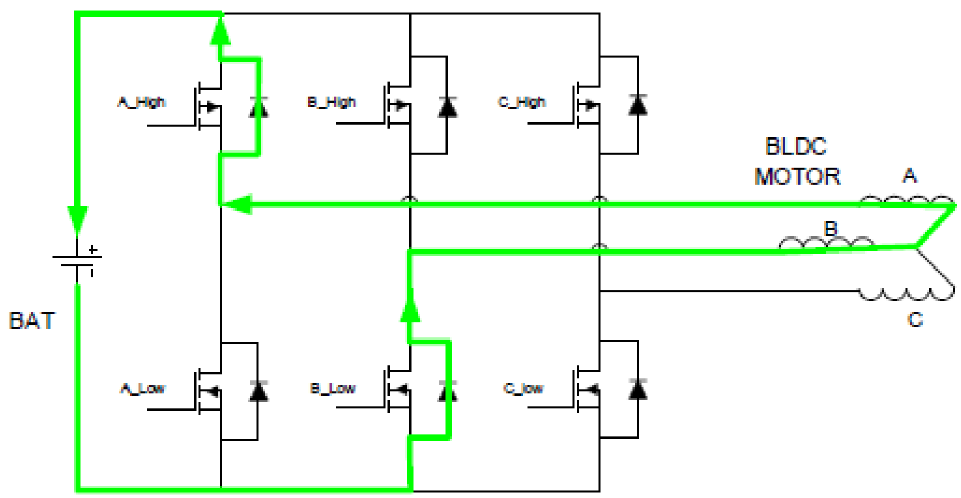


Figure 5: Current flow during regenerative braking

During the regenerative braking mode, current in the winding is toggles to flow in reversed direction and supplied back into the battery. All switches are OFF and current can flow back through the freewheeling diode of the high-phase high-side switch, A (HIGH), through the battery and through the *low*-phase *low*-side switch, B (LOW). The pulse width modulation PWM can be varied in order to control the level of braking. The maximum level of regeneration occurs when the low-side switches are all turned off [3].

Several publications for [4], [5], [6] and [7] are studied and reviewed but the detailed contents are not relevant to the project scope of study which is on how to incorporate the regenerative braking system in conventional friction pedal brake. Instead, the publications as above describe more on the process control of the regenerative braking system in terms of simulations, while others describe on other components of regen-braking like the freewheel and brushless motor. Therefore, they can only be considered as an extended study and not to be included in the literature review.

CHAPTER 3
METHODOLOGY

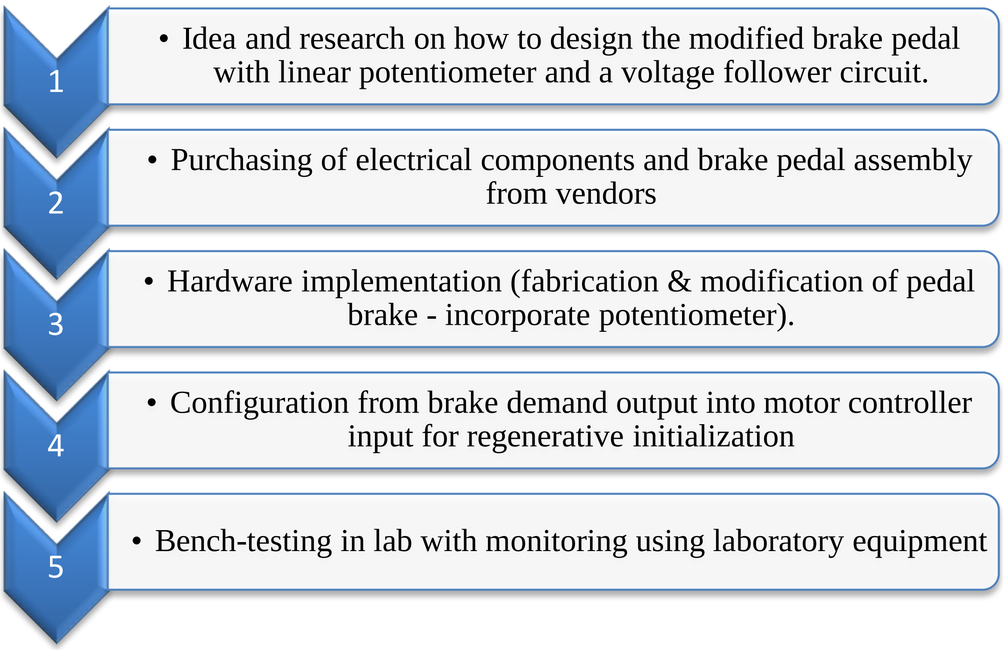
3.1 Research Methodology and Project Activities

The methodology for conducting this project is more towards self-exploration on the current solution implementations, and discovery of better ideas to design the solutions. The project activities in this research consist mainly of technical works. After thorough literature review is done, better solutions for the pedal brake design is finalized. Components needed for the project are selected and purchased to start implementing the hardware part of the brake pedal system. Lastly, the hardware prototype is tested in the lab for performance comparison.

3.2 Experimental Procedures/Approach

The figure below shows the general procedures that will be implemented in this project.

Table 1: General steps approach in the project



3.3 Flowchart

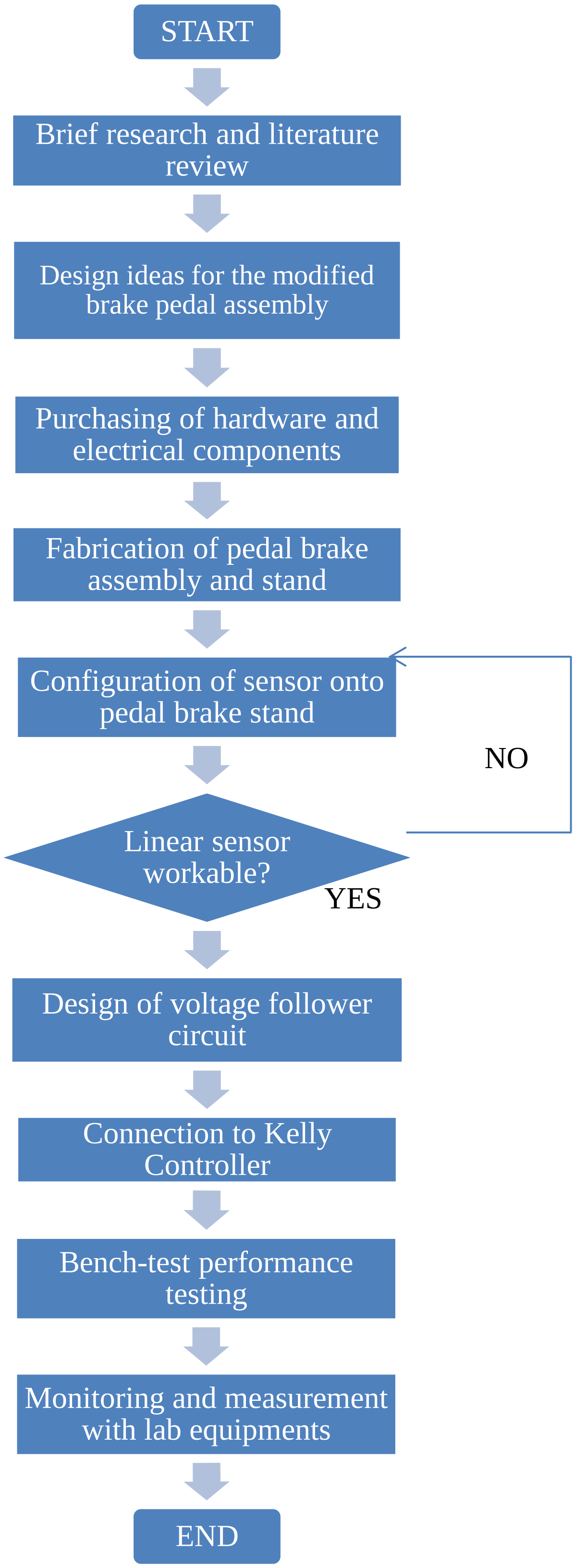


Figure 6: Project Methodology

3.4 Materials/Components

In this experiment, several components have been identified and purchased. The cost for all the components used for the project is listed in the table below:

Table 2: Project's Material and Cost

Quantity	Part Description	Purchased from	Price (each)
1	Pedal assembly	Scraping centre	RM 180
1	10 kilo-ohm linear potentiometer	RS Malaysia	RM4.92
1	Vero-board	State Electronics	RM 1.20
1	12 kilo-ohm resistor	State Electronics	RM0.50
2	#4-40x1'Bolts	ME Department	-
2	#4-40 Nuts	ME Department	-
1	Long pieces wire	EE Department	-
1	Aluminium Linkage	ME Department	-
1	741 Op-amp	State Electronics	RM0.60
1	Voltage Regulator LM7805	State Electronics	RM1.00
1	12V Battery	State Electronics	RM10.00
		Total	**RM 198.22**

Comparing the cost of this modified brake pedal (which has the linear potentiometer mounted) with that of the available electronic brake pedal (approximately RM250-RM350), it is found out that we are able to actually save up twice as much as the electronic brake pedal.

Lab equipment involved:

a). Oscilloscope

b). Multimeter

c). Tachometer

d). Clamp-meter

3.5 Key Milestones

Several key milestones for this research project must be achieved in order to meet the objective of this project:

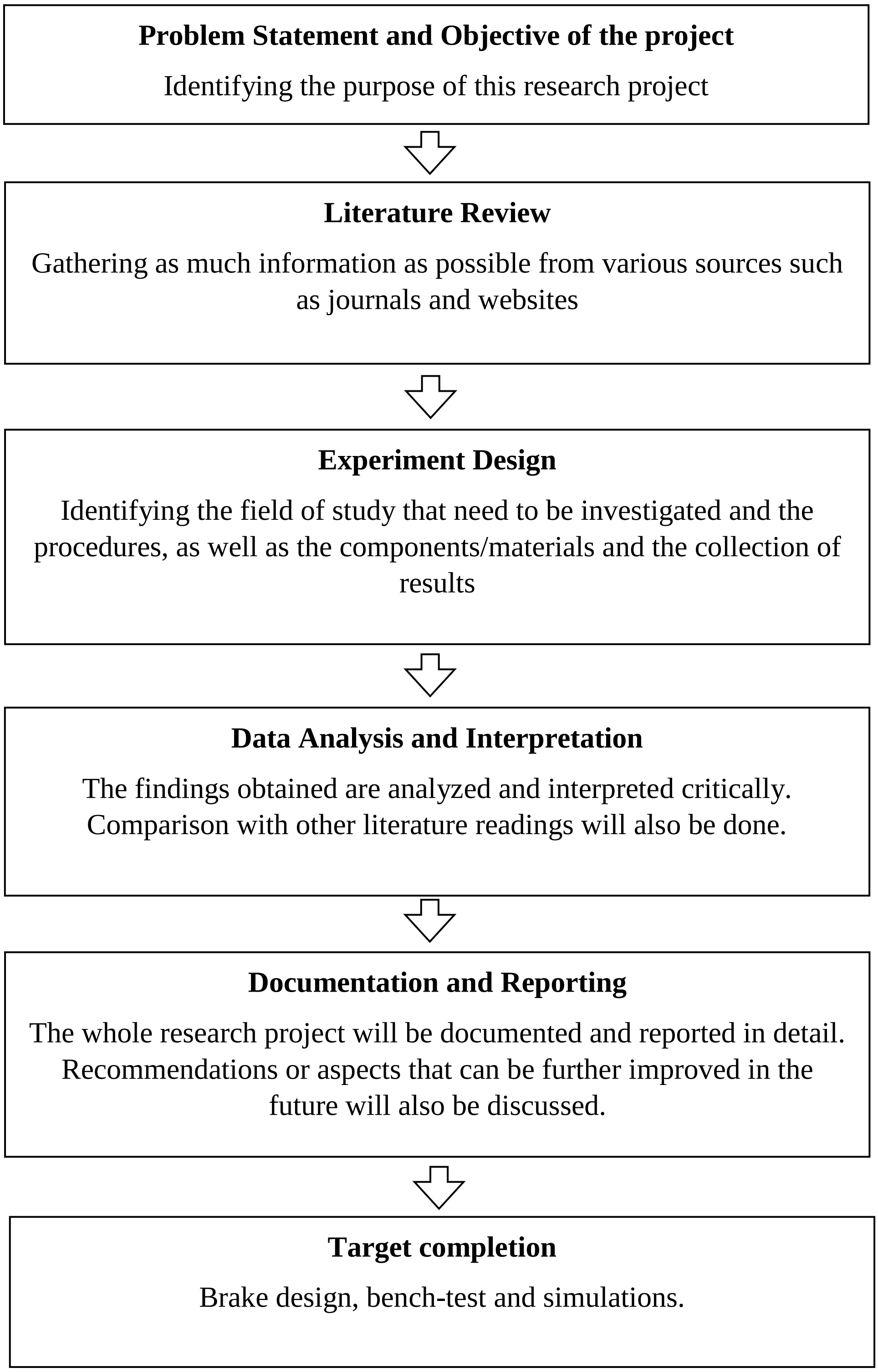


Figure 7: Key Milestones

CHAPTER 4
RESULT AND DISCUSSIONS

Basically, there are five main parts for the project development:

1. Fabricating existing brake pedal onto a bracket stand with configuration to the brushless (BLDC) motor for bench test purpose.
2. Design and configuration of the linear sensor onto the pedal brake assembly.
3. Design of a voltage follower circuit to output voltage in range of 0-5V.
4. Configuration of brake output demand to Kelly Controller.
5. Lab simulation to monitor regenerative current, using the lab equipment.

4.1 Fabricating Existing Pedal onto a Bracket Stand

The very first task involves purchasing a brake pedal from the scrapping center and mounting it onto a made bracket stand using 4 bolts and nuts. The process was done using the drilling machine in the mechanical lab.

Figure 8: Pedal brake assembly on bracket stand

The second part involves the work of mounting the brushless DC (BLDC) motor onto the brake pedal assembly stand for experimentation.

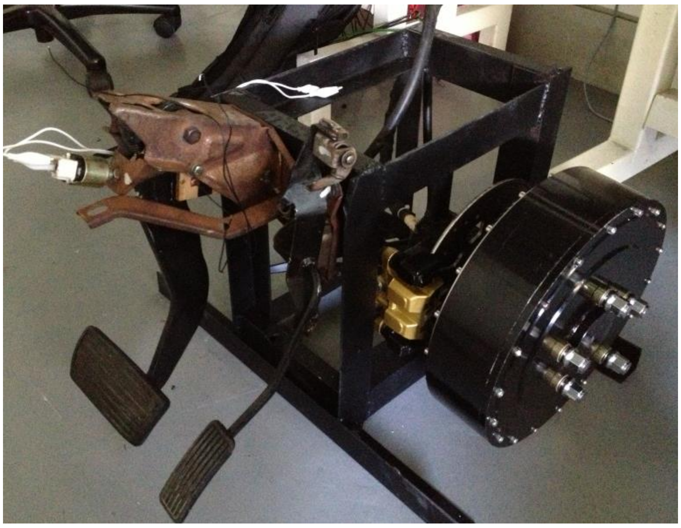


Figure 9: Complete brake pedal assembly with BLDC motor

4.2 Design and Configuration of Linear Sensor onto Pedal Brake Assembly

In the first step of this stage, calculation has been performed to calculate the linear sensor displacement upon the exertion of force onto the pedal brake. Illustration below shows the working of it:

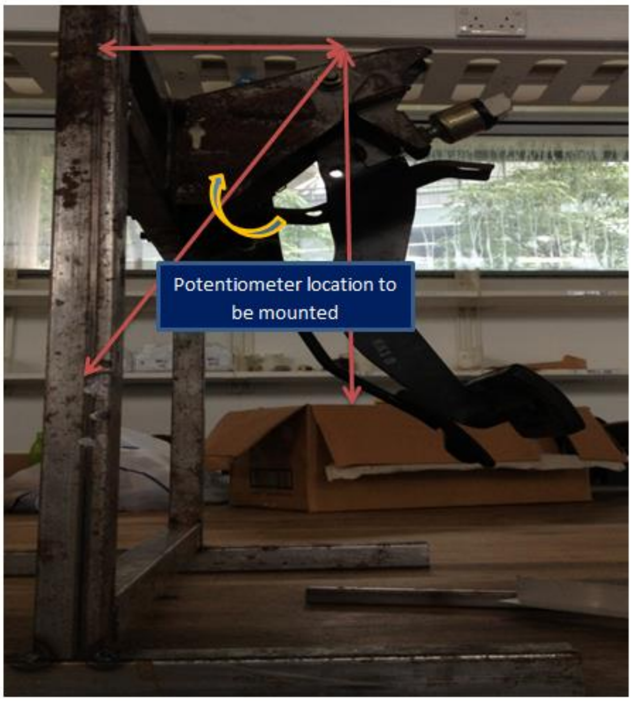


Figure 10: Illustration to design and calculate the position for linear sensor

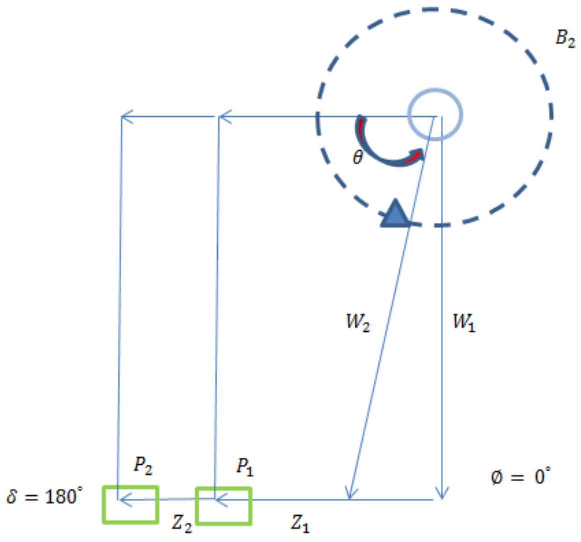


Figure 11: Measurement diagram

Firstly, we start calculating with the vector loop equation:
$w_2 + z_2 - p_{21} - z_1 - w_1 = 0$

By substituting the complex number equivalents for the position vectors:
$we^{j\theta}(e^{j\beta 2} - 1) + ze^{j\emptyset}(e^{j\alpha 2} - 1) = p_{21}e^{j\delta 2}$

By substituting with the Euler equivalents:

$w(\cos\theta + j\sin\theta)((\cos\beta_2 + j\sin\beta_2) - 1) + z(\cos\phi + j\sin\phi)((\cos\alpha_2 + j\sin\alpha_2) - 1) = p_{21}\,(\cos\delta_2 + j\sin\delta_2)$

Separating into real component:

$w\cos\theta(\cos\beta_2 - 1) - w\sin\theta\sin\beta_2 + z\cos\phi\,(\cos\alpha_2 - 1) - z\sin\phi\sin\alpha_2 = p_{21}\sin\delta_2$

Solving for p_{21}, so that the total displacement the linear sensor will encounter is known using the following given values from the design:

$w_1 = w_2 = 26.5$cm
$z_1 = z_2 = 7.0$ cm
$\theta = 95$ degrees
$\beta_2 = 348$ degrees
$\phi = 0$ degrees
$\alpha_2 = 4$ degrees

These parameters give a value of p_{21} = ***3.50 cm***. Therefore, we expect to see a linear travel of 3.5 cm of the linear sensor.

From the displacement calculated and verified with on-spot measurement (3.5cm), a suitable linear sensor has been ordered and purchased from RS Malaysia online store.

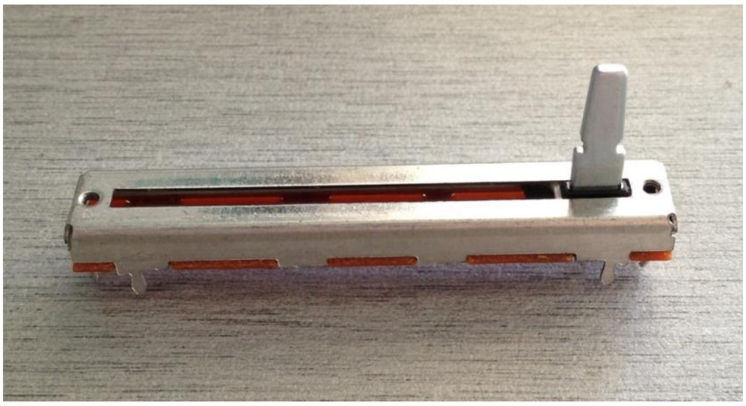
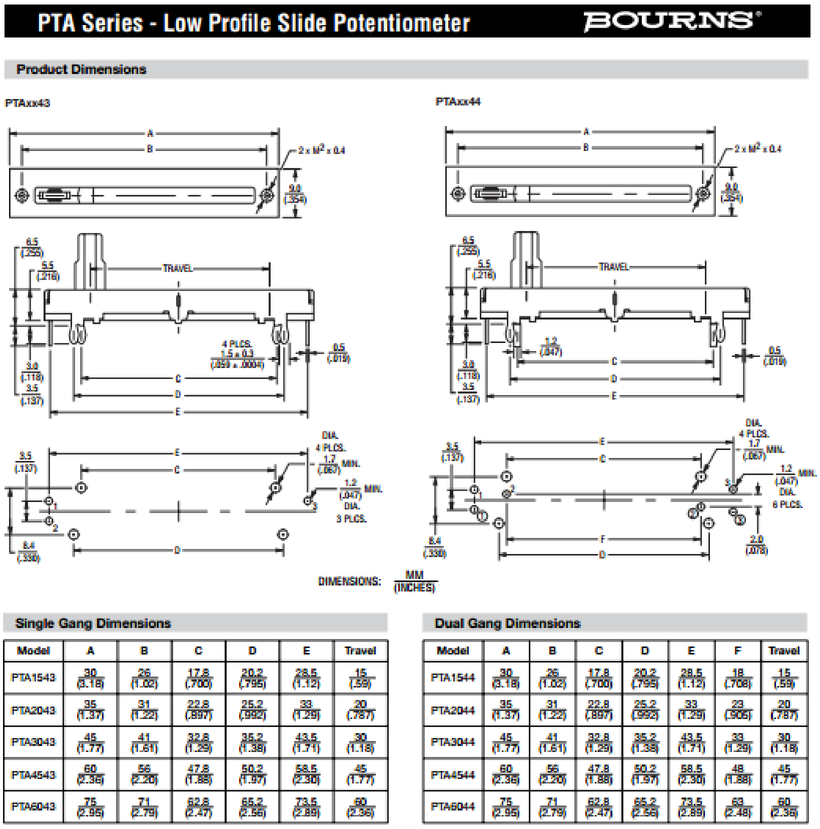


Figure 12: Linear sensor selected



PTA Series - Low Profile Slide Potentiometer BOURNS®

Product Dimensions

PTAxx43

PTAxx44

DIMENSIONS: MM / (INCHES)

Single Gang Dimensions

Model	A	B	C	D	E	Travel
PTA1543	30 (3.18)	26 (1.02)	17.8 (.700)	20.2 (.795)	28.5 (1.12)	15 (.59)
PTA2043	35 (1.37)	31 (1.22)	22.8 (.897)	25.2 (.992)	33 (1.29)	20 (.787)
PTA3043	45 (1.77)	41 (1.61)	32.8 (1.29)	35.2 (1.38)	43.5 (1.71)	30 (1.18)
PTA4543	60 (2.36)	56 (2.20)	47.8 (1.88)	50.2 (1.97)	58.5 (2.30)	45 (1.77)
PTA6043	75 (2.95)	71 (2.79)	62.8 (2.47)	65.2 (2.56)	73.5 (2.89)	60 (2.36)

Dual Gang Dimensions

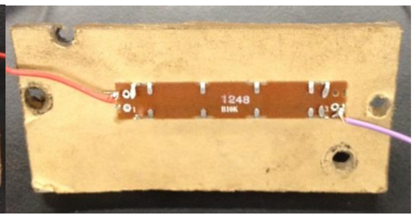
Model	A	B	C	D	E	F	Travel
PTA1544	30 (3.18)	26 (1.02)	17.8 (.700)	20.2 (.795)	28.5 (1.12)	18 (.708)	15 (.59)
PTA2044	35 (1.37)	31 (1.22)	22.8 (.897)	25.2 (.992)	33 (1.29)	23 (.906)	20 (.787)
PTA3044	45 (1.77)	41 (1.61)	32.8 (1.29)	35.2 (1.38)	43.5 (1.71)	33 (1.29)	30 (1.18)
PTA4544	60 (2.36)	56 (2.20)	47.8 (1.88)	50.2 (1.97)	58.5 (2.30)	48 (1.88)	45 (1.77)
PTA6044	75 (2.95)	71 (2.79)	62.8 (2.47)	65.2 (2.56)	73.5 (2.89)	63 (2.48)	60 (2.36)

Figure 13: The datasheet for the linear sensor ordered

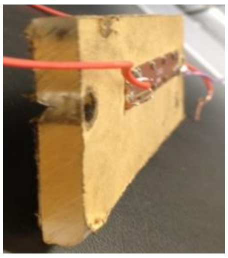
In order to mount the linear potentiometer onto the pedal assembly as shown in Figure 9, some considerations were taken into account. First, the sensor is made up of aluminum which is light and not suitable to be bolted into the steel casing of the pedal assembly, as this will damage the potentiometer.

Therefore, an idea suggested was to fabricate the potentiometer onto the perspex in order to have a larger and harder surface for bolting purpose, without damaging the linear sensor. New dimension of the linear potentiometer along with the Perspex is shown below:

Front view



Back view



Side view

Parameter	Dimensions
Length	9.8cm
Width	4.3cm
Thickness	0.6cm

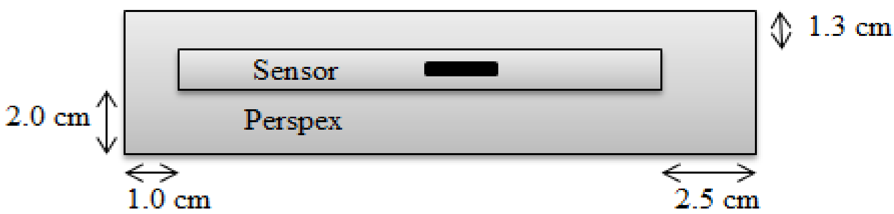


Figure 14: Dimensions of the fabrication of linear sensor onto perspex

The fabrication of the linear sensor onto the Perspex is then bolted firmly to the pedal assembly. A thin aluminium foil was also cut and attached along with the pedal assembly to be clinged onto the linear sensor's input trigger. The reason is to enable the linear sensor's input to follow the exertion force of pedal, and returns back to original displacement when the pedal is released. Since cost minimization is focused in this project, we do not intend to purchase the linear sensor with a build in spring mechanism as this usually costs around RM100 to RM 300 which is expensive, although reliable.

The aluminium foil is designed in a way which contains a tiny dimension of hook to cling onto the linear sensor's input trigger.

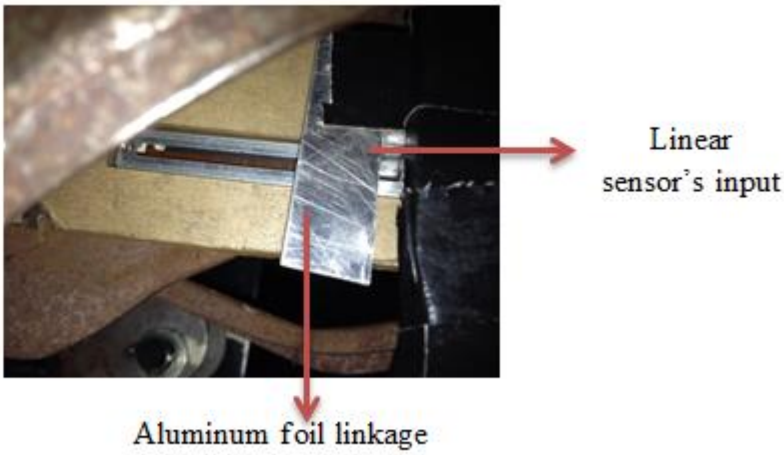


Figure 15: Aluminum foil clinged to linear sensor

4.3 Design of a Voltage Follower Circuit

Part of this stage involves designing and fabricating a simple voltage follower circuit to be connected to the output of the linear sensor. For this, a simulation using the Multisim software was conducted to test the schematic circuit.

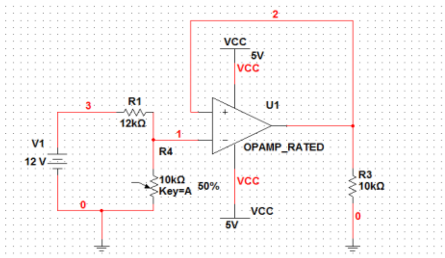


Figure 16: Multisim schematic of voltage-follower circuit

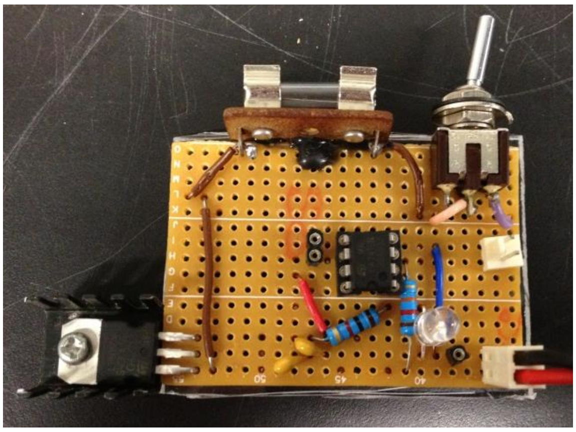


Figure 17: Veroboard soldered circuit connection

The circuit consists of a 5V voltage regulator which converts 12V battery into 5V output for Kelly controller. An operational amplifier is used to function as a voltage follower so that the output voltage follows the input voltage, thus allowing a more stable output voltage range to be fed into the Kelly Controller. This is very important to ensure there is no variation or spikes in the output voltage. The circuit will converts the brake demand voltage output (range of 0-5V) into a more stable value to be fed into the Kelly Controller. Depending on the level of voltage output from brake demand, the controller will initiate the associate regenerative level required.

Several testing have been conducted in the lab to compare the actual result with the theoretical calculated result. In this case, the field of interest is with the linear potentiometer's output, whether it will give out an output voltage range between 0-5V as what is being calculated theoretically when the sensor's displacement is minimum or maximum.

At minimum and maximum potentiometer's displacement,

Table 3: Minimum and maximum potentiometer's displacement

Runs	R_{min} (ohm)	R_{max} (ohm)
1	6.3	6880
2	6.0	6900
3	6.3	6650
4	7.8	6720
5	6.2	6960
Average	**6.52**	**6822**

The potentiometer is measured with a multimeter. For every displacement of 5mm, the resistance of it is recorded. The purpose is to compare the resistance value of the potentiometer embedded into the pedal brake assembly. Since it is difficult to observe how much displacement that the pedal brake force exerts on the potentiometer, we use the value measured earlier as a reference to predict and estimate how much displacement has been lifted in actual scenario.

Table 4: Relationship between pedal displacement and resistance of potentiometer

Pedal Displacement (mm)	Resistance (ohm)
0	6.7
5	617
10	1900
15	3183
20	4600
25	5920
30	7300
35	8700
40	10,200
45	11,300

Battery voltage without load: $V_{bat\ (no-load)} = 12.05V$

Battery voltage with load: $V_{bat\ (with-load)} = 12.02V$

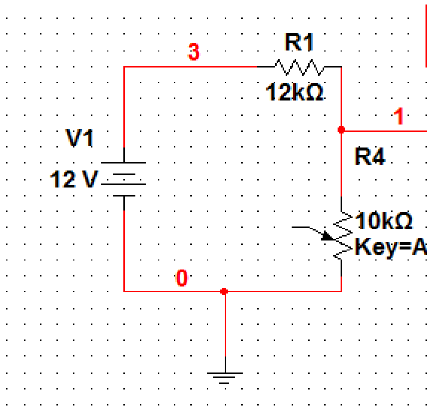
$R_{1\ (actual)} = 12.48\ kilo\ ohm$

$R_{1\ (theory)} = 12\ kilo\ ohm$

$R_{pot\ (actual)} = 11.3\ kilo\ ohm$

$R_{pot\ (theory)} = 10\ kilo\ oh$

The output voltage from the linear potentiometer based on the force exertion form pedal brake can be calculated as follow:



$$V_{out} = \frac{R_{pot}}{R_1 + R_{pot}}(12.02V)$$

Table 5: Experimented output voltage against theoretical output voltage

Distance (mm)	Output voltage measured from multimeter (V)				Output voltage calculated (V)
0	1	2	3	Average	
5	0.154	0.143	0.177	**0.158**	**0.0065**
10	0.378	0.443	0.472	**0.431**	**0.567**
15	1.854	1.854	1.854	**1.854**	**1.59**
20	1.967	2.354	2.47	**2.264**	**2.44**
25	3.1	3.2	3.354	**3.218**	**3.24**
30	4.084	4.09	4.167	**4.113**	**3.87**
35	4.24	4.267	4.268	**4.258**	**4.43**

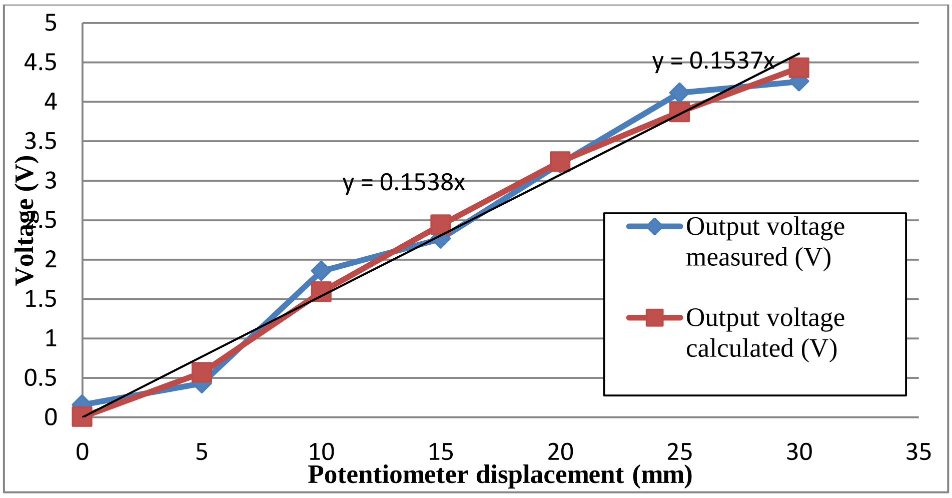


Figure 18: Graph of measured voltage against calculated voltage

From the graph, it is clearly shown that although there is little deviation from the calculated results and the experimented result, the error is little and can be negligible. The potentiometer is reliable in this case.

4.4 Configuration of Brake Output Demand to Kelly Controller

In order to configure the connection from brake output demand to the Kelly Controller, an instruction manual is required. In this case, we are referring to the Kelly KBL Series Brushless Motor Controller User's Manual**.**

Figure 19: Kelly KBL Series Motor Controller

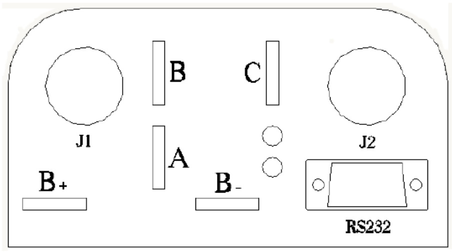


Figure 20: Figure-19: Front panel of Kelly Controller

B+ : Battery positive

B- : Battery negative

A : Output U/1/A phase

B : Output V/2/B phase

C : Output W/3/C phase

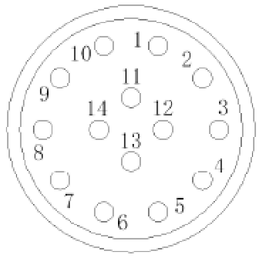


Figure 21: J1/J2 pin definition

For J1 pin definition,

1: Fault Code-Red LED
2: Reserved
3: Reserved
4: ALARM
5: Ground
6: Running Indicator-Green LED
7: Ground
8: RS232 Receiver
9: RS232 Transmitter
10: CAN bus HIGH
11: CAN bus LOW
12: Reserved
13: Power supply Ground
14: Controller Power Supply

For J2 pin definition,

1: Controller Power Supply
2: Ground
3: Ground
4: Motor temperature input
5: Throttle analogue input 0-5V
6: Brake analogue input 0-5V
7: 5V power supply
8: Throttle switch input
9: Reverse switch input
10: Brake switch input
11: Hall phase C
12: Hall phase B
13: Hall phase A
14: Ground

Based on the configuration from the manual, connections had been established into J2 pin number 6 and pin number 10. Brake demand output which generates 0-5V is connected to pin number 10 whereas the brake switch which activates regenerative mode in the Kelly Controller is connected to pin number 5.

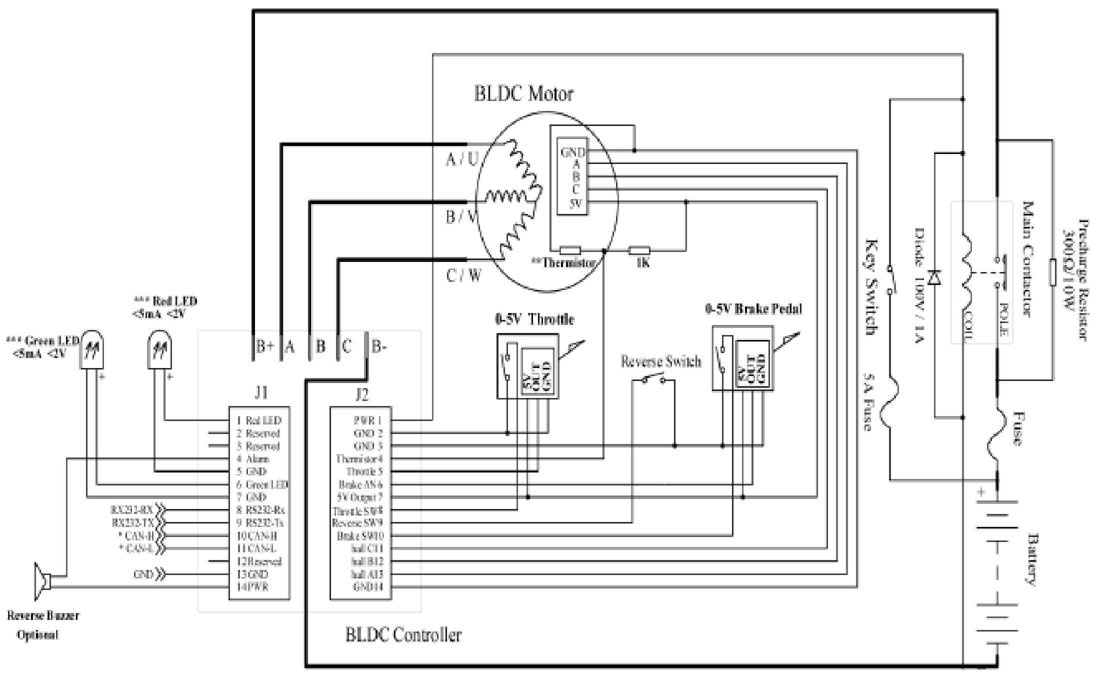


Figure 22: Standard wiring of BLDC Kelly Controller

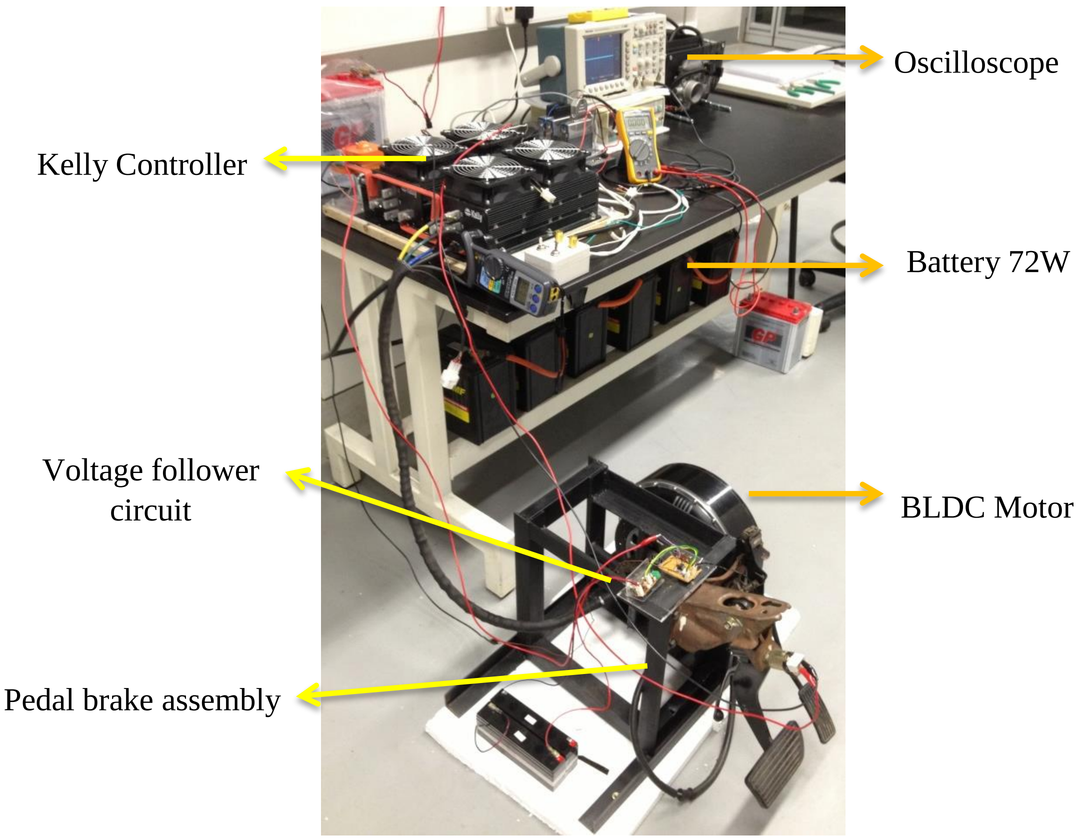


Figure 23: Overall test-bench configuration

4.5 Lab Simulation to Monitor and Study Regenerative Performance

4.5.1 Monitoring motoring stage

The first step in this step is to monitor the brushless DC (BLDC) motor speed with respect to the current drawn from the battery. In order to rotate the BLDC motor to move, there is a need of supplying voltage from the battery. Hence, we need to monitor the relationship between the motor's rpm (rotation per minute) speed and the voltage drawn from the battery.

Table 6: Tabulation data for motoring

Motor Speed (rpm)	Torque command (V)	Current flowing out (A)
443	0.6	4.5
587	0.8	6.0
712	1.0	7.4
782	1.2	8.4
286	0.4	3.2
102	0.2	1.6

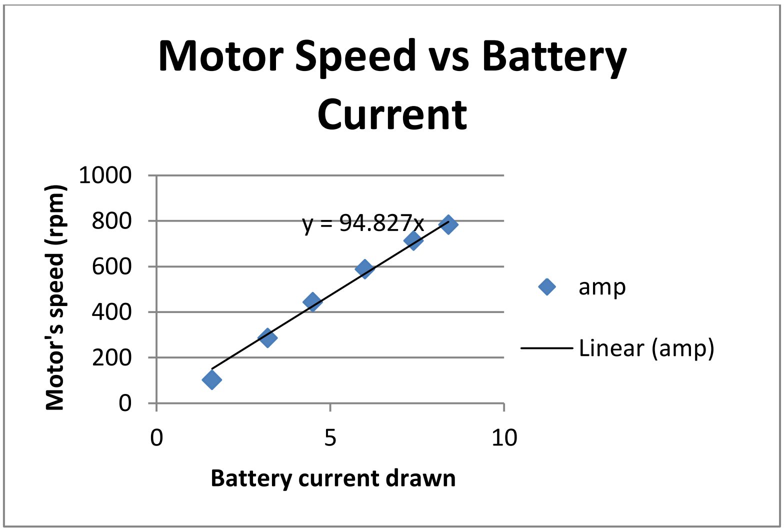


Figure 24: Monitoring current with respect to motor speed

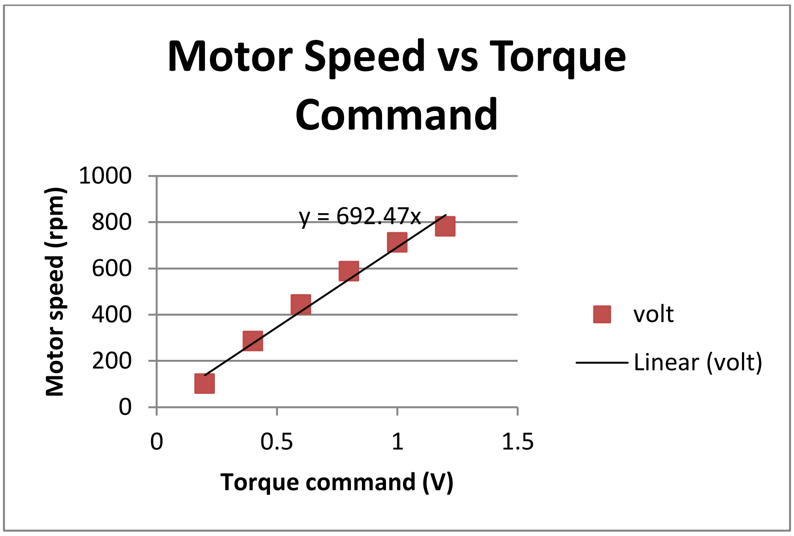


Figure 25: Monitoring torque command with respect to motor speed and current drawn

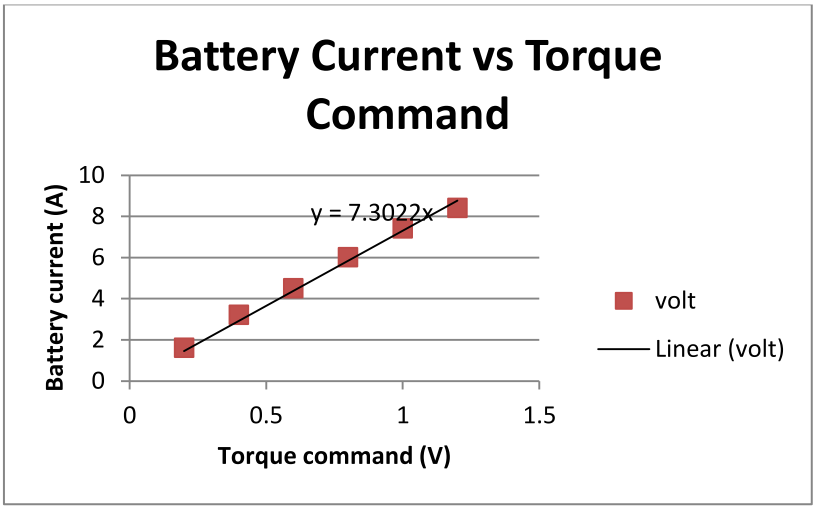


Figure 26: Monitoring torque command with respect to motor speed and current drawn

The above graphs show a near linear relationship between current flowing from battery, the torque command from motor and also the speed of the motor. In Figure 24, it is clearly shown that as the motor speed is increased, current drawn from the battery to power the motor will also increase. This relationship as shown is a linear relationship.

In Figure 25, we are able to know that a larger torque command (measured in volt) is required to support a higher motor speed revolution and also higher battery current drawn. This relationship, as plotted in the graph is a linear increment as well.

In Figure 26, the graph is plotted to show the relationship between the current flow from the battery and the torque command measured from the motor. It is observed that the torque command increases linearly with the current drawn from battery.

This confirms that the results obtained are acceptable, since the BLDC motor for the bench-testing is on zero-load condition. In zero or free load condition, the motor is not experiencing any extra load friction, thus the torque command required is directly proportional to the battery current drawn.

4.5.2 Monitoring braking stage

The BLDC motor is initially allowed to rotate at low speed and slowly increase to higher speed, in which the speed is controlled by the throttle output. After the motor reaches the desired stable speed, the brake pedal is pressed at its maximum force. Current flowing from the battery during motoring and the current flowing into the battery during braking is measured by using the clampmeter. The time taken for the current to discharge after the motor stops rotating is recorded using the stopwatch.

The results are recorded in the table below.

Table 7: Data tabulation during braking

Speed of motor (rpm)		Current flowing out of battery (A)	Current flowing into battery (A)	Current settling time during braking (s)
Motoring	Braking			
24.6	0	0.2	0	0
182	93.3	1.4	0.5	0.9
254.3	125.3	2.7	0.8	1.3
413.6	211.1	4.2	0.9	1.8
453.8	230.4	5.6	1.1	2.1
487.7	245.6	6.3	1.4	2.4
535.5	270.3	7.2	1.7	2.8
637.1	318.3	8.6	2.1	3.2
660	327.7	8.9	2.3	3.7

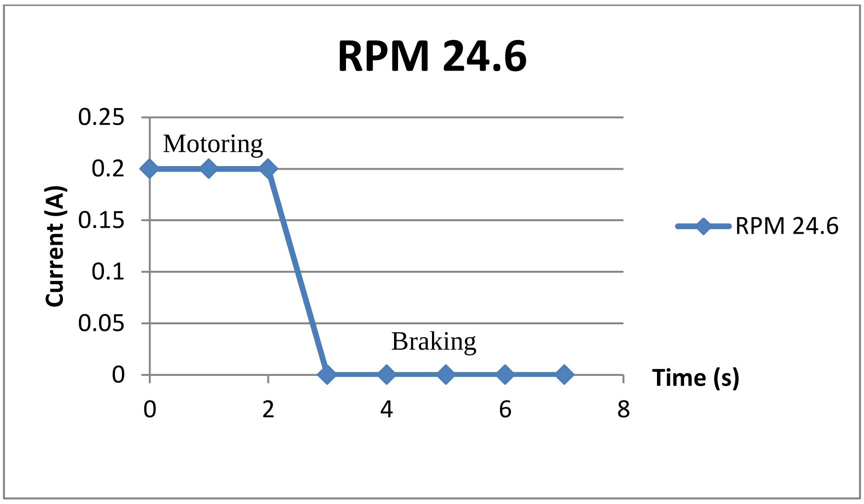


Figure 27: Current vs Time at 24.6 rpm

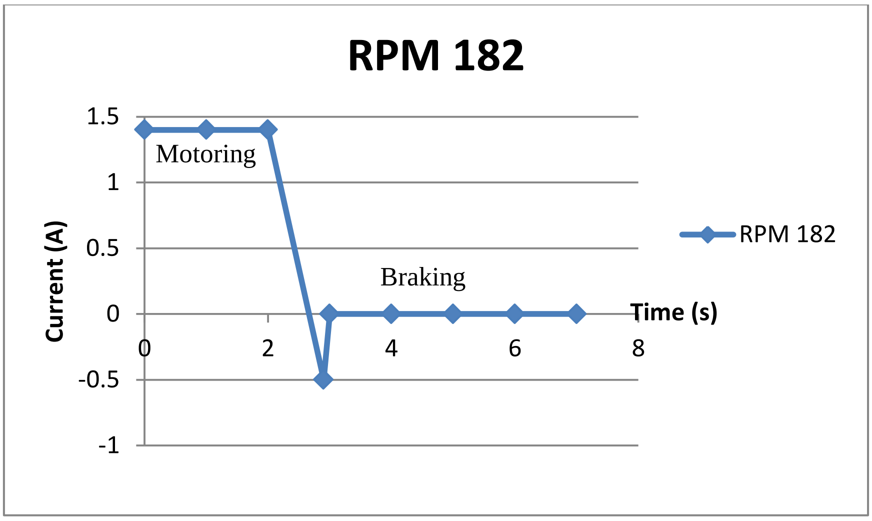


Figure 28: Current vs Time at 182 rpm

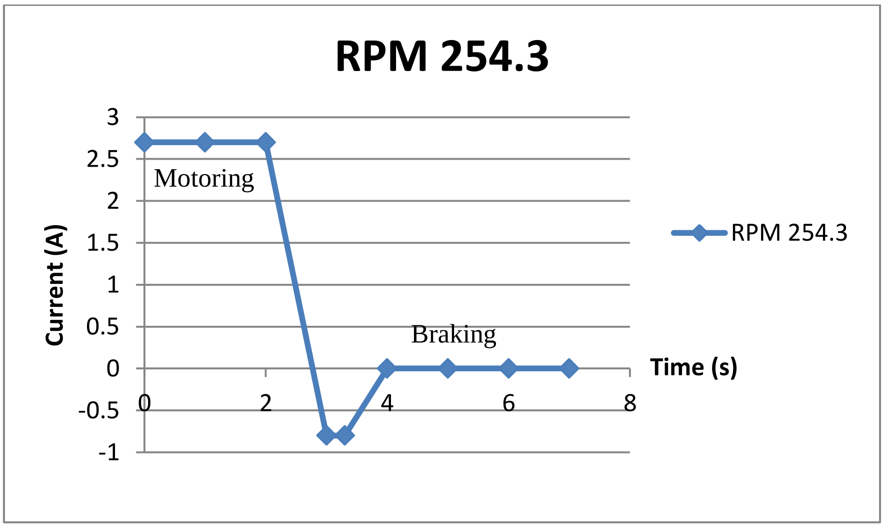


Figure 29: Current vs Time at 254.3 rpm

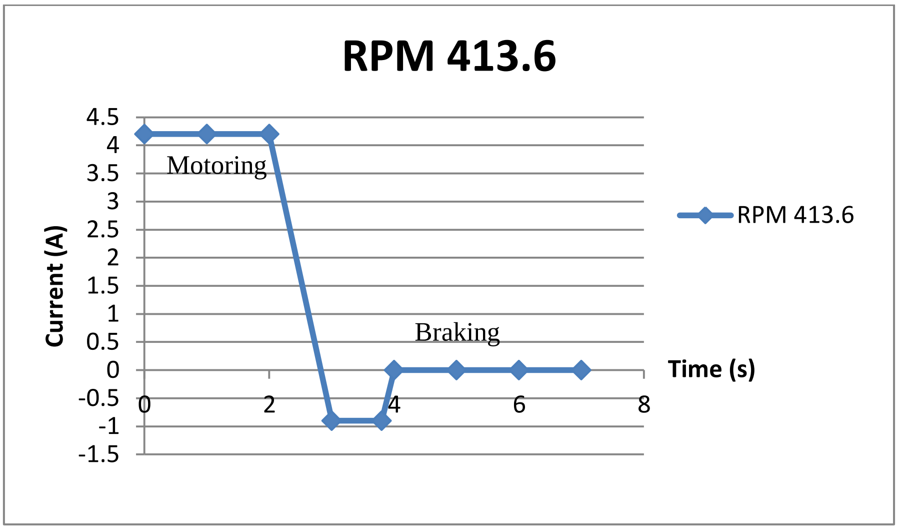


Figure 30: Current vs Time at 413.6 rpm

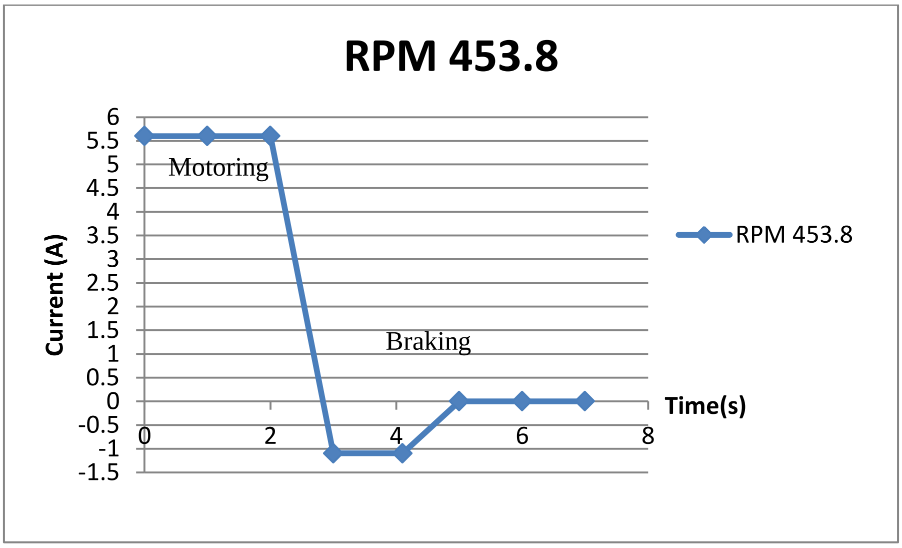


Figure 31: Current vs Time at 453.8 rpm

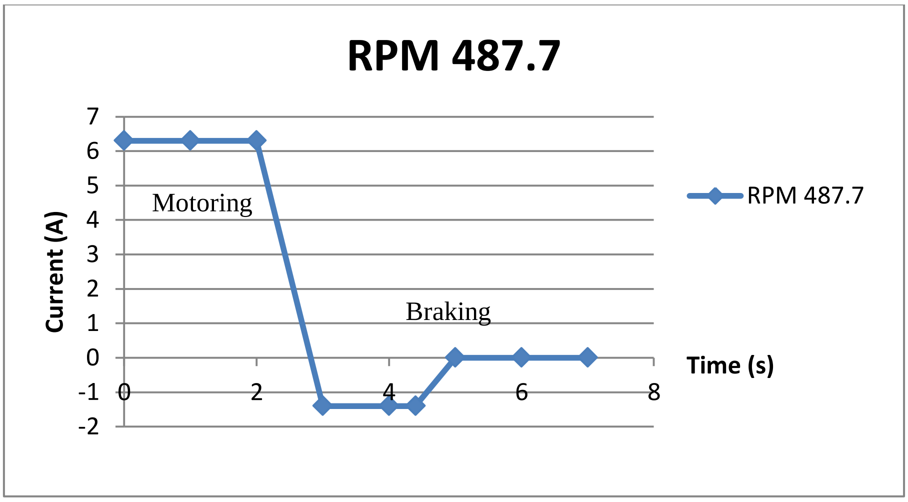


Figure 32: Current vs Time at 487.7 rpm

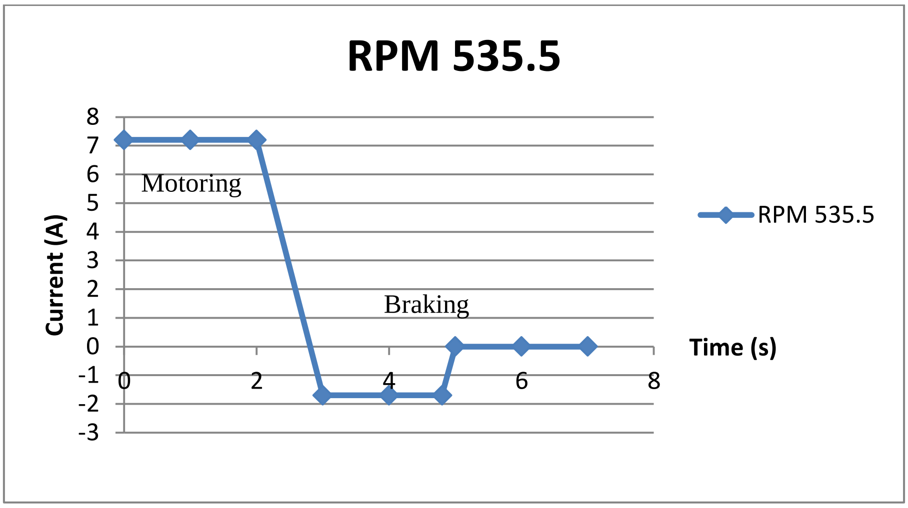


Figure 33: Current vs Time at 535.5 rpm

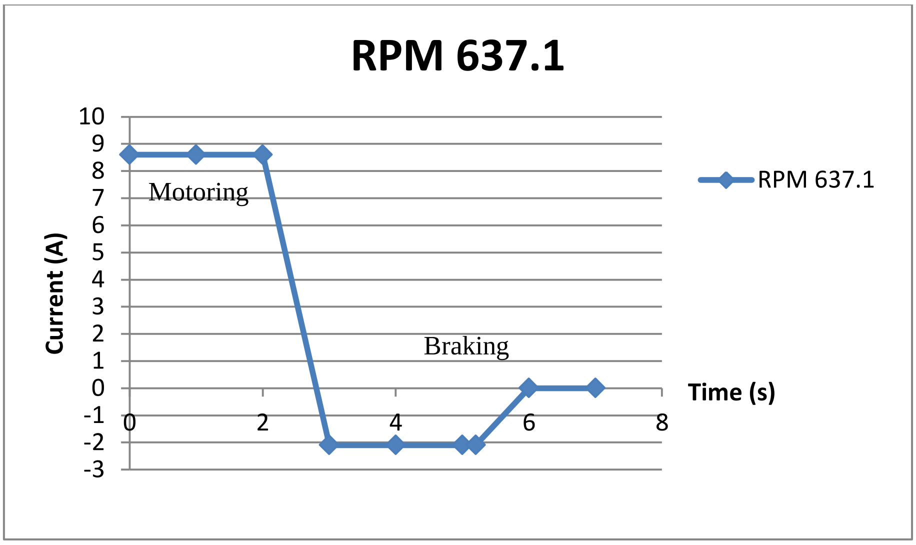


Figure 34: Current vs Time at 637.1 rpm

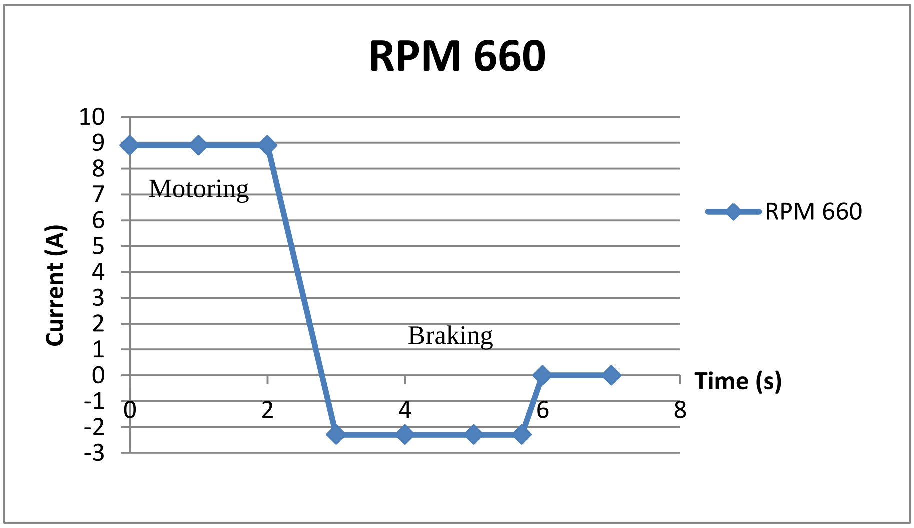


Figure 35: Current vs Time at 660 rpm

In order to illustrate the important detail of the graph in a larger perspective, the graph which gives the most significant result is chosen as a sample. In this case, the graph of RPM 660 is selected.

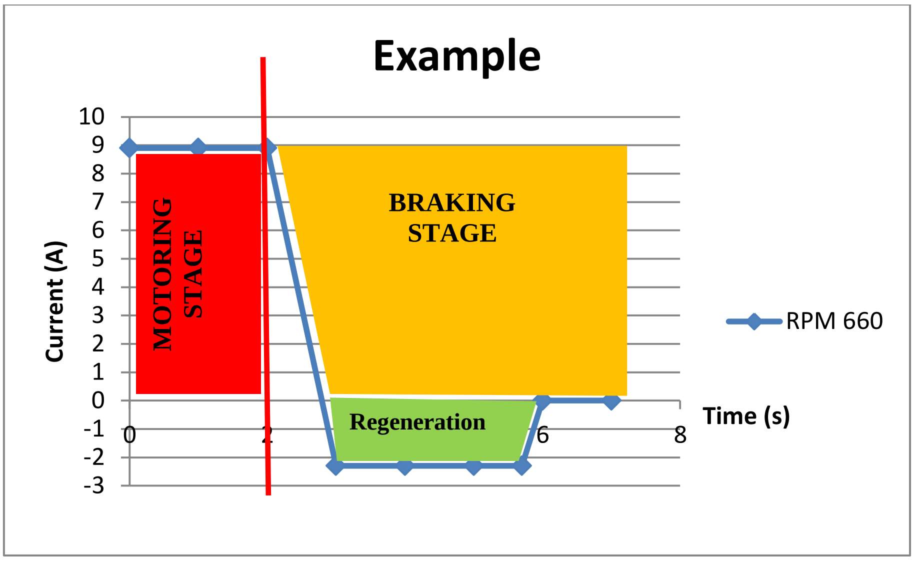


Figure 36: Illustration of graph details

From the above illustration, some observations can be highlighted:

1. The positive current indicates the measured current value which is drawn from the battery during the BLDC motoring.
2. The negative current indicates the measured current value which is flowing into the battery during the braking stage. Negative value indicates opposite direction flow.
3. The regeneration as labeled in green indicates the regenerative current during braking. The duration for the regenerative current which flows into the battery can be observed from the graph. In this case, the regen-current is only flowing for 3.7s.
4. Zero current value or the graph origin indicates that no current is present, simply because the motor has stopped completely due to braking process.

4.5.3 Discussions from the results obtained in the lab

All the results have been tabulated and graphs have been plotted to represent the research findings. Several observations are made and discussed:

1. At the minimum motoring speed of the BLDC motor (24.6 rpm), there is no regeneration occurs. This is because the motor speed is too low, and little brake exertion force will instantly stop the motor movement.
2. As the motor speed increases, the regenerative current flowing back into the battery is also increases. However, the value of the current is not significantly high to achieve pro-longed regeneration. The highest current value achieved in this research project is only 2.3A with the highest motor speed tested in the lab which is around 660rpm.
3. As the motor speed increases, the duration where constant regenerative current flowing back into the battery also increases. When the brake pedal force is demanded and exerted to stop a fully-moving motor of speed 660 rpm, it is observed that the regenerative current into the battery last for 3.7s. At the early part when motor speed is 182 rpm, and brake pedal is exerted, the regen-current measured only last for less than a second.
4. The regenerative braking system built in this project is not significant enough because the test is conducted through a free-load benchtest. In a free or zero-load benchtest, basically the BLDC motor is driven by battery, and running without any load. There is no load friction which sustains and prolongs the stopping time of the BLDC motor which will help in regenerative performance. As shown in the graphs plotted, we can clearly observe that the time taken to stop the maximum full-speed of motor at 660rpm is only 3.7s, which is very short. Regenerative performance is not possible to be carried out.
5. In this lab experiment, although the author is able to measure and discuss about the slight regenerative current feed back into the battery when the braking is in process, however, it is still unconfirmed if the regenerative current is able to flow fully into the battery. In order for regenerative current to fully flow to the battery,

$$V_{emf} > V_{battery}$$

And V_{emf} can be calculated with the formula:

$$V_{emf} = K_{emf} X V_{battery}$$

where $K_{emf} =$ back emf constant of the BLDC motor.

In this experiment, the author is unable to acquire the K_{emf} of the BLDC motor used. Therefore, it is not possible to measure the back emf voltage of the motor in order to determine if full regenerative performance is possible. This is because, firstly, without the K_{emf}, the resistance of the motor is not known, therefore the current in the motor cannot be measured. All these details are not being enclosed by the suppliers. Secondly, as mentioned earlier, the motor is running at free-load condition, and it stops very quickly when the brake is applied. Thus, the time is not long enough to let any residual current from the driving voltage to diminish completely. So, calculating back emf is not possible.

6. Full regenerative performance can only be measured and tested efficiently when the whole brake pedal assembly, sensor, controller and battery is all mounted into the vehicles for on-load testing. In this way, the total load weight and friction will be momentarily long enough to stop the car at desired pace, thus ensuring regenerative braking to work. Up till this point, the author is only able to study the regenerative braking on a free-load bench-testing and confirm that the performance is not that good, as the current being fed back into the battery is too little and short. However, the regenerative braking system concept is still present. The prototype which is built along with the sensor is able to simulate regenerative braking mode in the motor controller, and we are able to measure the small regen-current flowing back into the battery.

CHAPTER 5
CONCLUSION

5.1 Conclusion

This regenerative-braking related project will be very helpful for deeper understanding of the implementation of this system into hybrid vehicle. From the design of the modified pedal brake until the configuration of the brake output demand circuit into the motor controller to initiate regen-braking command for the motor operation, these steps serve as a good platform for readers to get an idea on how the regenerative braking system actually works, and importantly, the mechanism and tools involved in the implementation process.

As a conclusion, it can be said that the project has reached most of the targeted objectives, with the construction of hardware prototype for bench-testing which includes fabrication of modified brake pedal with linear sensor, the design of a voltage follower circuit to output stable voltage into the Kelly Controller, as well as testing in the lab to study the performance using the laboratory equipment. There is only part which the author do not expect; that is the condition of the free-load bench-testing which affect the performance of the regenerative braking of the BLDC motor.

5.2 Recommendation

The author would like to recommend another kind of sensor which can be used to detect rotational force displacement of the pedal brake such as the rotational sensor and angular sensor. These sensors may be easier and simpler to be design on the brake pedal, and also producing better result. Another recommendation is that further work and research can be conducted to study the regenerative braking system when the test-bench prototype is fully implemented in the vehicle. With the presence of necessary load and friction from the vehicle, it is believed that the results will be more significant and useful to be presented.

REFERENCES

[1] Carnago, R., Koch, S., Pawlik, B., & Smith, P. (2007). Design of Hydraulic Hybrid Vehicle (HHV) subsystems.

[2] Yoong, M. K., Gan, Y. H., Gan, G. D., Leong, C. K., Phuan, Z. Y., Cheah, B. K., & Chew, K. W. (2010, November). Studies of regenerative braking in electric vehicle. In *Sustainable Utilization and Development in Engineering and Technology (STUDENT), 2010 IEEE Conference on* (pp. 40-45). IEEE.

[3] Cody, J., Göl, Ö., Nedic, Z., Nafalski, A., & Mohtar, A. (2009). Regenerative Braking in An Electric Vehicle. *Zeszyty Problemowe–Maszyny Elektryczne*, *81*, 113-118.

[4] Yeo, H., Kim, D., Hwang, S., & Kim, H. (2004). Regenerative braking algorithm for a HEV with CVT ratio control during deceleration. In *the International Continuously Variable and Hybrid Transmission Congress*.

[5] Guo, J., Wang, J., & Cao, B. (2009, June). Regenerative braking strategy for electric vehicles. In *Intelligent Vehicles Symposium, 2009 IEEE* (pp. 864-868). IEEE.

[6] Wang, F., Yin, X., Luo, H., & Huang, Y. (2012, March). A Series Regenerative Braking Control Strategy Based on Hybrid-Power. In *Computer Distributed Control and Intelligent Environmental Monitoring (CDCIEM), 2012 International Conference on* (pp. 65-69). IEEE.

[7] Feng, W., Hu, Z., Xiao-jian, M., Lin, Y., & Bin, Z. (2007, December). Regenerative braking algorithm for a parallel hybrid electric vehicle with continuously variable transmission. In *Vehicular Electronics and Safety, 2007. ICVES. IEEE International Conference on* (pp. 1-4). IEEE.

[8] Liu, T., Jiang, J., & Sun, H. (2009, April). Investigation to Simulation of Regenerative Braking for Parallel Hydraulic Hybrid Vehicles. In *Measuring Technology and Mechatronics Automation, 2009. ICMTMA'09. International Conference on* (Vol. 2, pp. 242-245). IEEE.

[9] Melius, B., Gressler, B. (2010). "Regenerative Braking in Hybrid Electric Vehicles".

APPENDICES

APPENDIX A

GANTT CHART FYP 1

NO	DETAIL \ WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Title	■	■													
2	Preliminary Research Work and Literature Review		■	■	■	■										
3	Submission of Extended Proposal Defence						■									
4	Determination and Ordering of Required Components							■		■						
5	Design and fabrication of modification of pedal brake to incorporate distance sensor / potentiometer									■	■	■	■	■	■	
6	Configuration of modified pedal assembly with motor controller and associated controller programming												●	●	●	●
7	Bench test of modified pedal brake assembly on rotating in-wheel motor system													●	●	●
8	Oral Proposal Defence Presentation										■	■				
9	Preparation of Interim Report									■	■	■	■	■		
10	Submission of Interim Draft Report														■	
11	Submission of Interim Final Report															■

● Suggested milestone

■ Process

Figure 37: Gantt chart FYP 1

APPENDIX B

GANTT CHART FYP 2

NO	DETAIL \ WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Installation of brake pedal sensor (BPP) into existing brake pedal	■	■	■	■											
2	Design of interface circuit for BPP sensor's connection to motor controller	■	■	■	■											
3	Configuration of modified pedal assembly with motor controller					■	■	■		■	■					
5	Lab simulation to monitor regenerative performance by using lab equipment									■	■	■	■	■	■	■
6	Preparation for Progress Report													■		
7	Submission of Draft Final Report														■	
8	Submission of Final Report															■
9	Submission of Technical Paper															■

- ● Suggested milestone
- ■ Process

Figure 38: Gantt chart for FYP 2

APPENDIX C

EARLY PROTOTYPING IMAGES

Figure 39: List of earlier stage of project components used

APPENDIX D

IN-LAB TESTING AND WORKS

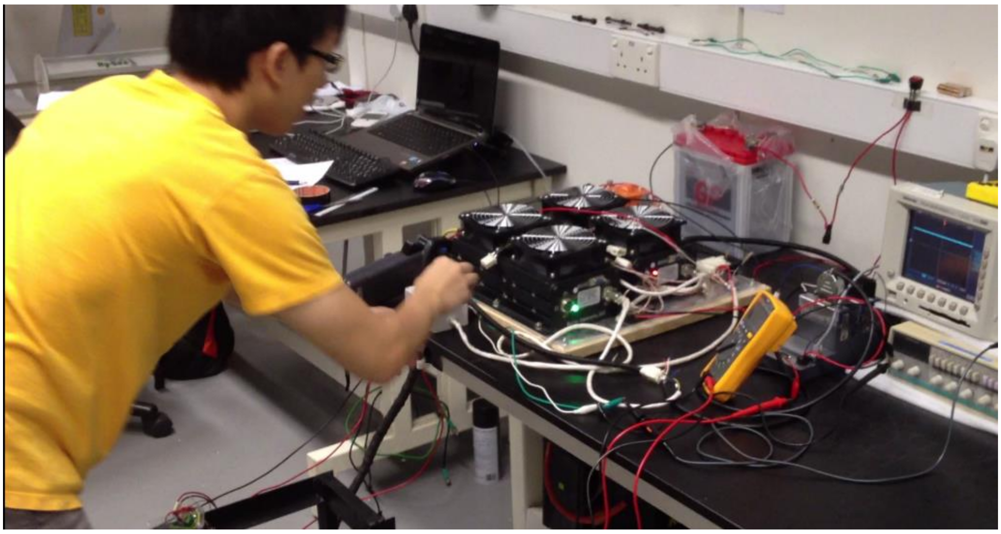


Figure 40: Testing the brake demand force on generated current

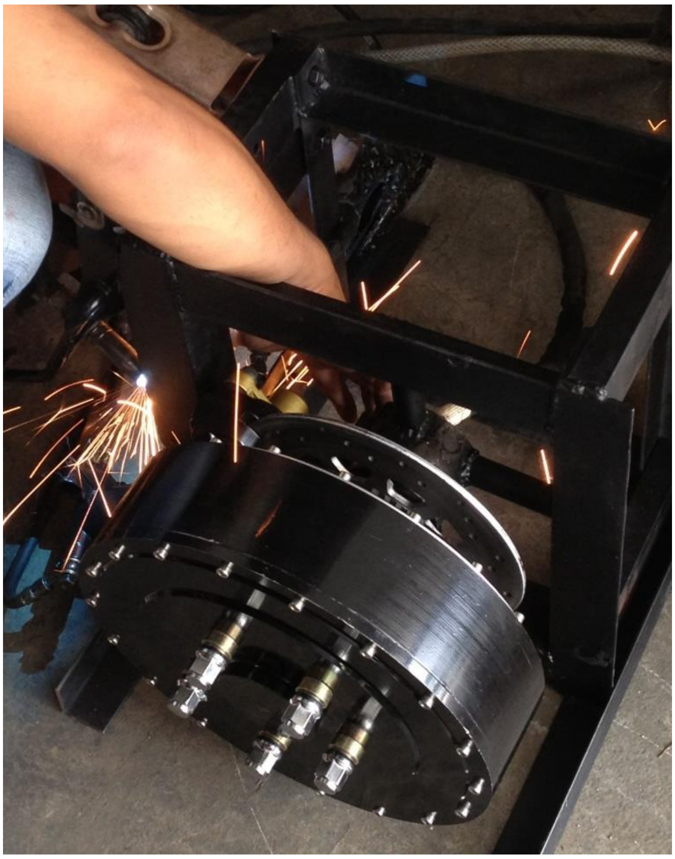


Figure 41: Wielding process for brake caliper

APPENDIX E

LAB EQUIPMENTS

Figure 42: Lab equipment used (Oscilloscope, Tachometer, Clamp meter and Voltmeter)