

ANALYSIS OF REGENERATIVE BRAKING USING BRUSHED DC MOTOR

By

Mohammad Ryan Avila Ramadhan  
11111035

BACHELOR'S DEGREE  
in

Mechanical Engineering - Mechatronics Concentration  
Faculty of Engineering and Information Technology



SWISS GERMAN UNIVERSITY  
The Prominence Tower  
Jalan Jalur Sutera Barat No. 15, Alam Sutera  
Tangerang, Banten 15143 - Indonesia

**Revision after Thesis Defense on 19 January 2018**

### STATEMENT BY THE AUTHOR

I hereby declare that this submission is my own work and to the best of my knowledge, it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma at any educational institution, except where due acknowledgement is made in the thesis.

Mohammad Ryan Avila Ramadhan

Student

Date

Approved by:

SWISS GERMAN UNIVERSITY

Benny Widjaja S.T. M.T.

Thesis Advisor

Date

Dr. Irvan Kartawiria, S.T., M. Sc.

Dean

Date

Mohammad Ryan Avila Ramadhan

## ABSTRACT

### ANALYSIS OF REGENERATIVE BRAKING USING BRUSHED DC MOTOR

By

Mohammad Ryan Avila Ramadhan  
Benny Widjaja S.T. M.T, Advisor

SWISS GERMAN UNIVERISTY

The purpose of this study is to analyze and develop a Regenerative Braking System using a Permanent Magnet DC Motor. The aim is to create a system capable of triggering a Regenerative Braking event and then boosting that energy to charge a storage element. The system utilizes an H-bridge circuit to drive the DC motor, with a Boost Converter to regulate the input to the battery load. Gate drivers are implemented to allow faster switching of the semiconductors. DC motor parameters will be analyzed to better understand the behavior of the motor. Back-emf measuring will also provide extra insight on the braking energy that can be potentially recovered during each regenerative phase.

*Keywords: Regenerative Braking, Permanent Magnet DC Motor, H-Bridge, Gate Driver, Metal-Oxide Semiconductor Field Effect Transistor*



## **DEDICATION**

I dedicate this work to God,  
My dearest Mom and Dad,  
For providing me with unfailing support,  
And continuous encouragement throughout my years of study.



## ACKNOWLEDGEMENTS

I am grateful to God for the good health and wellbeing to complete this thesis. I would like to thank Marshanette Regina Maramis for all the love and support she has given me throughout this thesis.

I also wish to express my sincere thanks to Benny Widjaja, my advisor, for giving me the chance to finish the research and provide me with all the necessary inputs for the successfulness of this thesis.

I also thank my parents and sisters for the never-ending encouragement, prayer, support and attention.

Not to forget, I also place on record my sense of gratitude to everyone, who directly or indirectly have contributed their support by giving encouragement and support in this venture. And lastly I would like to thank my fellow classmates for all their support and insight in which has helped me to finish this study.

SWISS GERMAN UNIVERSITY

## TABLE OF CONTENTS

	Pages
<b>STATEMENT BY THE AUTHOR.....</b>	<b>2</b>
<b>ABSTRACT.....</b>	<b>3</b>
<b>DEDICATION.....</b>	<b>5</b>
<b>ACKNOWLEDGEMENTS .....</b>	<b>6</b>
<b>CHAPTER 1 – INTRODUCTION .....</b>	<b>14</b>
1.1 Background.....	14
1.2 Research Problems.....	15
1.3 Research Objectives.....	16
1.4 Significance of Study.....	16
1.5 Scope and Limitations.....	16
<b>CHAPTER 2 – LITERATURE REVIEW.....</b>	<b>17</b>
2.1 Introduction.....	17
2.2 Types of Electrical Braking .....	18
2.2.1 Regenerative Braking System.....	18
2.2.2 Dynamic Braking .....	18
2.2.3 Plugging .....	19
2.3 Motor Controller .....	19
2.3.1 H-Bridge Circuit .....	20
2.4 Electronic Switches.....	21
2.4.1 Comparison Between Controllable Switches.....	22
2.4.2 Bipolar Junction Transistors (BJT).....	22
2.4.3 Metal Oxide-Semiconductor Field Effect Transistors (MOSFETs).....	24
2.5 Gate Drivers .....	26
2.5.1 Bootstrap Circuit.....	27
2.5.2 Charge Pump Circuit.....	29
2.6 DC-DC Converter .....	30
2.6.1 Step-Up (Boost) Converter .....	31

2.6.1 Step-Down (Buck) Converter .....	37
2.7 Battery .....	38
2.7.1 Valve-Regulated Lead-Acid battery (VRLA).....	38
2.8 Pulse Width Modulation .....	39
<b>CHAPTER 3 – RESEARCH METHODS .....</b>	<b>41</b>
3.1 Methodology Overview .....	41
3.2 Microcontoller.....	42
3.3 Motor Controller .....	46
3.3.1 Selection of the MOSFET.....	46
3.3.2 Selection of the Gate Driver IC.....	55
3.3.3 Gate Driver Design and Component Selection.....	60
3.4 Charge Pump Design .....	63
3.5 DC Motor .....	65
3.5.1 Initial Testing .....	68
3.5.2 Parameter Measurements .....	69
3.6 Boost Converter .....	72
3.6.1 Boost Converter Software Simulation .....	78
3.6. Current Sensing.....	81
3.7 Final Circuit Design.....	81
3.8 Regenerative Braking Switching Scheme.....	81
3.9 Pulse Width Modulation (PWM) Method.....	84
3.10 PCB Design Layout .....	84
3.11 Testing Methods.....	87
3.11.1 Gate Driver Transient Response Testing .....	87
3.11.2 MOSFET Testing.....	87
3.11.3 Charge Pump Testing.....	87
3.11.4 Boost Converter Switching.....	87
3.11.5 Delay Time Testing.....	88
3.11.6 Regenerative Braking Test.....	88
<b>CHAPTER 4 – RESULTS AND DISCUSSIONS .....</b>	<b>89</b>



4.1 H-Bridge Test and Result.....	89
4.1.1 Gate Driver Transient Response Test .....	91
4.1.2 MOSFET Gate-Source Voltage Test .....	96
4.1.3 MOSFET Drain-Source Voltage.....	99
4.2. Charge Pump Test Results .....	104
4.3 Boost Converter Test Results.....	110
4.4 Regenerative Braking Test Results .....	113
4.4.1 Regenerative Braking Type I and II.....	113
4.5 PCB Design Result .....	116
4.6 Arduino Delay Time Testing .....	116
<b>CHAPTER 5 – CONCLUSIONS AND RECOMMENDATIONS .....</b>	<b>119</b>
5.1 Conclusions.....	119
5.2 Recommendations.....	120
<b>GLOSSARY.....</b>	<b>121</b>
<b>REFERENCES.....</b>	<b>122</b>
<b>APPENDIX A – SCHEMATIC DIAGRAM .....</b>	<b>123</b>
A.1 Main Board Diagram .....	123
<b>APPENDIX B –DATASHEETS .....</b>	<b>124</b>
B.1 Arduino Mega 2560 .....	124
B.2 IRFZ44N N-Channel MOSFET .....	129
B.3 IR2110 Gate Driver.....	131
B.4 TLC555 CMOS Timer .....	134
B.5 MC34063 Switching Regulator.....	138
B.6 ACS712-5A Hall Effect Current Sensor .....	141
<b>APPENDIX C – ARDUINO CODE .....</b>	<b>146</b>
C.1 Main Program.....	146
<b>APPENDIX D – BILL OF MATERIALS.....</b>	<b>151</b>
<b>CURRICULUM VITAE.....</b>	<b>152</b>