REGENERATIVE BRAKING SYSTEM USING SUPERCAPACITOR

By

Mohammad Muzakkir b Mohamad Hanafiah

Final report submitted in partial fulfillment of
The requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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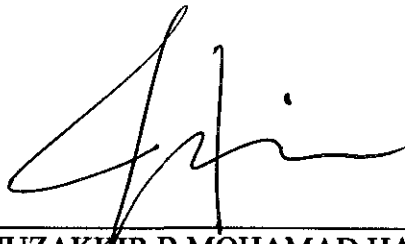(ELECTRICAL & ELECTRONICS ENGINEERING)

Approved by,

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(Assoc Prof Dr Mumtaj Begam Kasim Rawthar)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
SEPTEMBER 2011

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.

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MOHAMMAD MUZAKKIR B MOHAMAD HANAFIAH

ABSTRACT

Recently, a lot of people are concern on the environmental pollution that is getting worse day to day and energy crisis that would implicate to the global economy. Most organizations and car manufacturers are putting to a rest on the dependencies of natural resources and try to find a new solution to the problems. Therefore, Electric Vehicles (EVs) are seen to be a promising alternative to the current main energy resources, natural gases. Even though the electric vehicles are seen to be the perfect candidate for this problem, EVs are still suffering from the major problem of any EVs that is short driving range. Hence, a system to manage the energy consumption of an EV is should be developed. According to a study on electric car braking energy consumption, the energy consumed during braking is around 43% of the total energy of the whole process [1].

When an electric car running in urban city without regenerative braking system, a lot of energy is wasted through the braking, while on the other hand, during the acceleration the battery's current may reach as high as 450 ampere [1][2]. A regenerative braking system is comprised of hydraulic motor, hydraulic accumulator, electric controller and other components. During braking, the transmission shaft is still rotating which then will drive the hydraulic pump under the inertia. The rotation allows energy to be regenerated during the braking and will be stored, preventing from the energy to be wasted. During the accelerating, the energy stored from the braking will be used again to feed the energy consumption of the system [3]. Implementing the regenerative braking system allows the energy to be recycled. The energy that will be used during the decelerating and accelerating is merely from the energy used during braking.

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1.1 Background of Study

Regenerative braking system is a braking system that is applied in most of electric/hybrid cars and allows recovering energy lost during braking. The recovered energy is stored in energy storage (i.e. battery or supercapacitor) for later use [4]. In recent studies of Toyota's Prius Generation 3 has shown that the regenerative braking system may regain around 33% to 50% of energy under normal city driving which is better than wasting all the energy through the friction in the conventional braking system [5].

Understanding the basics of braking system is essential before moving on to the technical part of this paper. In this project, it is important for us to distinguish the difference between conventional braking system and regenerative braking system.

i. Conventional Braking System

In conventional braking system, when the driver pushes the brake pedal, the brake pads produce friction to the brake rotor slowing down the car until it stops. The conventional braking system decelerates the car by converting the kinetic energy of the moving tires into heat produced by the friction between the brake pads and the brake rotor. The most common types of conventional braking systems are the disk brake and the drum brake [6].

In general, these two types of braking systems decelerate a vehicle by producing the friction through brake pads to the brake rotor, converting kinetic energy to heat energy. The converted heat energy is considered to be energy loss since it cannot be recovered and it is a waste because the kinetic energy produced by the velocity of the car is in a huge amount. One way to recover the kinetic energy is introducing the regenerative braking system to the car [6].
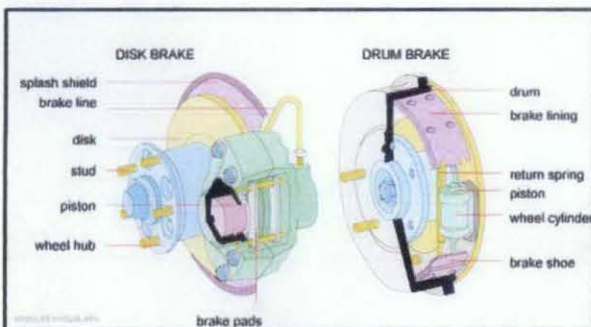
Figure 1: Two types of the most common conventional brakes found in any car: disk brake and drum brake.

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ii.   Regenerative Braking System

Regenerative braking system allows recapturing the kinetic energy during the braking and storing it in the battery or supercapacitor rather than converting it into heat loss as in the conventional braking system does [4][6]. When the driver steps on the brake pedal of a vehicle that applies regenerative braking system, the system puts the vehicle's electric motor in reverse mode which caused the vehicle's motor to run backwards. At certain speed, when the brake is applied, the momentum of the vehicle caused it to slowly decelerate when the electric motor running in backward. At the same time, while the electric motor running backwards, it also acts as electric generator producing electricity and stores in the battery or supercapacitor.
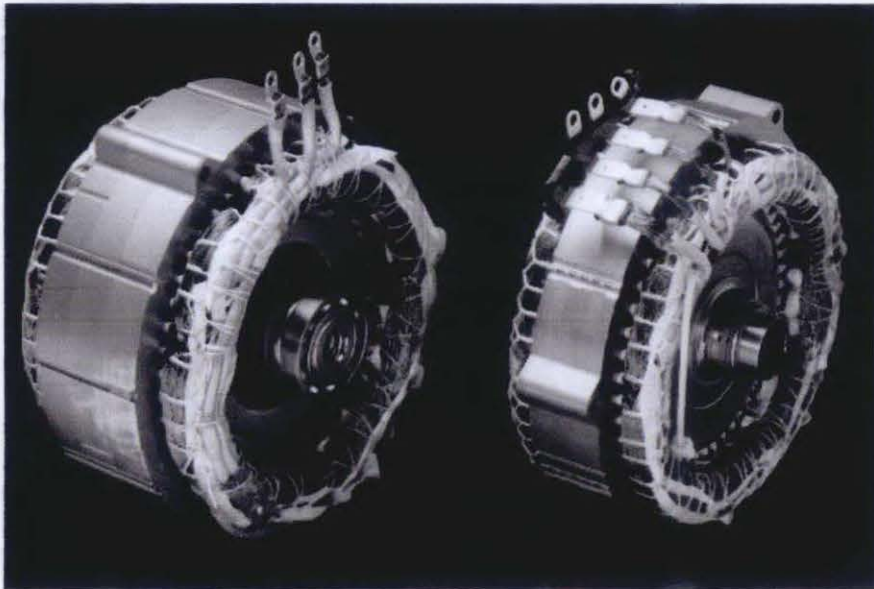
Figure 2: Hybrid transaxle components that can be found in
Second Generation Prius.

Regenerative braking system can be implemented to different types of energy storage devices such as battery and bank of capacitors. This paper will focus on the development of regenerative braking system using supercapacitor as the energy storage device.

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1.2   Problem Statement

Regenerative braking system acts as an energy recovery mechanism which allows a vehicle to recover the energy loss during the braking by converting the kinetic energy into another form. The energy will be stored for later use in an energy storage element. The criteria that need to be fulfilled in choosing the suitable energy storage element are as followed:

- Charging and discharging thousands of times without performance deterioration to withstand fast and sudden discharge during acceleration and fast charge during braking.
- High specific power which is necessary to accelerate the vehicle right after braking [7][8].

This paper will focus on implementing the supercapacitor as the energy storage element. Supercapacitor is chosen as the energy storage element because it can be charged and discharged over and over again without performance deterioration and compare to a conventional battery, supercapacitor's specific power is ten times higher which allows it to supply higher energy [9].

1.3   Objectives and Scope of Study

1.3.1 Objectives

The objectives of my research are:

- To determine the most suitable component to be used as the energy storage element by providing information on the specific power (W/I), specific energy (Wh/I) and the performance deterioration of the selected components.
- To design the circuit for the system based on the buck-boost converter circuit for supercapacitor charging and discharging mode during acceleration and braking.

1.3.2 Scope of Study

The scope of study revolves around the development of the circuitry for switching modes between the charging mode during braking and discharging mode during acceleration, simulation of the developed circuit using software and lab components and analysis of resulting energy produced and the efficiency of power during regeneration and release state. The study is comprised of two stages, the first stage is to study and understand the regenerative braking system. The second stage is to simulate the system using computer software and lab components.

The study is within the scope of designing electrical circuits and electrical machines. Based on the earlier studies and case histories, regenerative braking system has proven to reduce fuel consumption around 25 to 50 percent. According to www.HybridCars.com website, regenerative braking systems could provide even more impressive gains, potentionally reducing fuel use by 25 to 50 percent. The added efficiency of regenerative braking also means less pain at the pump, since hybrids with electric motors and regenerative brakes can travel considerably farther on a gallon of gas, some achieving more than 50 miles per gallon at this point and that is something that most drivers can really appreciate.

Chapter 2: LITERATURE REVIEW & THEORY

2.1 Regenerative Braking System

2.1.1 Energy Storage Elements

Energy storage device is a device that stores electrical energy such as batteries and capacitors. The difference between the two devices is the form of the electrical energy is stored. Battery stores the electrical energy in the form of chemical while capacitor stores electrical energy in the electrical field between its two conductors.

    i.   Electrical energy storage mechanism of a battery.

Battery stores electrical energy in chemical form and thus converts chemical energy into electrical energy. It consists of one or more voltaic cells. Each voltaic cell comprises of two half cells, the negative electrode (the cathode) and the other is the positive electrode (the anode), which are connected in series connection to a conductive electrolyte. The battery is powered by the electron transfers during redox reaction occurs. During redox reaction, two reactions occur simultaneously, reduction occurs in the cathode, while oxidation occurs in the anode. The electrodes are made of different materials in order for redox reaction to occur. Both electrodes are not contacted but electrically connected by the electrolyte (solid or liquid) [9].
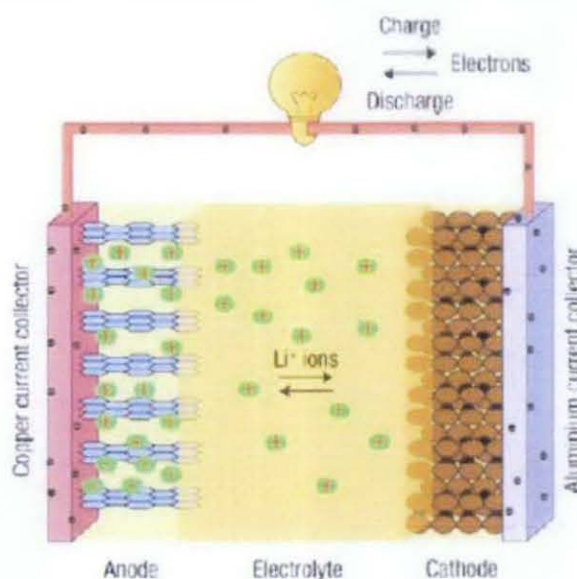

Figure 3: Li-ion battery diagram

ii.   Electrical energy storage mechanism of a supercapacitor.

A supercapacitor stores electrical energy as a charge (concentration of electron) in an electrochemical double layer on a surface of a material. Consequently, they are also quite properly referred to as electric double layer capacitors. The energy density is 10 times higher than in a classical battery. Supercapacitors move electrical charges between solid-state materials with no chemical or phase changes taking place, the process is highly reversible and the discharge-charge cycle can be repeated over and over again [8][9].

Electrodes and current collectors are the main components of supercapacitor. The electrodes are immersed in electrolyte for electrons to flow. The electrodes are separated by a dielectric separator which may comprise of water solution of potassium hydroxide (KOH) or sulphuric acid (H_2SO_4). The purpose of using dielectric made of these water solutions of KOH or H_2SO_4 is to limit the voltage to 1V. Above this value, water will decompose to hydrogen and oxygen. The electrodes are made of porous carbon and when a voltage is applied between the electrodes, negative ions from the electrolyte flow to the positive electrode. In the same time, positive ions from the electrolyte flow to the negative electrodes. The separator prevents the charge to reach the concerned electrode creating indeed a double layer of charge [8][9].
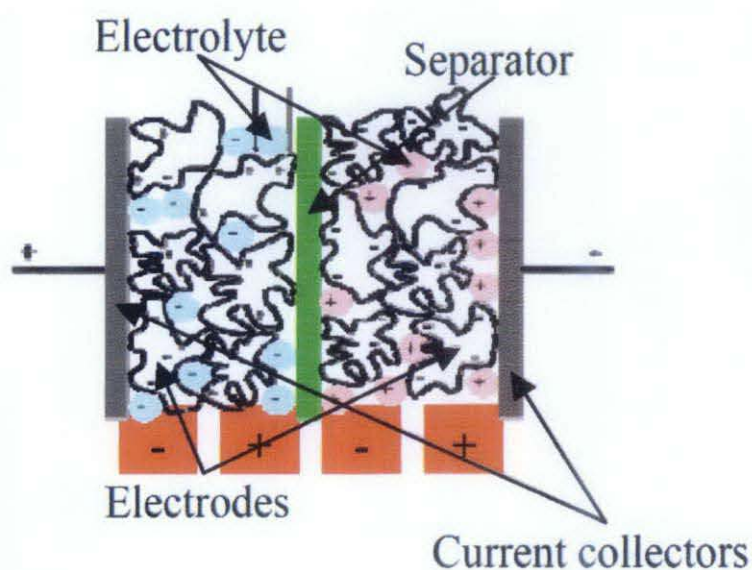
Figure 4: A diagram of supercapacitor

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The amount of energy that can be stored in a supercapacitor is small compared to battery but the energy is released quickly. Supercapacitors is capable to store a larger amount of energy but release the energy slower compared to a simple capacitor. The Ragone diagram below shows the comparison of capacitors, supercapacitors, batteries and fuel cells in terms of specific power (W/I) versus specific energy (Wh/I) [8][9].
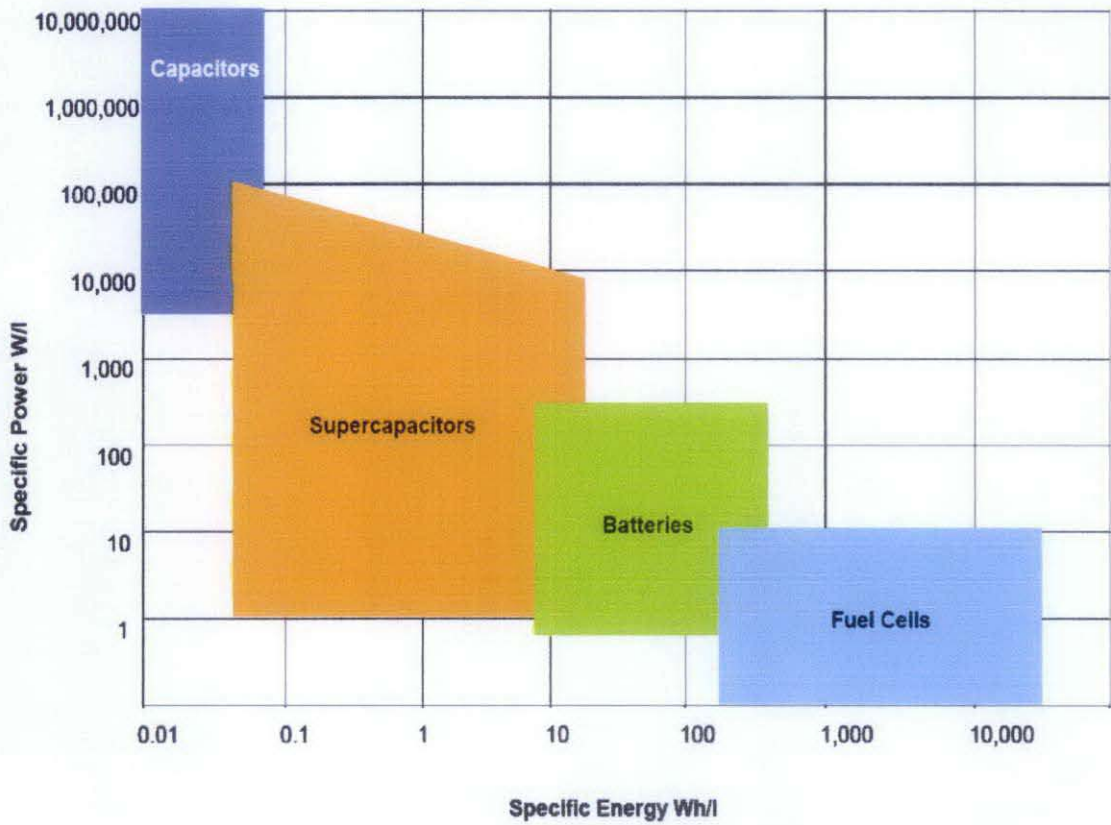
Figure 5: Ragone Diagram – Specific power vs. Specific Energy

The capacitance of a supercapacitorr can reach as high as several hundred farads. The high power density shown of the supercapacitor presents a lot of advantages of supercapacitor compares to battery. Before implementing the supercapacitor in the system, a close look on the components development to predict the electrical and energetic behavior of supercapacitor is taken into consideration. Figure 6 shows an equivalent model of a supercapacitor. The model is used only for the principle verification [10].
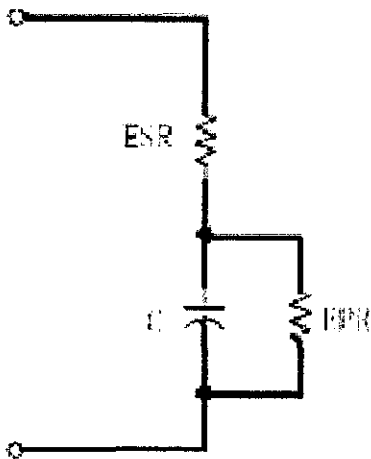
Figure 6: Equivalent model of Supercapacitor
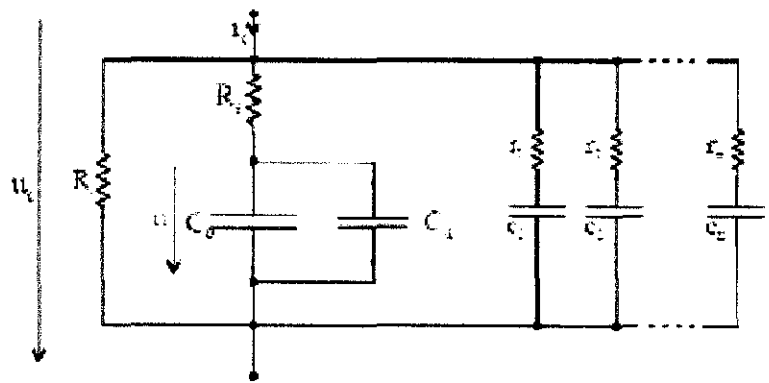
Figure 7: Multi-branch model of a supercapacitor

Illustration of the supercapacitor model can be seen by the equivalent model of a multi-branch RC (resistor-capacitor) circuit (see Figure 7). The supercapacitor is illustrated as an infinite number of RC branches connected in parallel to show the capacitive behavior of the supercapacitor [11][12].

The multi-branch model of supercapacitor shows the parallel connection of capacitors. The total capacitance of the model with capacitors connected in parallel is:

Total Capacitance

$$C_{total} = C_1 + C_2 + C_3 + \ldots + C_n$$

n = number of capacitors in parallel.

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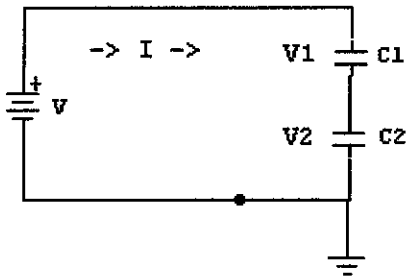
Figure 8: Capacitors Connected in Series   **Figure 9**: Capacitors Connected in Parallel
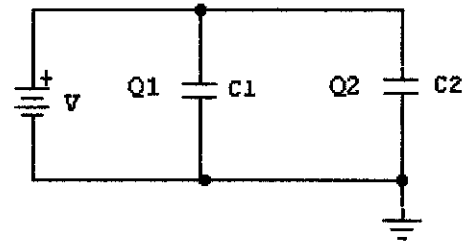
To differentiate between the series and parallel connection of capacitors in terms of the capacitance and voltage, both circuits above are shown to explain the differences [13].

Series Connection

In series capacitor connection (see figure 8) the voltage V from source is divided among the two capacitors, C_1 and C_2. By definition the total Capacitance will be,

$$C_{total} = Q/V \text{ or } Q/(V1 + V2)$$

$$1/C_{total} = (V1 + V2)/Q = V1/Q + V2/Q$$

$$1/(Q/V1) + 1/(Q/V2) \qquad [13]$$

Hence, the total capacitance,

$$1/C_{total} = 1/C_1 + 1/C_2 \qquad [13]$$

Parallel connection

For capacitors connected in parallel (see figure 9), the voltage across either one is V. The charge in C_1 is Q_1 and the charge in capacitor C_2 is Q_2. By the electrical definition of capacitance we can also state that:

$$C_1 = Q_1/V \text{ and } C_2 = Q_2/V \qquad [13]$$

The total capacitance,

$$C_{total} = Q_1/V + Q_2/V = C_1 + C_2$$

By looking at the fundamental of the total capacitance and voltage of capacitors in both connections, we can relate to the Multi-branch model of supercapacitor earlier. The connection of the capacitors in Multi-branch model is parallel which will produce the total capacitance of the model is the sum of capacitance of each capacitor. This shows that supercapacitor allows more energy to be stored but voltage will not increase linearly during charging [14].

2.1.2 Supercapacitor

Supercapacitor, or also known as ultracapacitor and electrochemical capacitor, achieves the capacitances several orders of magnitude larger than conventional capacitors by utilizing high surface area electrode materials and thin electrolytic dielectrics.

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

C = Capacitance of the capacitor
A = The area of overlap of the plates of the capacitor
ε_r = Dielectric constant of the material between the plates
ε_0 = Electric constant
d = separation of the plates

As seen from the equation above, the capacitance is increased when A, area of the plates is increased and d, separation of the plates is reduced. Supercapacitor acquires high capacitances than conventional capacitor by having higher area of the plates and reduced separation between the two plates. By having these characteristics, supercapacitor is able to attain greater energy densities and at the same time, maintaining the high power density. To make a comparison between the supercapacitor and conventional capacitor, supercapacitor with the same weight can store 2000 to 6000 times energy [15]. The discharge current value of a supercapacitor can reach up to thousand amperes while the energy density is higher than a conventional capacitor for a

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few hundred times. Compared to a battery, the instantaneous discharge power of a supercapacitor is dozen times higher. This shows that, the supercapacitor has high efficiency and excellent operational life [15].

The supercapacitor that will be used as a reference in this paper is the supercapacitor produced by Kamcap Company. Connecting 120 units of supercapacitors in series will give a working voltage from 200V to 300V dc with rated capacity of 3.3 farads and maximum charge current 60A.

Supercapacitor has the advantages in many ways such as high charge rate, high efficiency, high power density, long cycle life and requires no maintenance makes the supercapacitor to be preferred as the energy storage system (ESS) for the system [15].

2.1.3 DC/DC Converter Circuit for Charging and Discharging Supercapacitor

Figure 10 shows the diagram of the DC/DC converter. The values of current inductor I_L and capacitor voltage C or load voltage u_0 are both constant when inductance L and capacitance C are both high enough.

The DC/DC converter has two modes of operations which are boost operation and buck operation. During boost operation, the supercapacitor will be discharged and works in the acceleration of the motor. While in buck operation, the the supercapacitor will be charged and works in the deceleration.
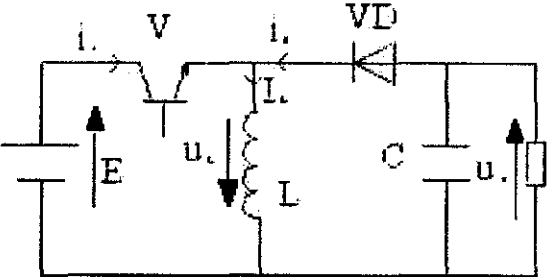
(a)
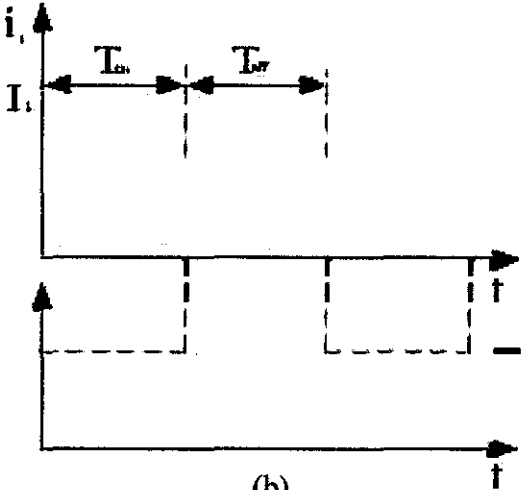
(b)

Figure 10: DC/DC Converter Circuit

2.1.3.1 DC/DC Converter – Buck Boost Converter

In boost mode of operation, the switch V will be turned on and allows the energy to be taken from electrical source, E and stored in the inductor L. During this cycle, the current i_1 is flowing from the electrical source through the switch into the inductor L as shown in Figure 10 (a). The voltage across the capacitor C is almost constant. During the next cycle, the switch V is turned off, allowing the energy stored in the inductor L to be transferred into C and the direction of the current i_2 is as shown as in Figure 10 (a).

In the steady state, during the cycle of T, the voltage u_L across as seen across the inductor L integral of time is zero, which is,

$$\int_0^T u_L \, dt = 0$$

During the first cycle, V is turned on which makes $u_L = E$, in the next cycle, V is turned off and makes the $u_L = -u_0$. So,

$$E t_{on} = U_c t_{off}$$

Therefore, the output voltage is,

$$\frac{t_{on}}{t_{off}} E = \frac{t_{on}}{T - t_{on}} E = \frac{a}{1-a} E$$

If the values of ratio a is changed, the supply voltage will not be equal to the output voltage. When $0 < a < \frac{1}{2}$, the DC/DC converter works in the boost operation mode. When $\frac{1}{2} < a < 1$, the DC/DC converter works in the buck operation.

The current i_1 and i_2 of the load are shown in Figure 1. I_1 and I_2 represent the two average values respectively. If there is sufficiently low pulse current, the following formula is founded

$$\frac{I_1}{I_2} = \frac{t_{on}}{t_{off}}$$

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Rearranging the statement above statement,

$$I_2 = \frac{t_{off}}{t_{on}} I_1 = \frac{1-a}{a} I_1$$

If V, VD are used without losing, then

$$EI_1 = U_o I_2$$

Based on this equation, it can be seen that the input power and the output power are equal.

2.1.3.2 Control Strategy of DC/DC Converter

In the process of braking, the motor is generating electricity. The energy produced during this interval is called regenerative energy which will be fed back to the supercapacitor for storing and later use. This energy is fed back to the supercapacitor through the diode rectifier that is associated with the inverter and as DC/DC converter. When accelerating, the converter will introduce the energy from the supercapacitor to motor.

The IGBTs (Insulated Gate Bipolar Transistor) in the system is periodically turning on and off at a controlled duty cycle as the current in the DC converter becomes pulsating current. Although the current in the DC converter becomes pulsating current, the output current maintains continuous smooth because of the presence of the inductance coil, freewheeling diode and filter capacitor. The regenerative braking control system is shown in Figure 11 and Figure 12. The charging process of the supercapacitor is controlled by a second current-control loop.
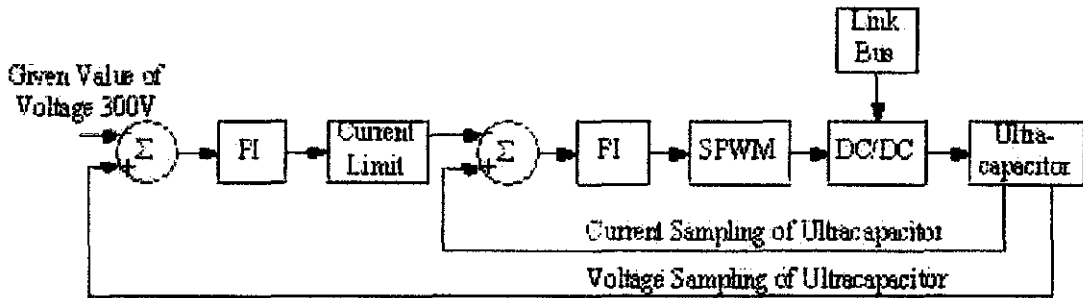

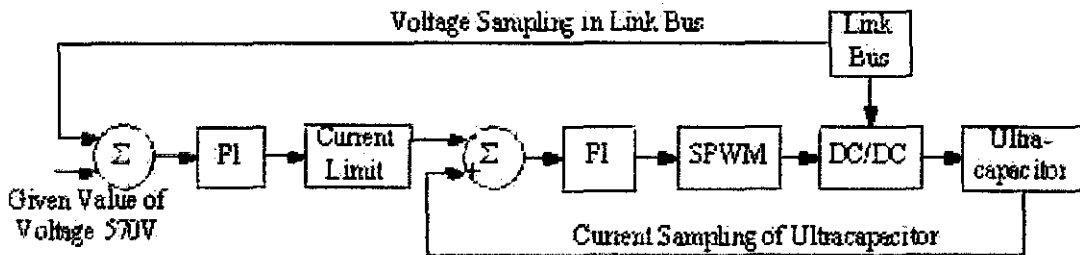**Figure 11**: Control Principle of DC/DC converter when supercapacitor is charging

Figure 12: Control Principle of DC/DC converter when supercapacitor is discharging

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2.1.3.3 Boost Converter

Figure 13 shows the simulation model of the control principle for the DC/DC converter when it is discharging the supercapacitor. The circuit is designed in PSIM simulation software to evaluate the effectiveness and availability of the control principle of the regenerative braking system.

During boost operation, the motor is in driving mode and the supercapacitor will be discharged. The IGBT2 in the DC/DC converter will be turned on and off at a controlled duty cycle which will transfer the required amount of energy from the supercapacitor to the DC link through the switches. During the first cycle, the IGBT2 is turned ON and IGBT1 is turned OFF, energy is transferred from the supercapacitor and stored in the inductor L1. For the next cycle, when IGBT2 is switched OFF and IGBT1 is turned ON, the energy stored in L1 is transferred into DC link through D1. During the discharges of supercapacitor, the boost converter adjusts the voltage automatically allowing the output voltage to be steady. As seen in the circuit, the double PI closed-loop is adopted with the purpose to ensure the supercapacitor works in a safe, reliable and high efficient condition.
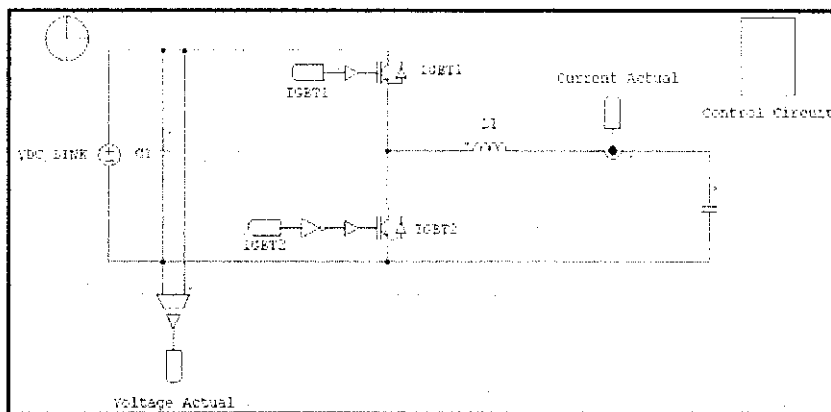
(a) Boost Converter Circuit
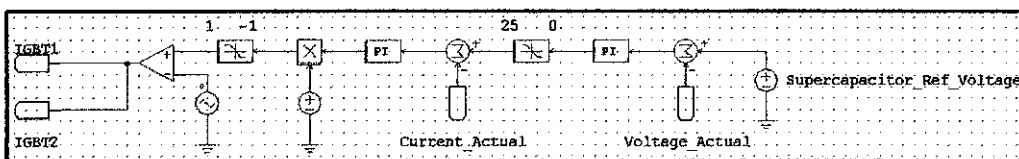
(b) Control Circuit

Figure 13: The Boost Converter Circuit for driving and discharging supercapacitor

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2.1.3.4   Buck Operation

In Figure 14 the DC/DC converter is working in the buck mode of operation which is used to charge the supercapacitor during the regenerative braking. During this mode of operation, the energy transfer is from the DC link to the supercapacitor through the switches.

During the first cycle, the IGBT1 is turned ON and IGBT2 is turned OFF, the energy goes from the link bus to the supercapacitor and part of the energy is stored in the inductor L1. During the next cycle, the IGBT1 is turned OFF and IGBT2 is turned ON, the remaining energy in stored in the inductor L1 is transferred to the supercapacitor. The presence of double PI closed –loop in the circuit is to regulate the duty cycle of the PWM of the IGBTs.
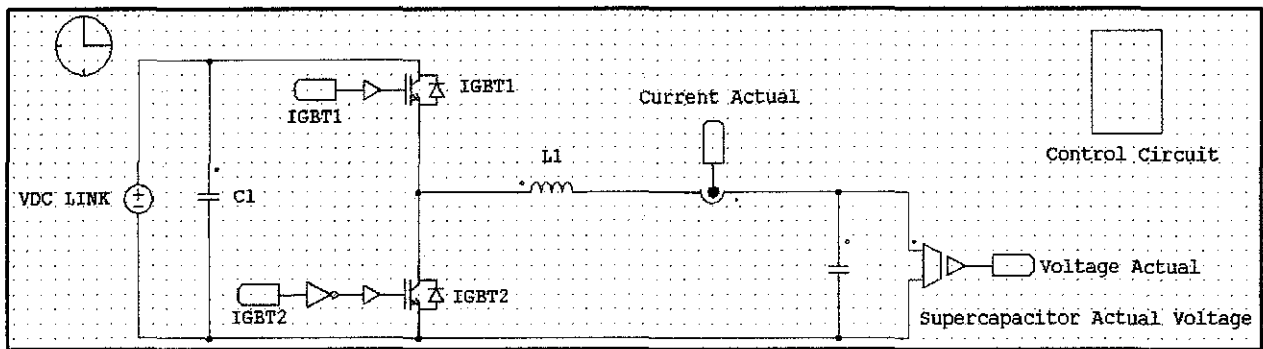
(a) Buck Converter Circuit
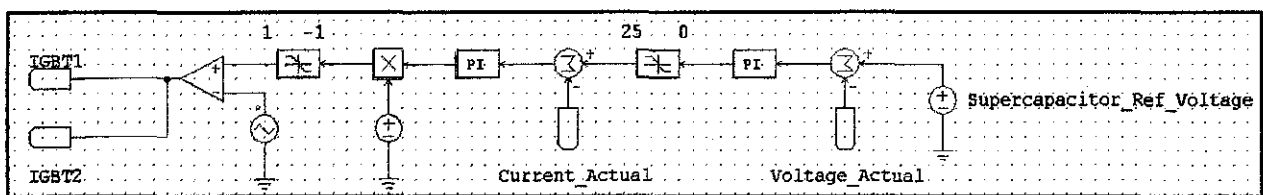
(b) Control Circuit

Figure 14: The Buck Converter Circuit for braking and charging supercapacitor

Chapter 3: METHODOLOGY

3.1 Research Methodology

The research methodology of this project, Regenerative Braking System using Supercapacitor, is comprised of five critical elements. The first element is performing research on the topic. After understanding the fundamental process of the system, modeling the regenerative braking system using PSIM software is performed. The third stage is modeling the system using the lab components and performed the experiments. The data is collected from the experiments and analysis on the data will be performed. The last stage is the documentation of all research works and the outcomes of the project.

3.1.1 Preliminary Research Work

During this preliminary research work stage, a lot of research is performed on the regenerative braking topic. Analysis is performed to a huge number of journal, technical papers and articles related to the subject. Comparison between different types of methods on recapturing the energy from braking is analyzed, the method that provides the best result will be selected to a further research. Apart from that, research on supercapacitor is conducted to illustrate the advantages and disadvantages of implementing the supercapacitor in the system.

3.1.2 Model Development

The development of the system is essential to simulate the real system on computer using computer software. The simulation is chosen to perform because simulation helps us to visualize the real working system in computer. The advantages of using simulation software instead of real working system are simulation can be performed many times and variables can be changed accordingly to fit for the best result. Simulation also does not cost a lot and provide with almost similar result to the real working system. For this project, the software that will be used to simulate the system is Power Simulation (PSIM) software. Later after this stage, the model will be used to perform in the lab experiment.

3.1.3 Lab Experiment

The developed model from the previous stage will be implemented in this stage to perform the lab experiment. The lab experiment is conducted to test for the efficiency and accuracy of the model in the real working system. Through this step, the error produce by the simulation result can be eliminated, discussion on the differences between the two results from different environments will help to illustrate the whole process and working principle of the system. The lab experiment will be conducted at Power Electronics lab at block 22.

3.1.4 Result analysis and discussion

The results of the simulations and lab experiments are collected to performed analysis. The actual result collected from both simulations and lab experiments will be compared with the expected result. The analysis will be performed to state the differences and similarities if any. The analysis will be discussed with the lecturers and experts. The simulations and lab experiments will have a re-run to get the ideal result that will fit with the objectives of this project.

3.1.5 Final Documentation

The literature review, methods used to perform this project, results and analysis will be documented for future references. All of the documents necessary for this project will be collected thoroughly and according to the chronology. This should be done to avoid the data loss.
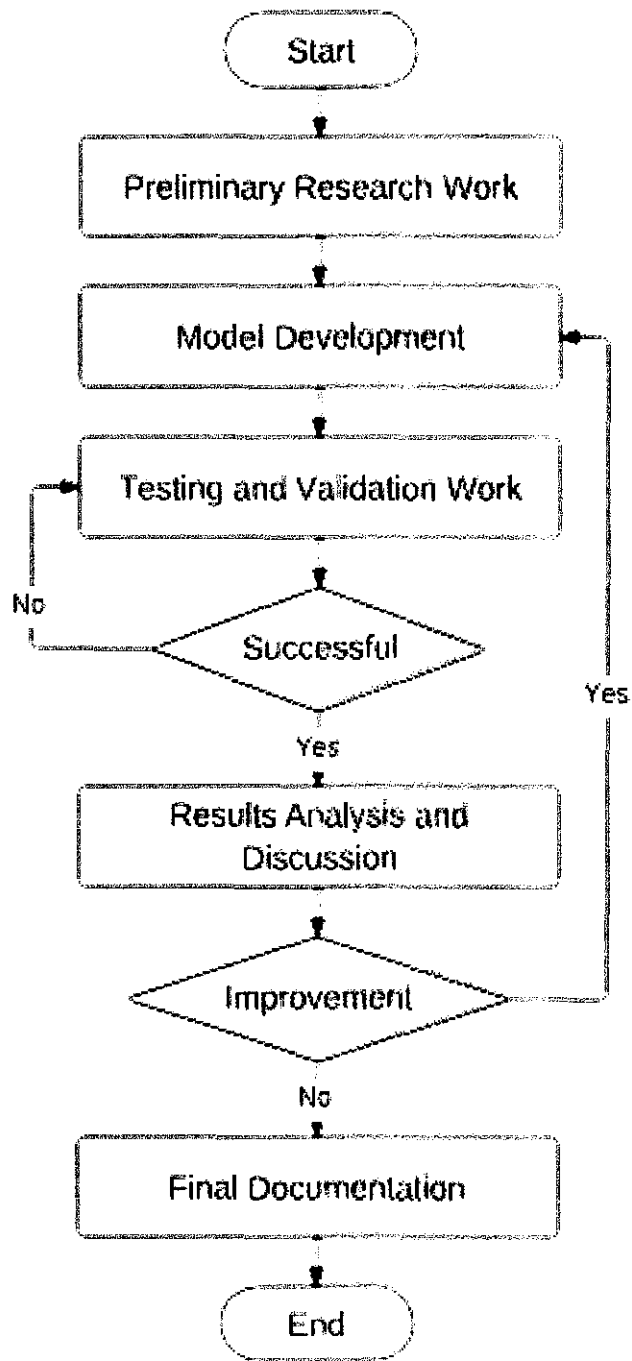
Figure 15: Flow Chart of Final Year Project

3.2 Key Milestones

At the beginning of this project, a key milestone is constructed to set the expected time for stage of a work or process of the project to end. This is an essential element to ensure the progress of the project is in schedule. The key milestone for both first and second semesters is as shown below.

FIRST SEMESTER															
No	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Completion of Preliminary Research Work														
2	Completion of PSIM Simulation Experiment														
SECOND SEMESTER															
No	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	Completion of PSIM Simulation														
4	Completion of Data Comparison														
5	Completion of Result and Discussion														
6	Completion of Final Documentation														

Figure 16: Table of Key Milestones for 1st and 2nd Semester

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3.3 Gantt Chart

The Gantt chart shown below is the timeline of the project for both 1st semester and 2nd semester when this project is commenced. The schedule of each timeline may differ from the expected timeline depending on the work progress.

3.3.1 Gantt Chart: First Semester

No	Detail/ Week	1	2	3	4	5	6	7	Mid-Semester Break	8	9	10	11	12	13	14
1	Selection and Confirmation of Project Title	■														
2	Preliminary Research Work on Related Topics															
3	Submission of Extended Proposal						■									
4	Simulation Experiment															
5	Proposal Defense										■					
6	Simulation Experiment Continues															
7	Submission of Interim Draft Report														■	
8	Submission of Interim Final Report															■

Figure 17: Gantt Chart for 1st Semester

3.3.2 Gantt Chart: First Semester

No	Detail/ Week	1	2	3	4	5	6	7	Mid-Semester Break	8	9	10	11	12	13	14
1	PSIM Simulation Process	▨	▨	▨	▨											
2	Data Comparison					▨	▨									
3	Submission of Progress Report									■						
4	Result and Discussion										▨	▨				
5	Pre-EDX												■			
6	Submission of Draft Report													■		
7	Submission of Dissertation														■	
8	Submission of Technical Paper														■	
9	Oral Presentation														■	
10	Submission of Project Dissertation															■

Figure 18: Gantt Chart for 2nd Semester

3.3.3 Tools Required For the Project

The basic necessary tool for this project to commence is the simulation software, PSIM. PSIM software is simulation software that allows the user to perform circuit modeling and simulation of the project. PSIM simulation software is manufactured by the Powersim Inc., a leading company providing CAD software and consulting services for power electronics and motor control applications. PSIM is most suitable software for power electronics and motor control because the software is specifically designed for that purposes. PSIM provides a user-friendly interface that allows the user to model and edit the project easily. The software also allows the user to run a graphical simulation and analyze the results using its graphical display program, SIMVIEW.

Other tool that is used during the simulation throughout this project is:

- MATLAB

Chapter 4: RESULTS AND DISCUSSIONS

The regenerative braking system is developed using a DC-DC converter which alternately charges and discharges the supercapacitor under its modes of operations and in this case, bidirectional buck-boost converter is chosen with the aim to adapt with the current and voltage levels. The two operating modes of the DC-DC converter are **Boost Mode** and **Buck Mode**. For a bidirectional buck-boost converter, the control input is the duty cycle of the converter that is triggered to the IGBTs in the system. By changing the duty cycle, the voltage and current of the system's DC link can be regulated. The simulation of the system is performed using PSIM simulation software. The DC-DC converter operation modes, buck and boost operation modes are simulated respectively.

4.1. Boost Mode

For Boost operation mode, the converter works as a boost converter which will discharge the supercapacitor. In this operation mode, the IGBT2 in figure 19 is switched on and off at a controlled duty cycle with the purpose to transfer the energy from supercapacitor to DC link.
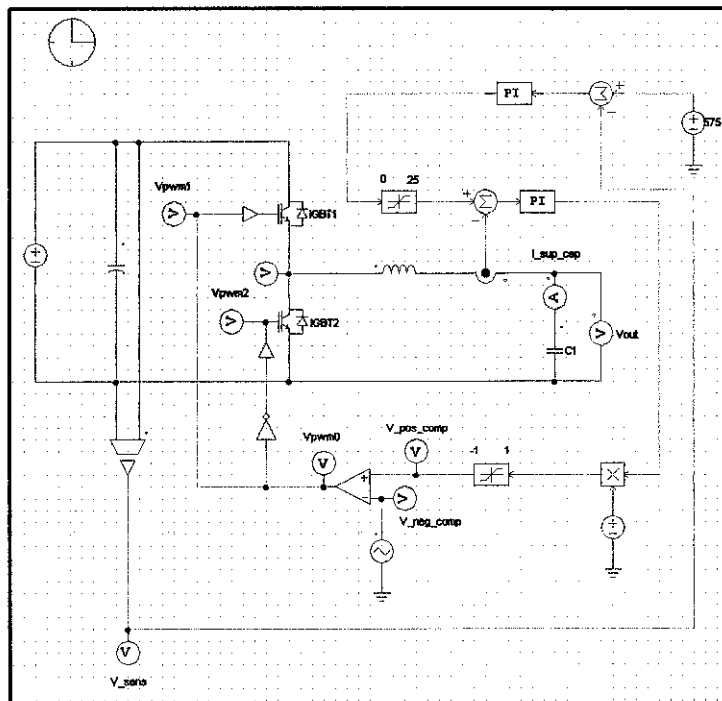

Figure 19: Control principle of Boost Converter

During the first cycle, IGBT2 is switched ON and IGBT1 is switched OFF, the energy transfer is from the Supercapacitor to the Inductor. During the next cycle, the IGBT2 is switched OFF and IGBT1 is switched ON which allows the energy that is stored in the Inductor to be transferred to the DC link.

The controlled duty cycle to switch on-off the IGBTs is controlled by the PWM circuit that compares a signal fed from the voltage sensor and current sensor (red line in Figure 20(a)) with saw-tooth signal (blue line in Figure 20(a)) to produce PWM signal in figure 20(b).
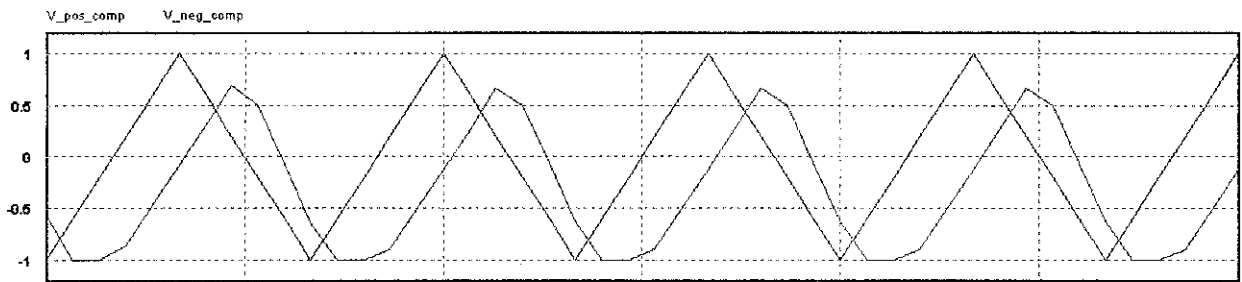
(a) Feedback and saw-tooth signal is fed into comparator to produce PWM signal
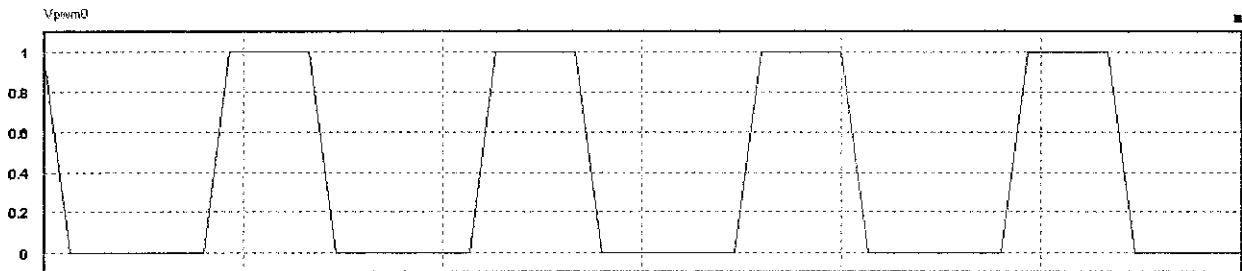

(b) PWM signal that controls the IGBTs switching modes
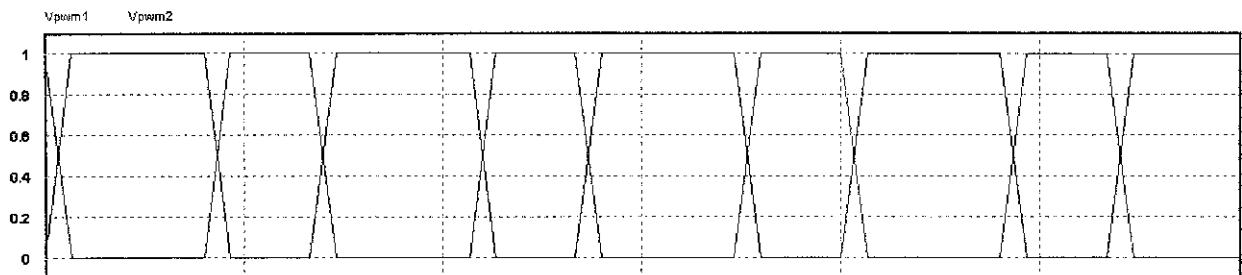
(c) PWM signals triggered to both IGBTs

Figure 20: PWM switching signals for Boost mode operation

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The boost converter simulation results are shown in the Figure 21. As seen in figure 21 (a), the current across the Supercapacitor is decreasing during the energy transfer from Supercapacitor to the DC link. From figure 21 (b), the graph shows that during the boost operation mode, the supercapacitor is discharging. The supercapacitor is fully discharged at nearly 33s.
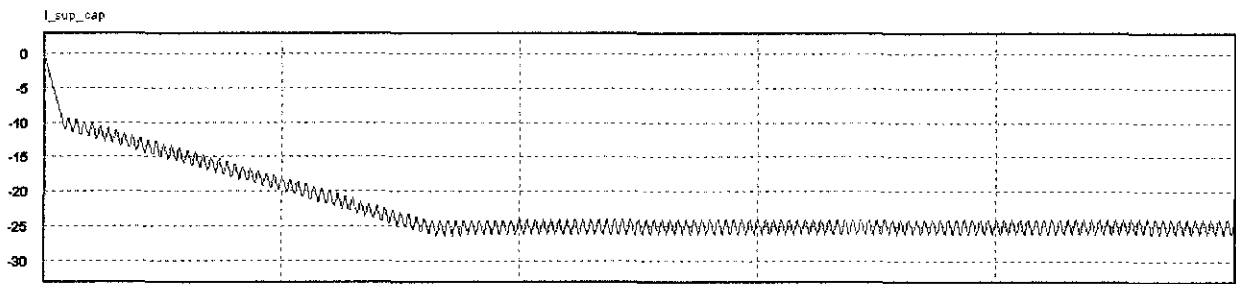
(a) Current across the Supercapacitor
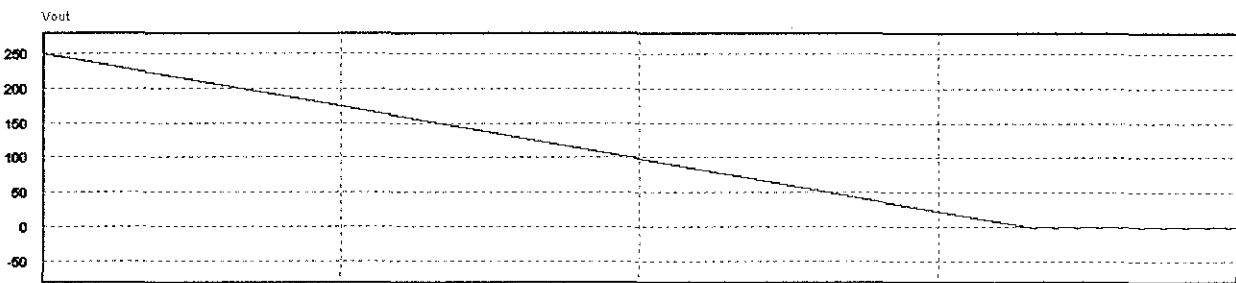
(b) Voltage across Supercapacitor

Figure 21: Result of Boost Mode Operation Simulation

4.2. Buck Mode

During the buck operation mode, the energy transfer is from the DC link to the Supercapacitor. The supercapacitor will be charged during this mode of operation. The buck mode operation can be achieved by controlling the IGBT1. Referring to Figure 22, during the first cycle, the IGBT1 is switched ON and IGBT2 is switched OFF, the energy is transferred from the DC link to the Supercapacitor with part of the energy is stored in the Inductor. During the next cycle, the IGBT1 is switched OFF and IGBT2 is switched ON allowing the energy stored in the Inductor transferred into the Supercapacitor through D2.
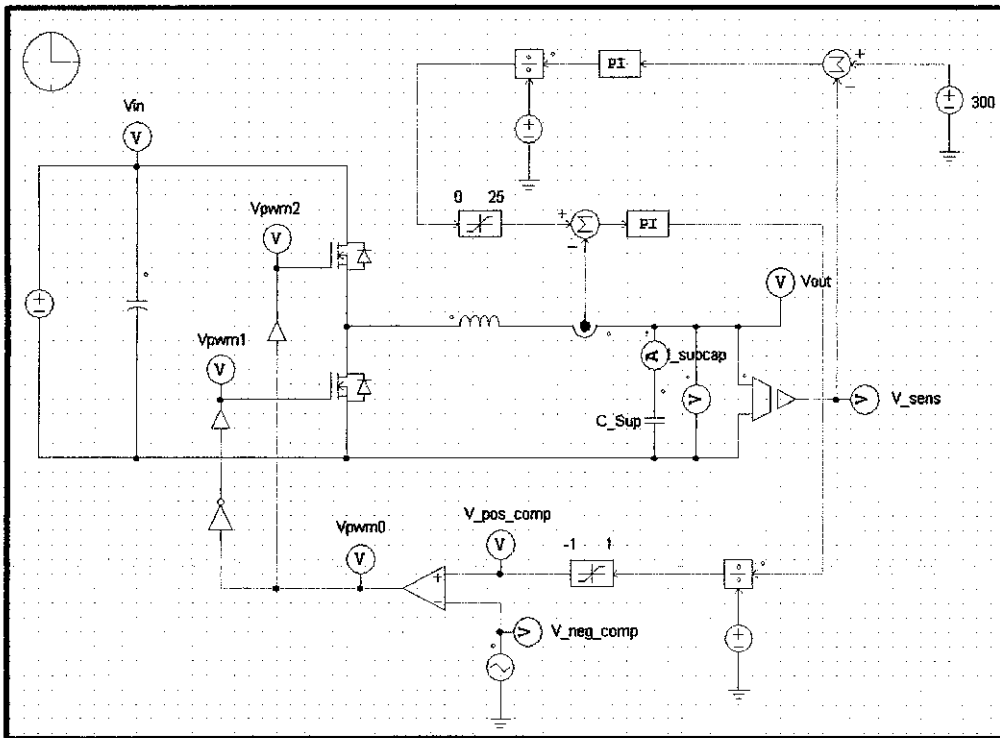
**Figure 22:** Control principle of Buck Converter

Figure 23(a) shows the signals that are fed into the comparator to produce PWM signals to control the switching modes of IGBTs during the first cycle and second cycle of the Buck converter mode of the DC-DC converter. The red line in Figure 23(a) indicated the saw tooth signal that will be fed into the comparator. The signal will be compared with the signal voltage sensor and current sensor taken to produce the PWM signal as shown in Figure 23(b).
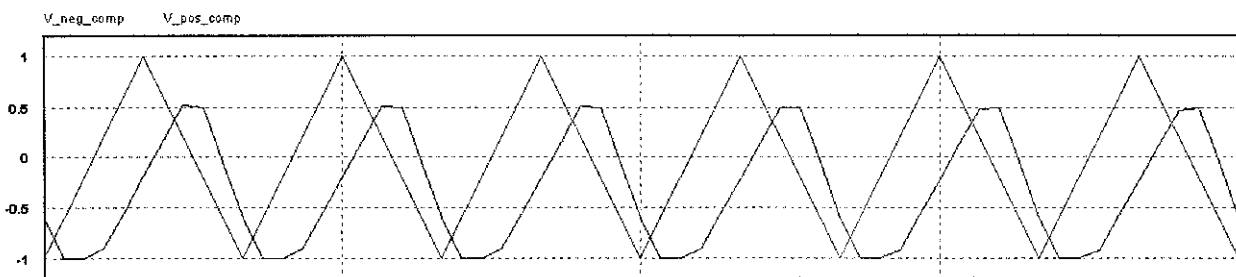
(a) Current and Voltage signals feedback are compared with saw-tooth signal
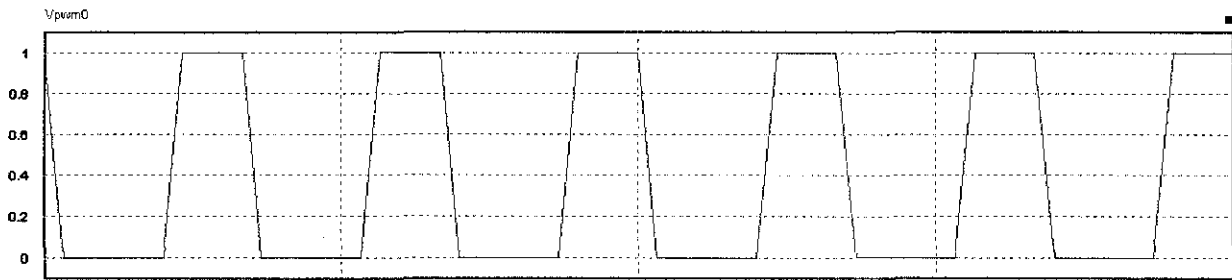
(b) PWM produced from the comparator for switching IGBTs
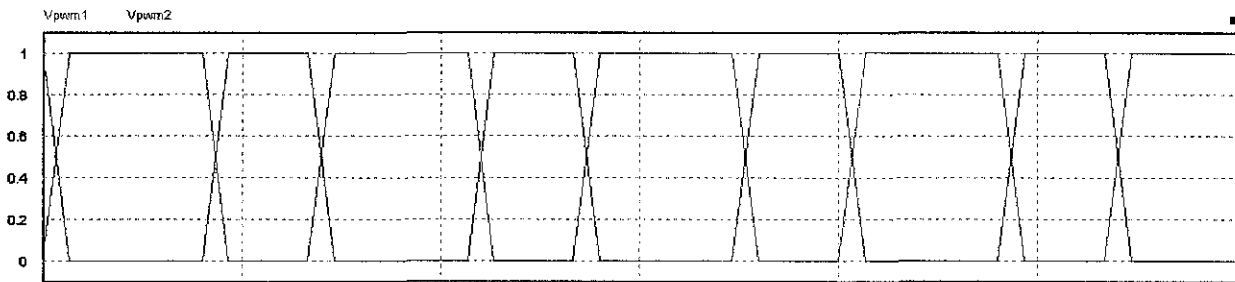
(c) PWM switching signals triggered to the IGBTs

Figure 23: PWM switching signals for Buck mode operation

The simulation result for Buck mode operation is shown in Figure 24. According to figure 24(a) the current across the Supercapacitor is increasing from 0 amp to nearly 25 amp and constant at 20 amp which indicates that the supercapacitor is being charged. In Figure 24(b), the voltage across the supercapacitor shows that the voltage is increasing from 0 V to fully charged at about 42s. These results showed that the supercapacitor is being charged during the Buck converter mode operation.
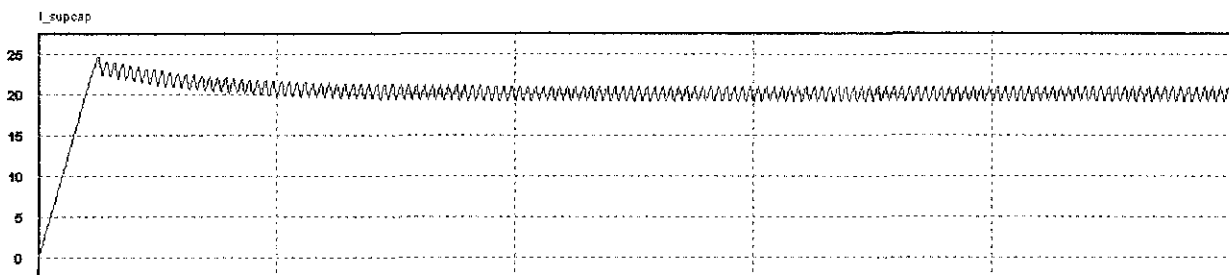
(a) Current across Supercapacitor

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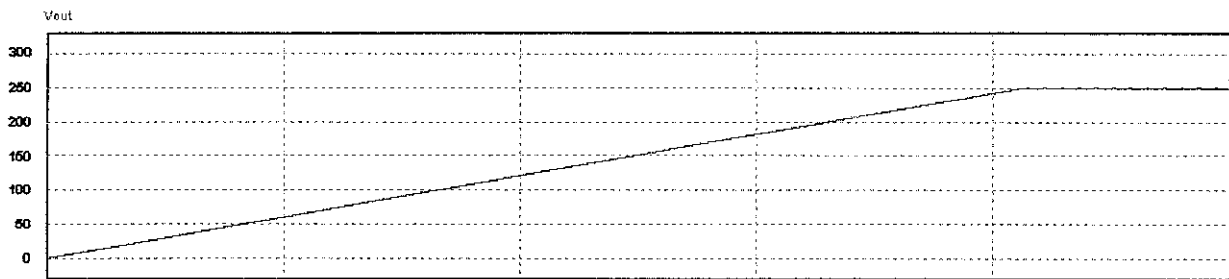
(b) Voltage across Supercapacitor

Figure 24: Result of Buck Mode Operation Simulation

Based on the results of both operation modes, Boost and Buck Modes, the supercapacitor is discharged during the Boost mode and takes about 33 seconds to fully discharge the Supercapacitor from 250V to 0V. During Buck mode, the Supercapacitor is being charged from 0V to 250V in about 42 seconds. The results show that the system successfully charges and discharges the Supercapacitor during the operation modes of the DC-DC converter.

Chapter 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Recommendations

The methodology of this project is expected to support the project and accomplish the objective that is to recover as much energy as possible from the braking to reduce the energy usage of a vehicle. This project is expected to have better efficiency on the recovering mechanism and with modification applied, better results and performance are expected.

The study of regenerative braking system is an important part to improve the energy efficiency of an electric car. Energy saving in the system would promote to the cost reducing and regenerative braking will be seen as an alternative to reduce cost consumption on vehicles as well as reduce the pollution. The study in this topic requires a very thorough study in the power electric control circuit and also knowledge on the related subjects such as control system is essential. I would like to recommend to students who will be taking their major in power systems engineering to at least have a fundamental knowledge on PSIM software as this software can be a helpful tool when simulating a power electronic circuit.

5.2. Conclusions

The rapid advancement in the power electronic technology today has allow us to explore the benefits of supercapacitor as a energy storage element that provides advantages in many ways apart from battery such as the energy storage deterioration. The implementation of supercapacitor in the regenerative braking system allows huge amount energy to be stored compared to a conventional capacitor, the energy stored is sufficient to be recycled and used for accelerating the car. This allows the energy used during the braking to be recycled instead of being wasted. The control strategy of the circuit allows energy to be stored and consumed in the supercapacitor efficiently.

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