# The Analyses of Hard- and Soft- Switching SiC Schottky- Buck Converter Performance

By

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**2475**

Dissertation report submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Electrical an Electronics Engineering)

November 2004

University Technology PETRONAS

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**CERTIFICATION OF APPROVAL**

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Approved by,

(Mr. Nor Zaihar bin Yahya)

UNIVERSITY TECHNOLOGY PETRONAS

TRONOH, PERAK, DARUL RIDZUAN

November 2004

## 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.

Batyr Amanov

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**ABSTRACT**

In this project two types of buck converters, hard switching and soft switching buck converters are compared in term of power loss and reverse recovery current of diode in DC applications. The test circuit used is dc to dc buck converter circuit. The main switch of circuit is the IGBT and the same type of IGBT is used for both techniques. The diode used is fast switching type Silicon Carbide Schottky (SiC) diode.

First semester theory research has been verified with simulations, which were conducted in Cadence Pspice 14.2. The power loss waveforms of diode and IGBT transistor were obtained. Using those power waveforms the energy loss of both circuits were calculated.

Second semester, hard and soft switching chopper circuits were constructed on PCB (Printed Circuit Boards), so that simulation results can be compared with experimentation results. All the PCB layouts were prepared in ARES IV. Power loss waveforms were obtained from digital oscilloscope.

The simulation and experimentation values are found to be quite close to one another. It has found that hard switching chopper has more energy losses comparing soft switching chopper. The main losses occur during SiC diode turn-off (caused by reverse recovery current), IGBT transistor turn-on (caused by $I_{CE}$ current spike) and the highest main loss is IGBT turn-off (caused by tailing time, tailing current). Reducing the turn-off and turn-on switching losses of the IGBT would imply decreasing of the total loss of the system. That could be done by implementing zero voltage switching across the IGBT transistor which would decrease IGBT turn-on and turn-off losses.

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# CHAPTER 1
# INTRODUCTION

## 1.1 Background

In this project, two types of buck converters, hard switching and soft switching buck converters (choppers) are compared in term of power loss and reverse recovery current of SiC diode in a DC applications. Soft switching chopper found to have less power loss compared to hard switching chopper

### 1.1.1 Introduction

In all the pulse-width-modulated dc-to-dc converter topologies the controllable switches are operated in a switch mode where they are required to turn on and turn off the entire load current during each switching. In this switch-mode operation the switches are subjected to high switching stresses and high switching power loss that increases linearly with the switching frequency of the PWM (Pulse Width Modulator) [1]. Another significant drawback of the switch-mode operation is the EMI (Electro Magnetic Interference) produced due to large di/dt and dv/dt caused by a switch-mode operation.

These imperfections of switch-mode converters are intensified if the switching frequency is increased in order to increase the power density. The imperfections are minimized if each switch in a converter during changing its status has the voltage across it and/or the current through it is equal to zero at the switching instant [2]. The converter topologies and the switching strategies, which result in zero-voltage switching, are discussed in this paper.

## 1.2 Problem Statement

For power electronic converters in medium- and high-power application, high efficiency and minimization of EMI (Electro Magnetic Interference) are major requirements. These requirements are very important in battery supplied systems for renewable energy conversion or UPSs [3]. To meet these requirements for mediumpower high-voltage applications, insulated gate bipolar transistors (IGBTs) are preferred to MOSFETs because of their lower conduction losses and higher power density. Although their characteristics are improving continuously, IGBTs still have high turn-off switching loss due to the current tail. Reducing the turn-off switching losses of the IGBTs would imply decreasing of the total loss of the system [4]. In recent years, a number of techniques and circuits for DC/DC conversion to reduce switching losses have been proposed. Most of them use soft switching techniques (zero-voltage switching) combined with classical topologies.

### 1.3 Objective and Scope of Study

The main objective of this project is to make comparison between two switching techniques; hard switching and soft switching. The comparison is made by measuring total power losses and reverse recovery current of diode in those circuits.
The scope of the project is limited to two type of switching; hard switching and soft switching. The efficiency of these switching techniques is compared and test circuit used is dc-dc buck converter circuit. The main switch of circuit is the IGBT and the same type of IGBT is used for both techniques. Diode used is Silicon Carbide Schottky diode.
First semester objective was to simulate both circuits in Pspice and get power loss waveform of SiC diode and IGBT. Second semester objective was to construct both circuits on PCB and get experimentation results from digital oscilloscope. Then simulation results were compared with experimentation results.
The limitation of this project is the fact that this project valuates two type of buck converter's total power loss at room temperature (25 $^{o}$C) and no comparison at different temperatures is made. Other aspect of efficiency such as switching speed and electromagnetic interference (EMI) are not investigated in this project.

# CHAPTER 2:
# LITERATURE REVIEW AND THEORY

## 2.1 Switching characteristics of IGBT

### 2.1.1 Turn-On

From Figure 1, during the turn on period $t_{on}$, the gate-to-emitter voltage, $V_{GE}$ increases gradually and when it reaches the threshold value, $V_{GE\ (th)}$ the device is turned on and the collector current, $I_C$ starts to flow. The duration for the $I_C$ to reach its steady value is termed the rise time, $t_{rise}$. At the same time, the $V_{GE}$ continues to increase. During turn- on, $I_C$ exhibits a short current spike before stabilizing [5]. The value of this current spike and its duration will determine the turn on loss of IGBT. When $I_C$ stabilizes, the collector to emitter voltage, $V_{CE}$ decreases rapidly for a short period of time and then gradually reduces to its on-state voltage or $V_{CE\ (sat)}$.

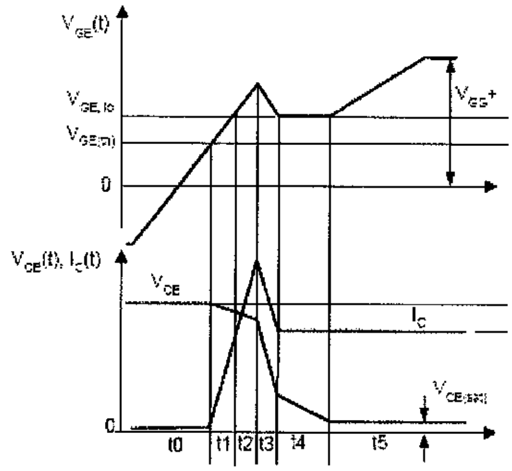



Figure 1: Turn-on switching waveforms of IGBT [4]

### 2.1.2 Turn-Off

For the turn off period $t_{off}$, the $V_{GE}$ starts to decrease and at a certain level, it will maintain steady for a while. The $V_{CE}$ will increase to a steady value within the period of the voltage rise time. When $V_{CE}$ stabilizes, $I_C$ begins to decrease rapidly until the $V_{GE}$ drops below the threshold value [5]. After that, $I_C$ will decrease slowly until it reaches zero value. This period is called the tailing time. A long tailing time will cause large power dissipation. This is the main drawback of IGBT transistor.

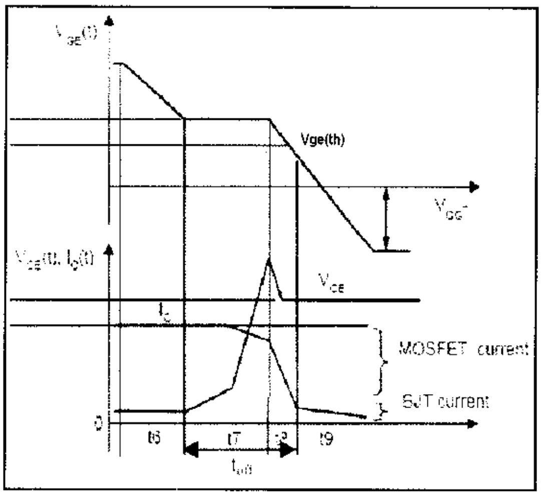



Figure 2: Turn-off switching waveforms of IGBT

## 2.2 Hard-switching Buck Converter Circuit

A DC-to-DC converter or chopper is used to obtain a variable DC voltage from a constant-voltage DC source. The average value of the output voltage is varied by changing the proportion of the time during which the output is connected to the input [3]. This conversion can be achieved with a combination of an inductor and capacitor and a solid-state device such as IGBT transistor operated in a high-frequency switching mode. In high-voltage and high-current applications, the switching devices used in chopper circuits are IGBT or MOSFET. When power transistor IGBT is used, they can be turned off easily by controlling the base or gate current.

The buck chopper produces an output voltage that is less than or equal to the input voltage. Choppers are used in many industrial applications where a constant DC source is available. Typical applications include dc motor control for electric traction, switching power supplies, inverters for uninterruptible power supplies (UPS), and battery-operated equipment [3].

In electrical trains buck chopper is used to control speed of the motor. The supply voltage from the trolley wires are 1500 V. When the motor works, a lot of energy loss in form of heat is dissipated from IGBT transistors. This makes IGBT transistors to wear out and burn.

A practical arrangement (shown in Figure 3(a)) includes an inductor *L* and a diode D, which are added to eliminate current pulsations. This circuit provides a smooth DC current to practical loads like a DC motor.

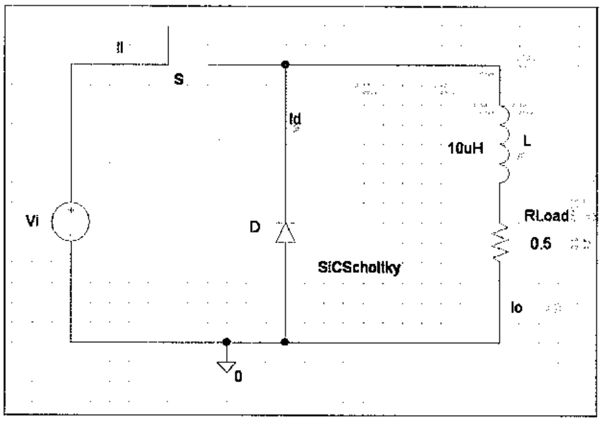



Figure 3(a): Basic step-down chopper circuit

When the switch S is closed, the diode D is off, since it is reverse-biased. It will stay off as long as S remains on. The equivalent circuit configuration is shown in Figure 3(b). The input current builds up exponentially and flows through the inductor *L* and the load. The output voltage is equal to $V_I$. The switch S is kept on for a time $T_{ON}$ and then turned off.

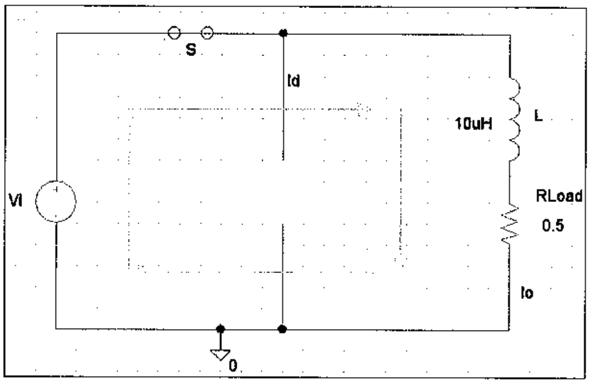



Figure 3(b): Equivalent circuit for the ON state

When the switch is opened, the current through the inductor starts decaying to zero (it cannot change instantaneously). This causes an induced voltage with opposite polarity across the inductor. The inductor voltage forward-biases the diode, and the current flowing through the inductor now freewheels through the diode D and the load. The purpose of the diode therefore is to provide a path for the load current when S is off. Therefore, turning off S automatically turns on D.

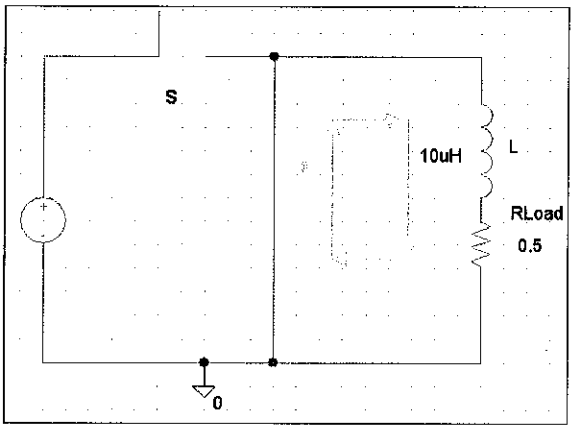



Figure 3(c): Equivalent circuit for the OFF state.

The new circuit configuration is shown in Figure 3(c). The voltage across the load is zero, and the current decays toward zero as long as S remains off, that is, for a period $T_{OFF}$. The energy stored in $L$ is delivered to the load. This circuit arrangement permits the use of a simple filter inductance $L$ to provide a satisfactory smooth DC load current for many applications [5]. When the switching frequency is high, a relatively small inductance is sufficient to reduce the ripple to an acceptable degree.

## 2.3 Soft-switching Buck Converter Circuit (Zero Voltage Switching)

In these converters, the resonant capacitor produces a zero voltage across the switch, at which instant the switch can be turned on or off. Such a step-down converter circuit is shown in Figure 4(a) where a diode Dr is connected in anti-parallel with the switch.

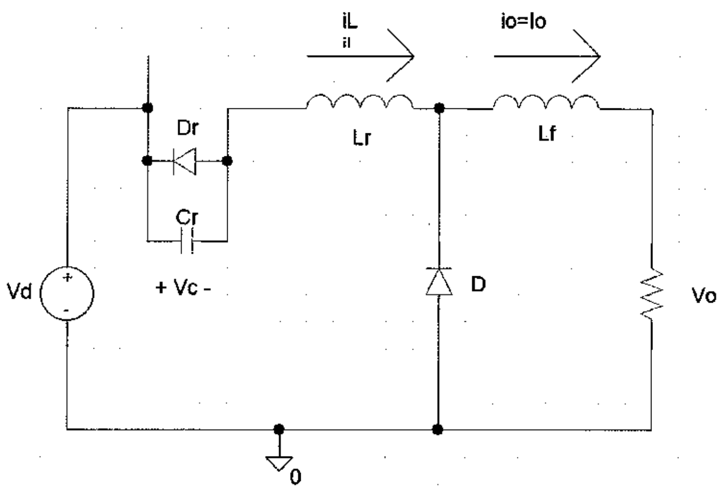



Figure 4(a): Soft-switching (ZVS -zero voltage switching) chopper

Initially, the switch is conducting $I_O$ and therefore, $I_{LO}$=$I_O$ and $V_{CO}$=0. The converter operation can be divided into following intervals for which the converter waveforms as well as the corresponding circuit are shown in Figure 4 (b).

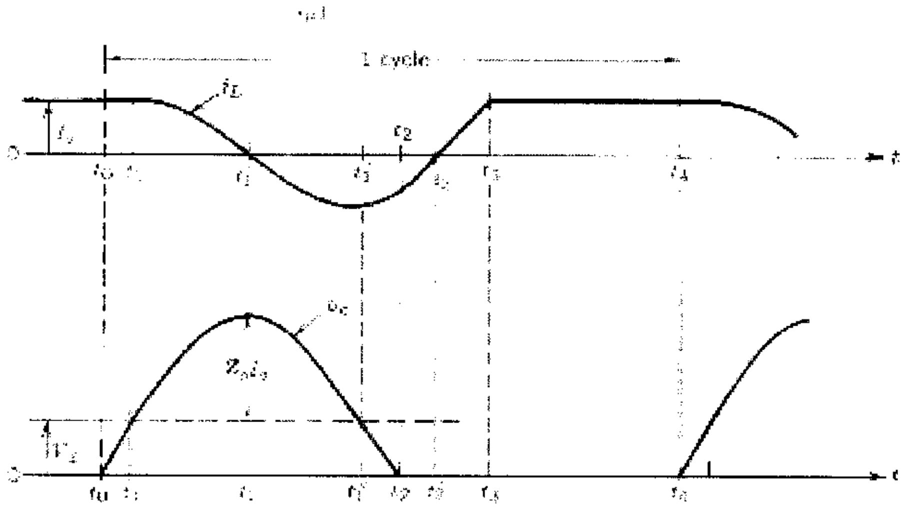
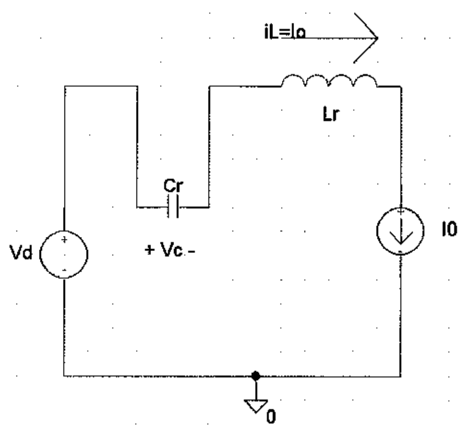
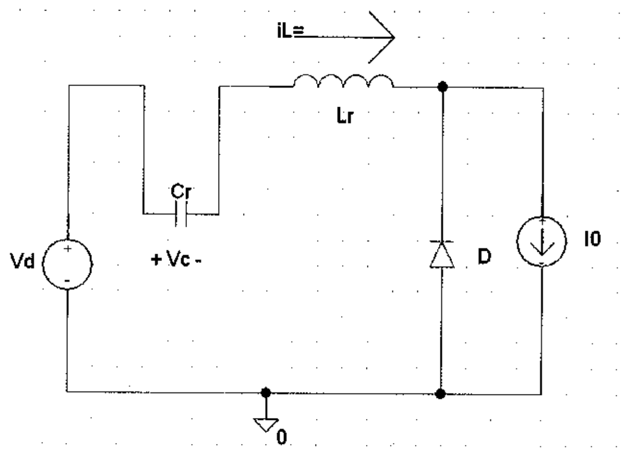



Figure 4(b): Voi and $i_L$ graphs of ZVS chopper

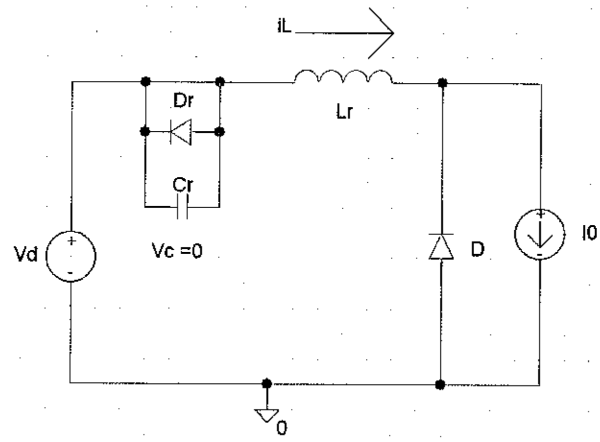
**1. Time interval 1 (between $t_0$ and $t_1$):** At time $t_0$, the switch is turned off. Because of Cr, the voltage across the switch builds up slowly but linearly from zero to $V_d$ at time $t_1$. This results in a zero-voltage turn-off of the switch. For equivalent circuit between $t_0$ and $t_1$ refer to Figure 5(a).



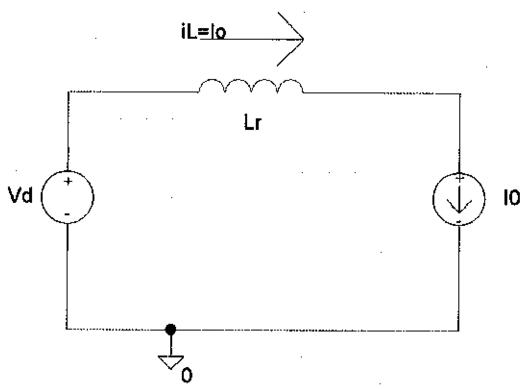

5(a)




5(b)




5(c)




5(d)

Figure 5 (a): Equivalent circuit between time $t_0$&$t_1$, (b): Equivalent circuit between time $t_1$&$t_2$,(c)Equivalent circuit between time $t_2$&$t_3$, (d) Equivalent circuit between time $t_3$&$t_4$

**2. Time interval 2 (between $t_1$ and $t_2$).** Beyond $t_1$, since Vc > Vd, the diode D becomes forward biased, Cr and Lr resonate. At $t'_1$, $i_L$ goes through zero and Vc reaches its peak of Vd+ $Z_O I_O$. At $t''_1$,Vc=Vd and $i_L$= -$I_O$. At $t_2$, the capacitor voltage reaches zero and can not reverse its polarity because the diode Dr begins to conduct [3]. For equivalent circuit between $t_1$ and $t_2$ refer to Figure 5(b).

The load current $I_O$ should be sufficiently large so that $Z_O I_O$ > Vd. Otherwise, the switch voltage will not come back to zero naturally and the switch will have to be turned on at a nonzero voltage, resulting in turn-on losses (the energy stored in $C_r$ will dissipate in the switch) [4].

**3. Time interval 3 (between $t_2$ and $t_3$):** Beyond $t_2$, the capacitor voltage is clamped to zero by Dr, which conducts the negative $i_L$. The gate drive to the switch is applied once its anti-parallel diode begins to conduct. Now $i_L$ increases linearly and goes through zero at time $t'_2$, at which instant $i_L$ begins to flow through the switch. Therefore, the switch turns on at a zero voltage and zero current. Here $i_L$ increases linearly to $I_O$ at $t_3$. For equivalent circuit between $t_2$ and $t_3$ refer to Figure 5(c).

**4. Time interval 4 (between $t_3$ and $t_4$):** Once $i_L$ reaches $I_O$ at $t_3$, the freewheeling diode D turns off. Because a small negative slope is associated with di/dt through the diode at turn-off, there is smaller diode reverse-recovery. The switch conducts $I_0$ as long as it is kept on until $t_4$. The interval $t_3$-$t_4$ can be controlled. At $t_4$, the switch is turned off and the next cycle ensues. For equivalent circuit between $t_1$ and $t_2$ refer to Figure 5(d).

## 2.4 IGBT Gate Drive

To employ IGBT as a switch, gate drive required (Figure 6).

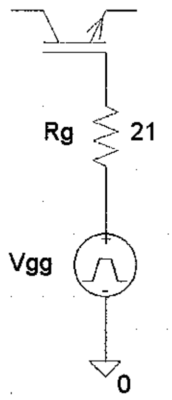



Figure 6: Gate drive

The gate drive circuit consists of a gate resistor, Rg and the function generator, Vgg, to provide the triggering pulses for activating the IGBT. There are three important parameters that have to be considered when designing the gate drive circuit;

- the gate voltage, Vgg
- gate resistor, Rg
- gate current, Ig.

Vgg is the gate to emitter voltage during conduction of the IGBT. The maximum value of Vgg is determined by the rated voltage between the gate and the emitter. If the value of Vgg exceeds the rated voltage, the gate oxide will be destroyed and the IGBT will become useless.

Vgg will affect the conduction loss of IGBT. Increasing the value of Vgg will reduce the collector-emitter saturation voltage ($V_{CE}$ sat) and this result in lower conduction loss. Besides conduction loss, Vgg also affects the turn-on and turn-off losses of the IGBT [6]. Vgg will increase the voltage across the gate resistor (Rg). A large gate current, Ig will flow through the gate during turn-on and turn-off. Vgg will increase faster and this will lead to a more rapid increase in collector current, Ic. The duration for Ic to changes will reduce and thus, the switching loss decreases.

## 2.5 Effects of Frequency, Gate Resistor, Rg and Duty Ratio, D on Switching Energy Loss

The most suitable frequency to be used is 40 kHz, where the loss is minimal for Silicon Carbide Schottky diode (SiC diode) [1]. Refer to Figure 7 for the total energy loss at different frequencies.

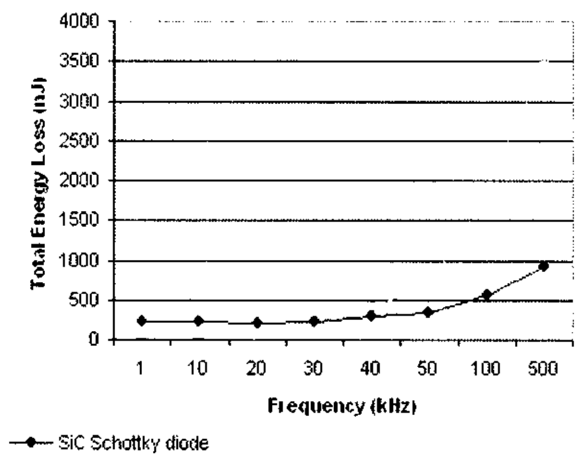



Figure 7: Total switching energy loss at different frequencies [6]

The value $R_G$ controls the total loss by determining the gate current supplied to the IGBT [6]. The smaller the value of $R_G$, the higher the gate current $I_G$ of the IGBT. A higher $I_G$ will increase the rate of increase of $V_{GE}$ and hence, the IGBT will be turned on faster. This will reduce the turn on loss of the IGBT and the total loss during turn-off of the diode. With reference to Figure 8 the most suitable Rg to be used is 21 Ω as it yields the lowest loss for SiC diode and IGBT [6].

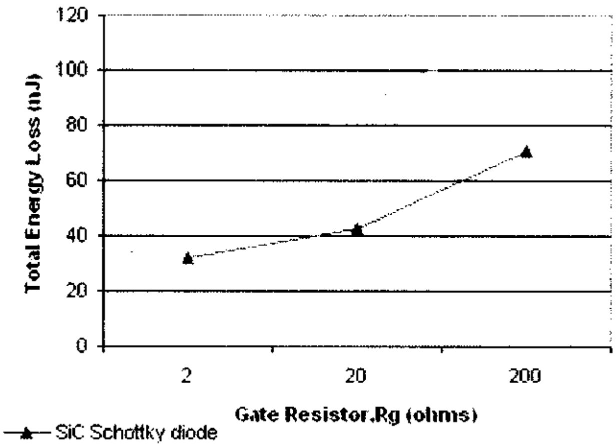



Figure 8: Total switching energy loss at Rg=2 Ω, 22 Ω and 200 Ω [6]

Duty ratio is the percentage of the turn-on time over the period of the signal:

Duty ratio= $(T_{on}/T) \times 100\%$

$T_{on}$ - Turn-on duration.

T- Period of signal.

From Figure 9, the ideal duty ratio to be used is in the range of 40% to 50%. The duty ratio used in this project is 50% as this allows the diodes and IGBT to fully turn-on and turn-off, as almost equal amount of the time period is given for turn-on and turn-off of the switches [6].

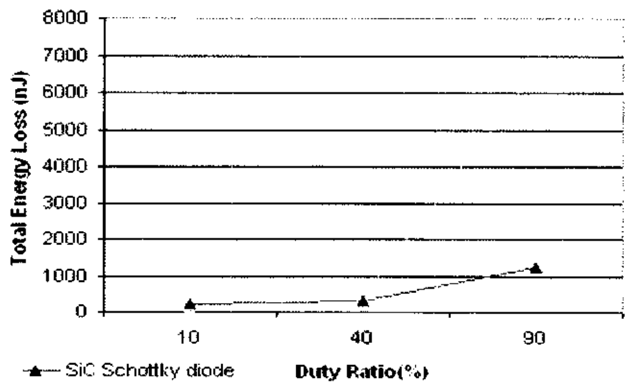
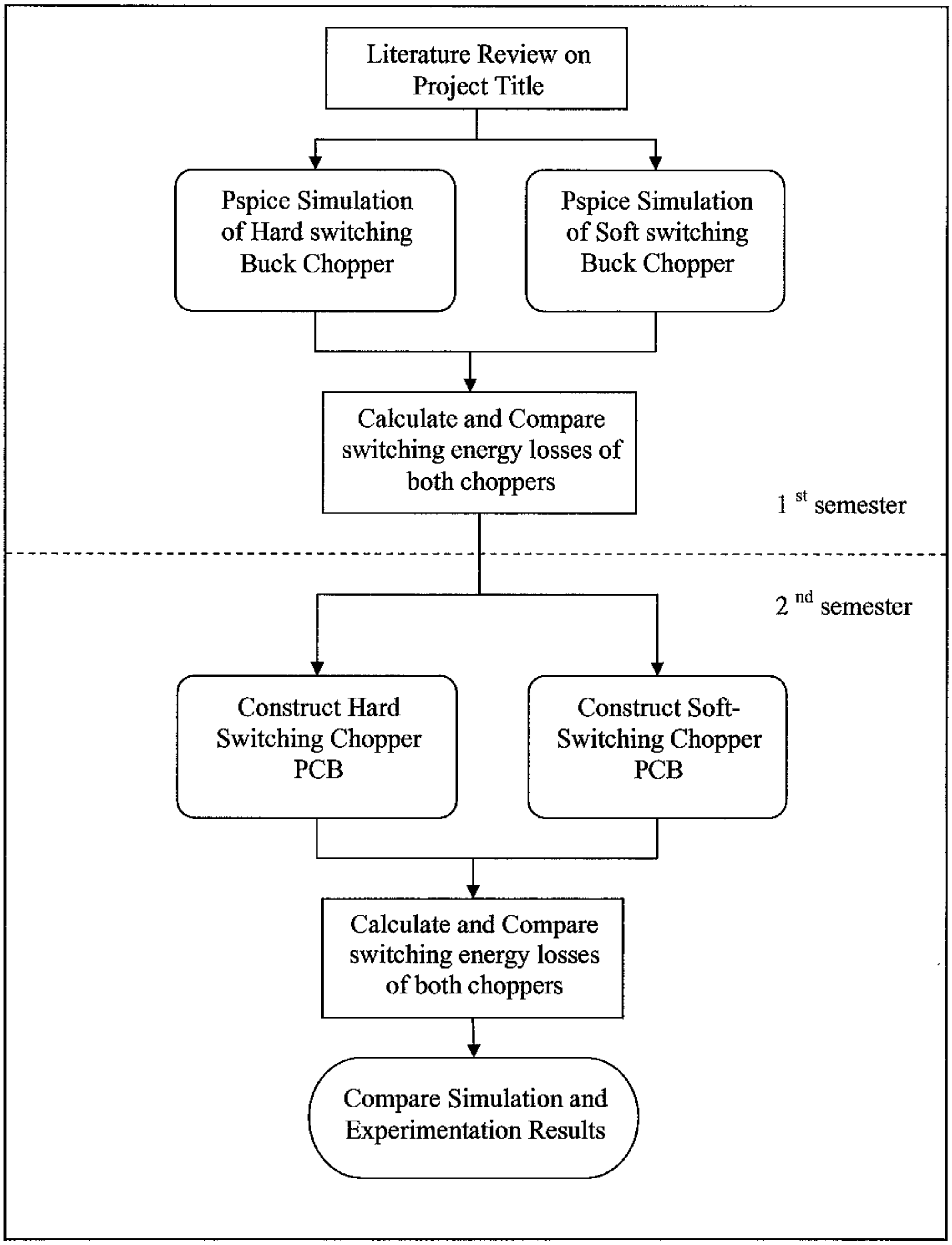



Figure 9: Total Switching energy loss at Duty ratio=10%, 40 % and 90% [6]

# CHAPTER 3:
# METHODOLOGY

## 3.1 Process Flow



## 3.2 Tool

### 3.2.1 Software

**Pspice** (Cadence Pspice 14.2) - is a computer-aided simulation program that enables circuit design and simulation on a computer. This software was utilized during first semester to obtain all the current and power loss graphs.

**Ares IV-** is a Routing and Editing Software, which is a powerful and easy to use PCB layout and routing software. PCBs (Printed Circuit Boards) layouts were prepared using this software.

### 3.2.2 Equipment

Also many types of equipment were utilized in the lab to perform experimentation. Those equipments are:

a) **DC Regulated Power Supply, Model ED-345 BM**: was used to source the circuit with DC voltage of 50 volt.

b) **Pulse Generator, Model 2114**: was used to trigger IGBT transistor.

c) **Digital Oscilloscope, DL 1520:** was used to get current and power loss graphs of components.

d) **Multimeter**: was used for troubleshooting.

### 3.2.3 Components

The list of components which were utilized in experimentation:

| No | Quantity | RS Stock No. | Description |
|---|---|---|---|
| 1 | 4 | 228-573 | mount,**10mH**,0.4A,4.74 Ω<br>Inductor, high current, radial, bobbin, PCB |
| 2 | 1 | 288-238 | ended,**2.4mH**,500W,240Vrms,0.4 Ω<br>Inductor, open, toroidal, wire |
| 3 | 1 | 820-927 | ended,400Vdc/160Vac,**1000pF**<br>Capacitor, polypropylene, radial, wire |
| 4 | 1 | 136-317 | Resistor, metal cased,power,300W,**22R**,5% |
| 5 | 1 | 136-345 | Resistor, metal cased,power,300W,**330R**,5% |

| No | Quantity | RS Stock No. | Description |
|---|---|---|---|
| 6 | 1 | 244-9788 | **Diode,Schottky**,DS06S60, $V_{RRM} = 600V$ $Q_C = 21$ nC, $I_F = 6$ A |
| 7 | 2 | 288-0218 | Transistor,**IGBT**,IRG4BC20W, $V_{CES} = 600V$ $V_{CE\ (on)typ.} = 2.16V$ $V_{GE} = 15V$ $I_C = 6.5A$ |

Table 1 List of the components

*Note; All the Stock numbers are referred to April 2004-RS catalogue.

### 3.3 Outputting Gerber Files

After finalizing PCB layout, Gerber files should be exported from ARES software. Gerber files are used to manufacture actual PCB. The output Gerber files settings should be as in Figure 10.

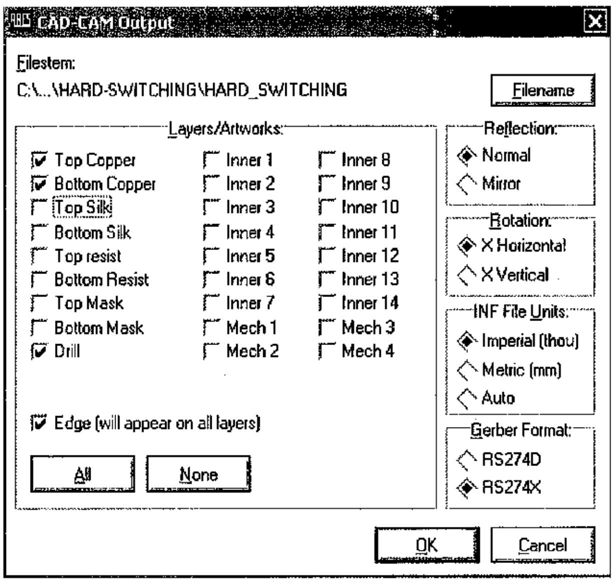


Figure 10: Gerber file output settings

Gerber format "RS274X" is selected. All the bus connections, components, holes and comments should be placed on 3 layers. Other layers should not be used for simplicity purpose during recognition of Gerber files by Isocam software, which is used in PCB burning lab to view the Gerber files. Those layers are:

1) Top Copper

2) Bottom Copper

4) Drill

### 3.4 PCB Board

The outputs from Ares PCB drawing software are;

1) Hard-Switching Chopper- Refer to Figure 11

2) Soft-Switching Chopper- Refer to Figure 12

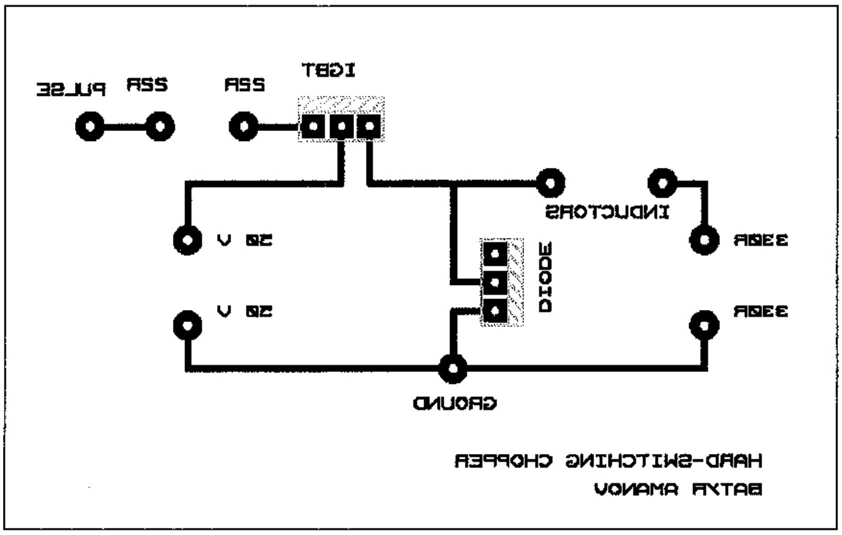


Figure 11: Hard-Switching Chopper circuit

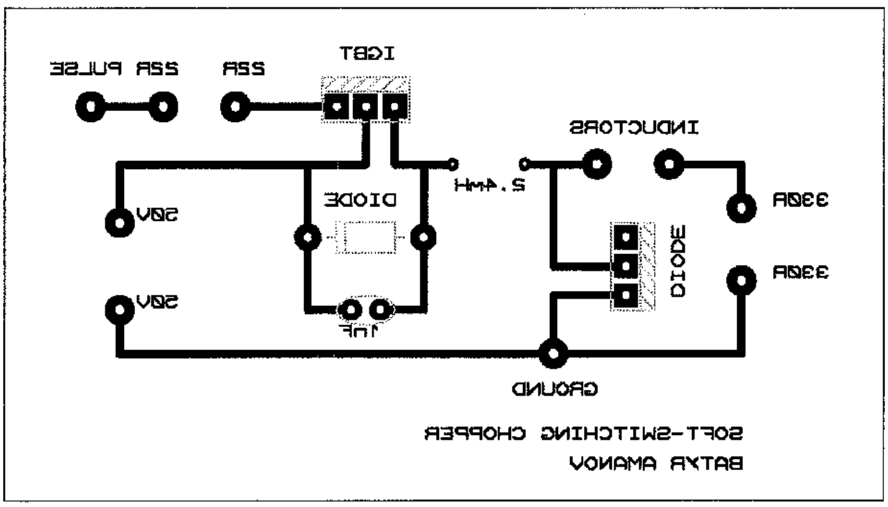


Figure 12: Soft-Switching Chopper circuit

## 3.5 Experiment Setup

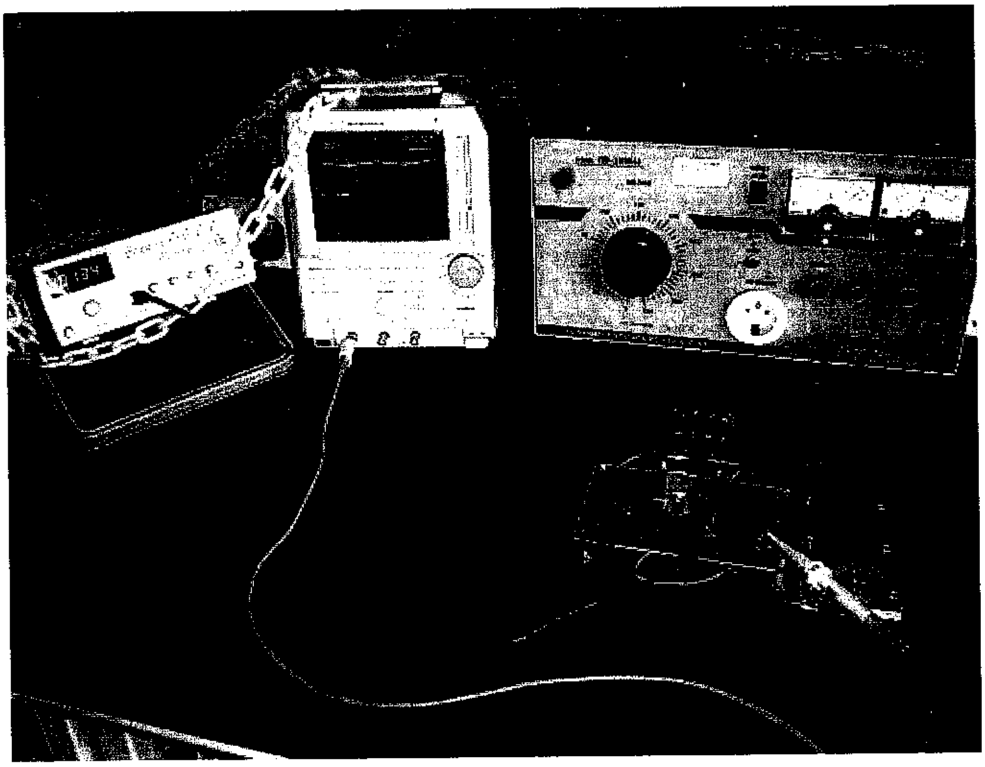


Figure 13: Experimental setup for hard-switching chopper

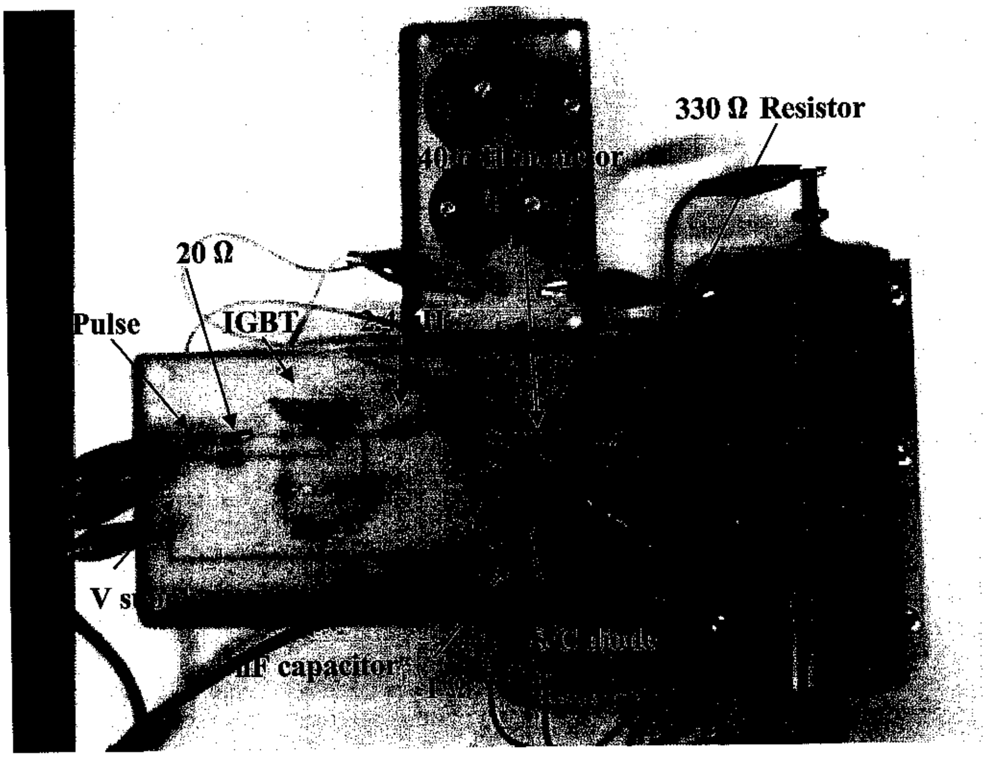



Figure 14: Experimental setup for soft-switching chopper (top view)

Experiment was setup with the equipment listed in Table 1.

### 3.6 Getting Current waveform of SiC diode

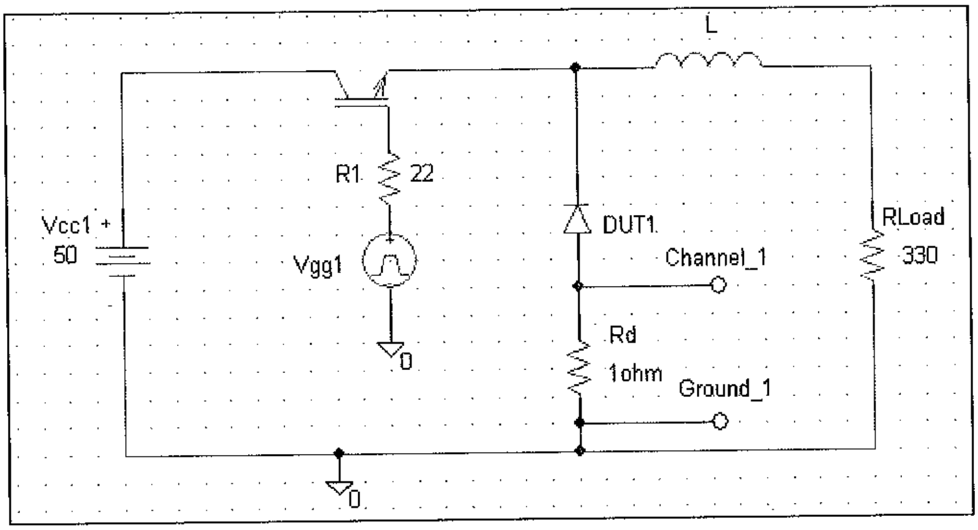



Figure 15: Configuration to get SiC diode Current Waveform

Quality Analyzer was set to get SiC diode current. The maximum circuit current in hard and soft switching chopper is 80 mA, but minimum detectible current for Quality Analyzer probe is 1 A.

Therefore, 1 Ω resistor and digital oscilloscope were utilized to get current waveform through resistor. When 1 Ω is used, the current flowing through resistor will be same with voltage output of resistor (Rd) (V= IR (R=1) => V=I). The set up for this method is shown in Figure 15.

The current waveform is shown in Figure 29 and 30.

## 3.7 Getting Power loss waveform of SiC diode

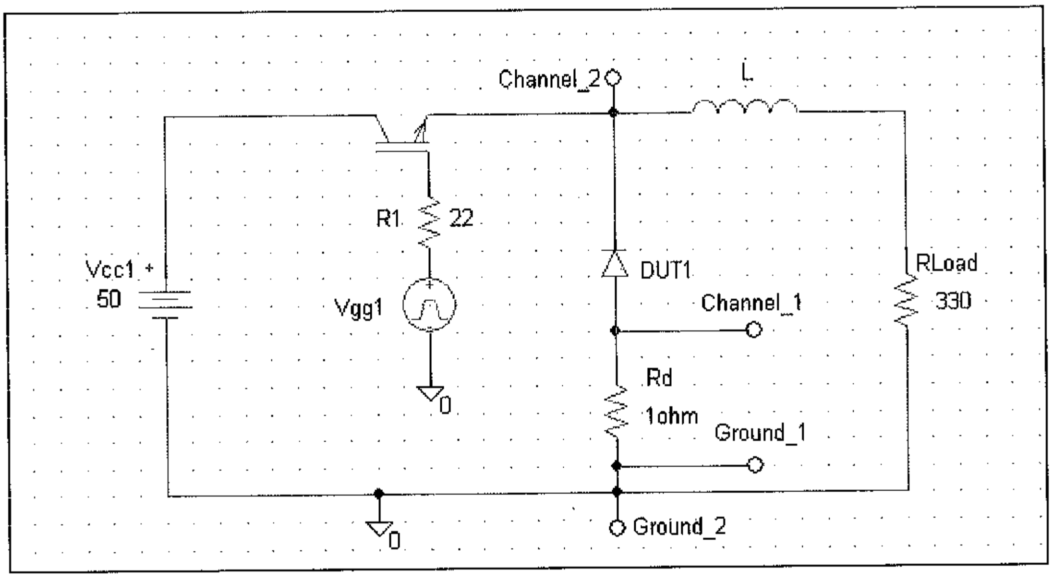



Figure 16: Configuration to get Power Waveform of SiC diode

The multiplication of Voltage across SiC diode and current flowing through 1 Ω resistor gives Power waveform of SiC diode. Two channels (Channel 1 and Channel 2) were used for this purpose.

Channel 1 is across resistor, to get current through SiC diode and Channel 2 is across SiC diode to get voltage waveform of SiC diode. Then those two channels were multiplied by MATH function of Digital oscilloscope. The current and voltage waveforms and resulting waveform after MATH function is shown in Figure 17.

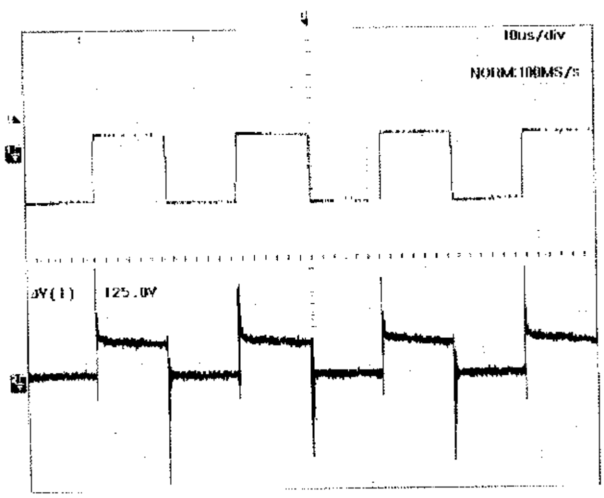


Figure 17: Voltage and Current waveforms

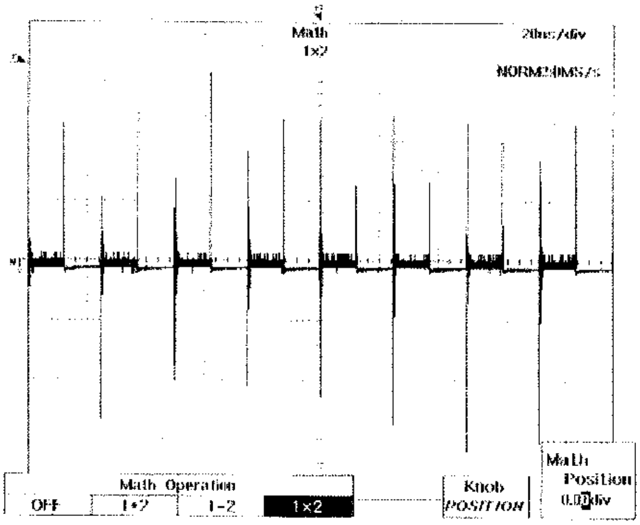



Figure 18: Power waveform obtained by MATH function of digital oscilloscope

## 3.8 Getting Current graph of IGBT

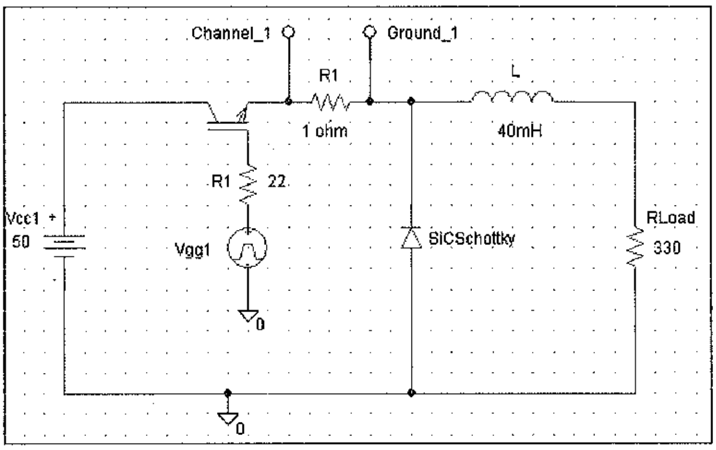



Figure 19: Faulty configuration to get Current Waveform of SiC diode

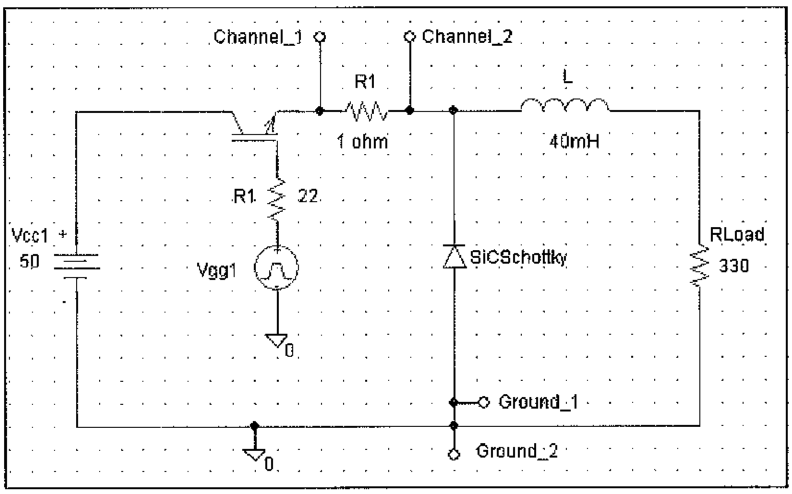


Figure 20: Configuration to get Current Waveform of SiC diode

The voltage supply trips (short circuited) when probe is connected across the resistor on the emitter output line of IGBT (Figure 19). So, IGBT current waveform across CE obtained using two channels (Figure 20). Channel 1 and channel 2 are connected as shown in Figure 20. Then these two channels should be subtracted, using MATH function of digital oscilloscope. The resulting IGBT current is shown in Figure 21.

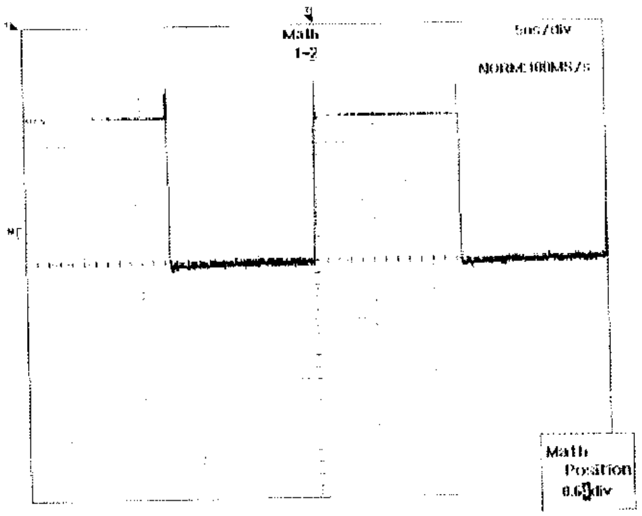



Figure 21: IGBT current waveform obtained by MATH function of digital oscilloscope

### 3.9 Project Planning

Please refer to APPENDIX, Table 2 and 3 for the Gantt chart for this project. The chart is divided into two parts; the first semester and second semester of the final year project. The project was planned to be completed in two semesters. The first semester was to understand concept and theories about the project. This was followed by circuit simulation to calculate and compare power losses of hard and soft switching chopper. The second semester was to construct the circuit on PCBs and carry out the actual experimentation. Then it is concluded by comparing the results from simulation and experimentation.

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1 Pspice Circuits

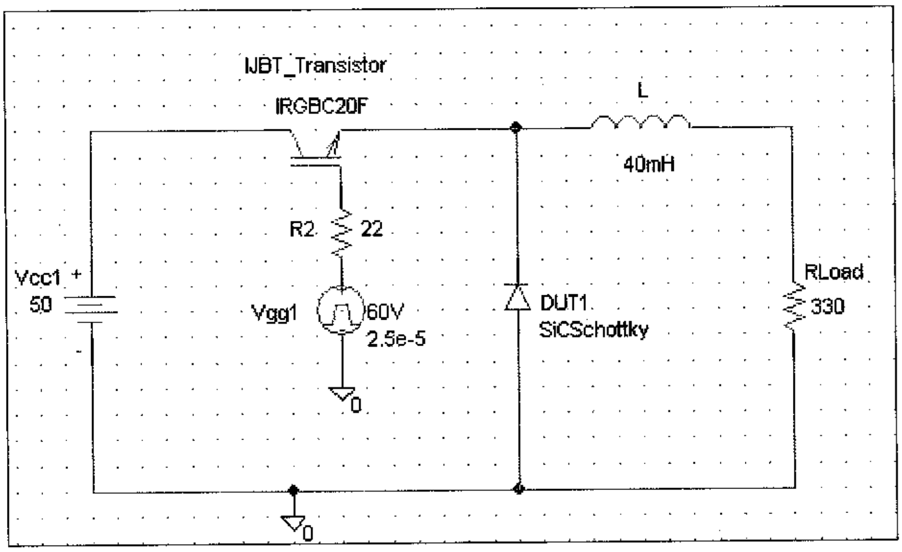



Figure 22: Hard-Switching Chopper circuit

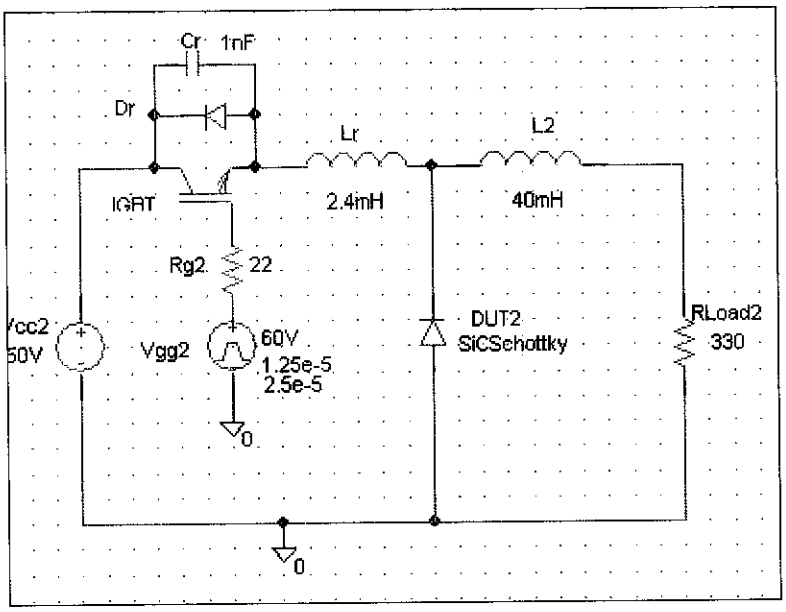



Figure 23 Soft-Switching Chopper circuit

## 4.2 PSPICE SIMULATION RESULTS

Circuits in Figure 22 and Figure 23 were drawn in Pspice and simulations were conducted employing Pspice. IBGT transistor gate trigger pulse (Vgg) is 60 V, frequency of 40 kHz and duty ratio of 50 %.

### 4.2.1 SiC diode Reverse Recovery Current

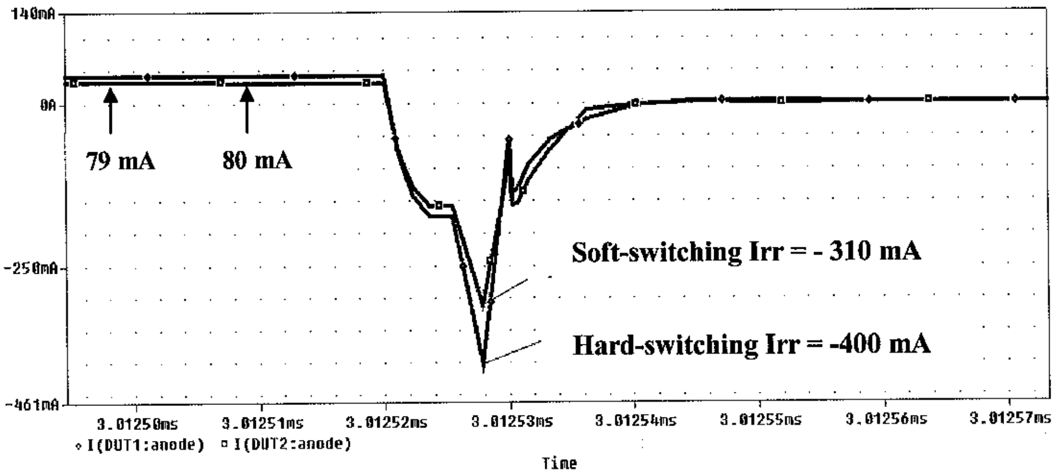



Figure 24: Reverse recovery current of SiC diode in hard- and soft switching choppers

From Figure 24 Soft- switching mode has a lower reverse recovery current compared to Hard-switching mode.

The switching losses were analyzed as Total SiC diode turn-off and Total SiC diode turn-on.

### 4.2.2 Total SiC diode turn-off loss

Total SiC diode turn-off loss includes:

1) SiC diode turn-off loss

2) IGBT turn-on loss

#### 4.2.2.1 SiC diode turn-off loss

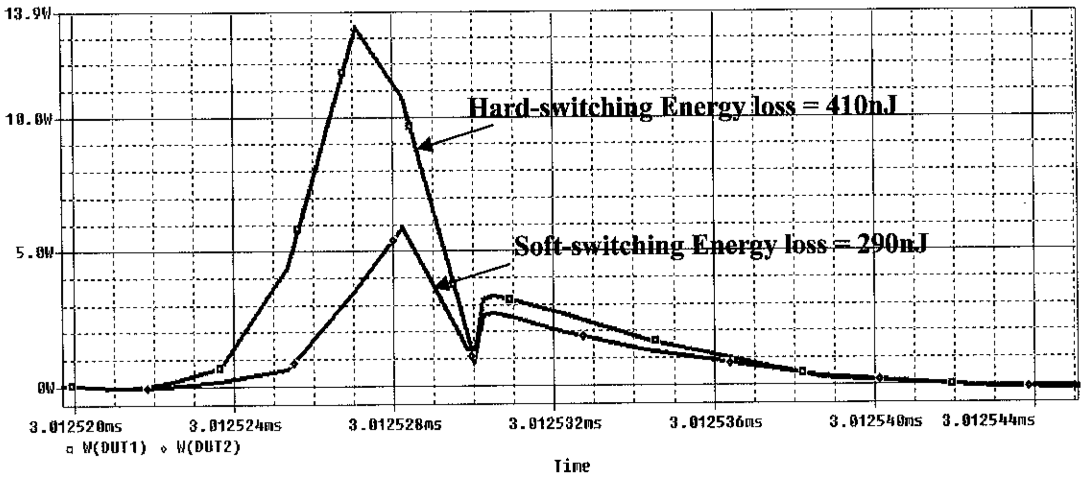



Figure 25: Power Dissipation of SiC diode during turn-off in Hard- and Soft-switching choppers

Refer below for the calculation of the reverse energy loss for both switching modes.

<u>Hard-switching buck converter</u>

1 division of time=10e-9s

1division of power=1W

1box=1e-9s X 1W =10nJ

Total number of boxes occupied= 41 boxes

Energy loss of hard-switching chopper=410nJ

<u>Soft-switching buck converter</u>

1 division of time=1e-9s

1division of power=1W

1box=1e-9s X 1W =1nJ

Total number of boxes occupied= 29 boxes

Energy loss of soft-switching chopper=290nJ

#### 4.2.2.2 IGBT turn-on loss

During SiC diode turn-off, the IGBT is turned on and the loss during that time must be taken into consideration when determining the total energy loss during Total SiC diode turn-off.

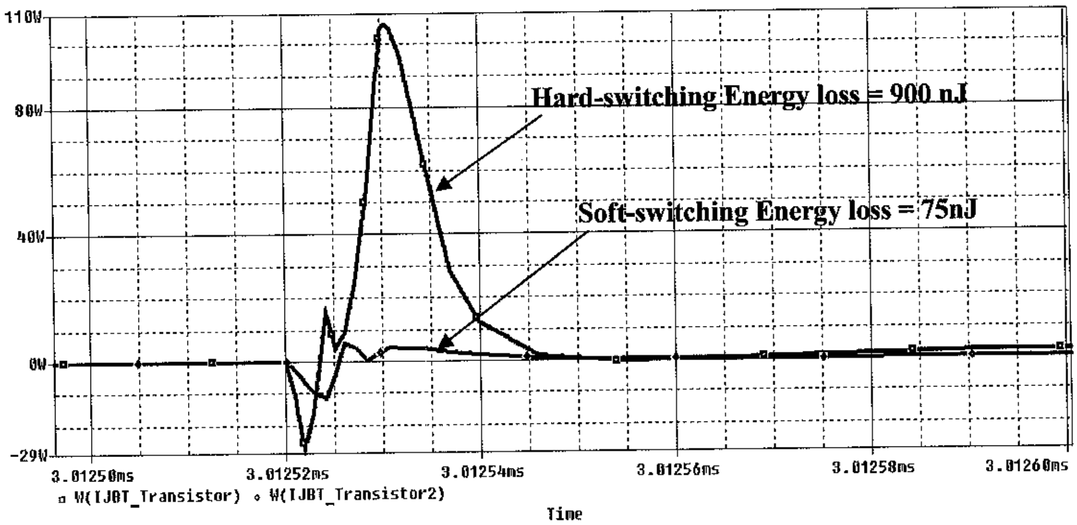



Figure 26: IGBT turn-on power loss in Hard- and Soft- switching choppers

Calculation of energy loss is similar to the calculation on page 24:

| |
|---|
| Energy loss of hard-switching chopper = 900nJ |
| Energy loss of hard-switching chopper = 75nJ |

### 4.2.3 Total SiC diode turn-on loss

Total SiC diode turn-on loss includes:

1) SiC diode turn-on loss

2) IGBT turn-off loss

#### 4.2.3.1 SiC diode Turn-On Loss

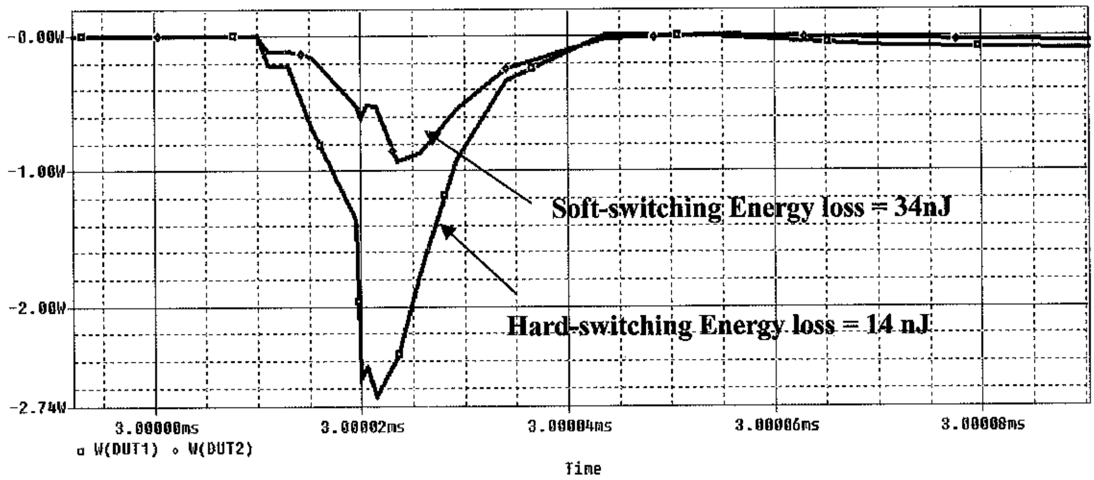



Figure 27: SiC diode Turn-On Power Loss in Hard- and Soft-switching choppers

This loss is caused by leakage current during SiC diode in off state. Power is negative because of leakage current being opposite to actual SiC diode current. Calculation of energy loss is similar to the calculation on page 24:

| |
|---|
| Energy loss of hard-switching chopper = 34nJ |
| Energy loss of soft-switching chopper = 14nJ |

#### 4.2.3.2 IGBT turn-off loss

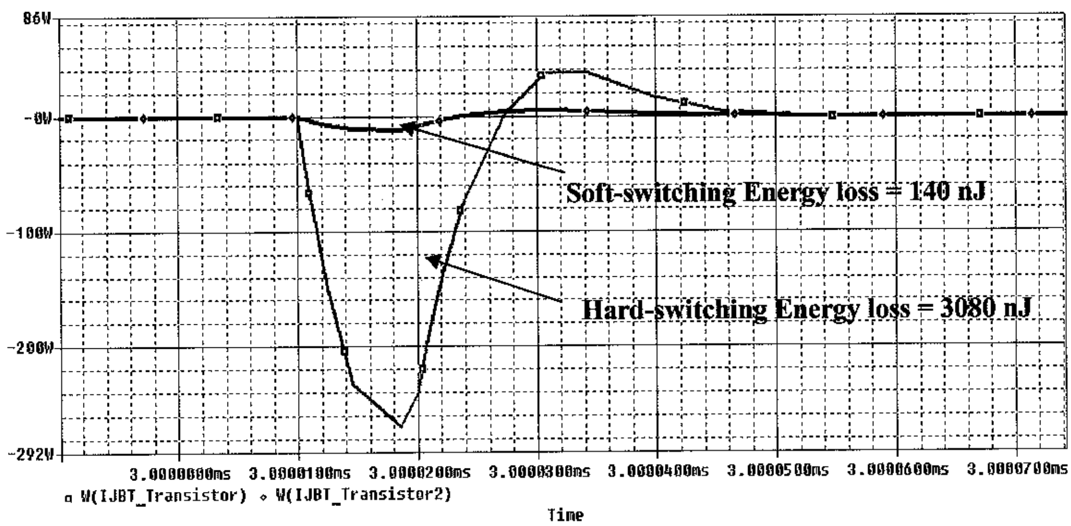



Figure 28: IGBT turn-off power loss in Hard- and Soft- switching choppers

Calculation of energy loss is similar to the calculation on page 24.

| |
|---|
| Energy loss of hard-switching chopper = 3080nJ |
| Energy loss of soft-switching chopper = 140nJ |

### 4.2.4 Summary of Simulation results

| Characteristics | Hard-switching | Soft-switching | Soft-switching chopper has: |
|---|---|---|---|
| Reverse Recovery Current | - 400mA | - 310mA | 1.29 times better performance |

Table 4 (a): Reverse Recovery Current

| Characteristics | Hard-switching | Soft-switching | Soft-switching chopper has: |
|---|---|---|---|
| SiC diode Turn-Off Loss | 410nJ | 290nJ | 1.41 times better performance |
| IGBT Turn-On Loss | 900nJ | 75nJ | 12 times better performance |
| **Total SiC diode turn-off loss** | **1310nJ** | **365nJ** | **3.59 times better performance** |

Table 4 (b): Total SiC diode turn-on loss

| Characteristics | Hard-switching | Soft-switching | Soft-switching chopper has: |
|---|---|---|---|
| SiC diode Turn-On Loss | 34nJ | 14nJ | 2.43 times better performance |
| IGBT Turn-Off Loss | 3080nJ | 140nJ | 22 times better performance |
| **Total SiC diode turn-on loss** | **3114nJ** | **154nJ** | **20 times better performance** |

Table 4 (c): Total SiC diode turn-on loss

| Characteristics | Hard-switching | Soft-switching | Soft-switching chopper has: |
|---|---|---|---|
| Total Energy Loss | 4424 nJ | 519 nJ | 8.5 times better performance |

Table 4 (d): Total Energy Loss

### 4.2.5 Discussion of Simulation Results

Referring to Table 4 (a), (b), (c), (d) we can make following conclusions:

i) Hard switching chopper has more energy losses (4424 nJ) compared to Soft switching chopper (519 nJ).

i) Reverse recovery current of SiC diode in hard switching chopper is higher (- 400 mA) compared to soft switching chopper (- 310 mA).

ii) The main losses occur during SiC diode turn-off (410 nJ) (caused by reverse recovery current), IGBT turn-on (900 nJ) (caused by $I_{CE}$ current spike) and the highest main loss is during IGBT turn-off (3080 nJ) (caused by tailing time, tailing current).

iii) The highest main losses which are in IGBT are significantly decreased during soft switching (from 900 nJ to 75 nJ and from 3080 nJ to 154 nJ), which proves the theory statement.

iv) SiC diode turn-off loss (410 nJ) is much higher than SiC diode turn-on loss (34 nJ). These losses are not drastically affected by soft switching chopper. These values are quite close compared to hard switching chopper.

## 4.3 EXPERIMENTATION RESULTS

Experimentation is conducted with Hard (Figure 22) and Soft (Figure 23) switching choppers. For the experimentation settings with the full list of equipment used, please refer to Table 1 and Figure 22 and Figure 23.

### 4.3.1 SiC diode Reverse Recovery Current

To get current graph of SiC diode, 1 Ω resistor has been employed. For detailed set up for this measurement please refer to page 18.

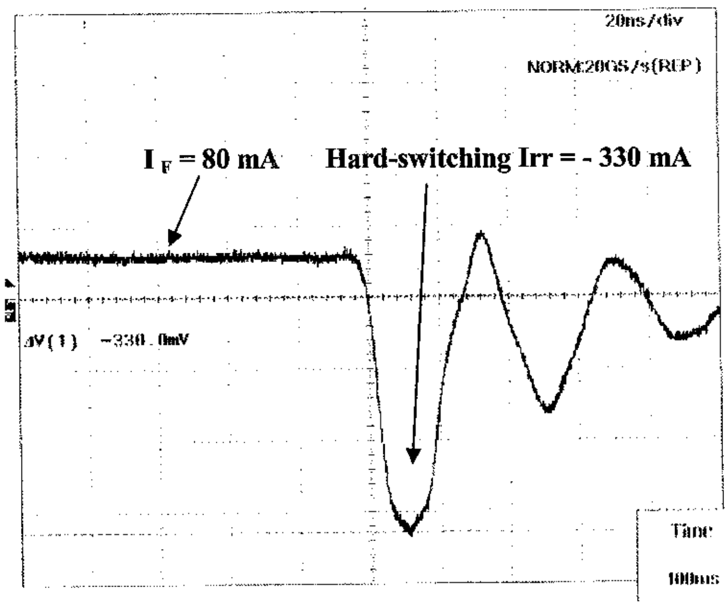



Figure 29: Reverse recovery current of SiC diode in Hard-switching chopper

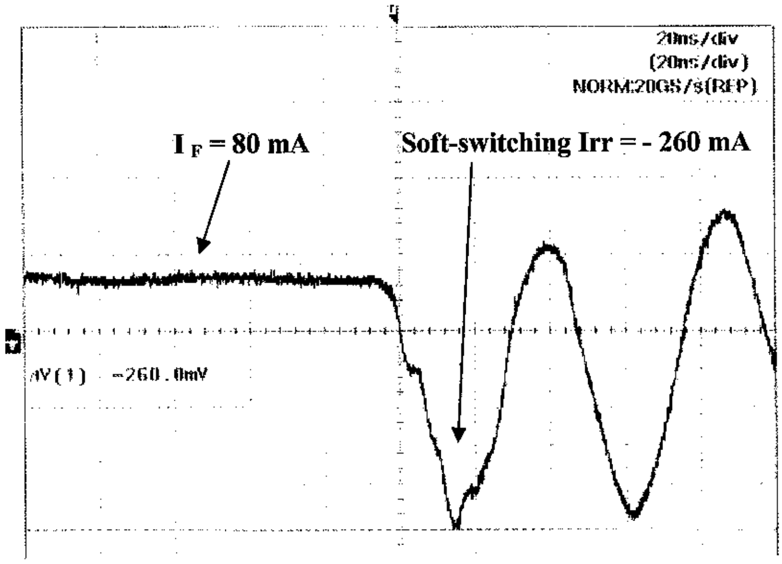



Figure 30: Reverse recovery current of SiC diode in Soft-switching chopper

From Figure 29 and Figure 30, we can conclude that experimentation value for reverse recovery current of Soft- switching chopper ($I_{DIODE\text{-}off}$ = -330 mA) has lower amplitude compared to Hard-switching chopper ($I_{DIODE\text{-}off}$ = -260 mA). These values are very close to the simulation values. For comparison of simulation and experimentation values refer to Table 5.

### 4.3.2 SiC diode turn-off Power loss

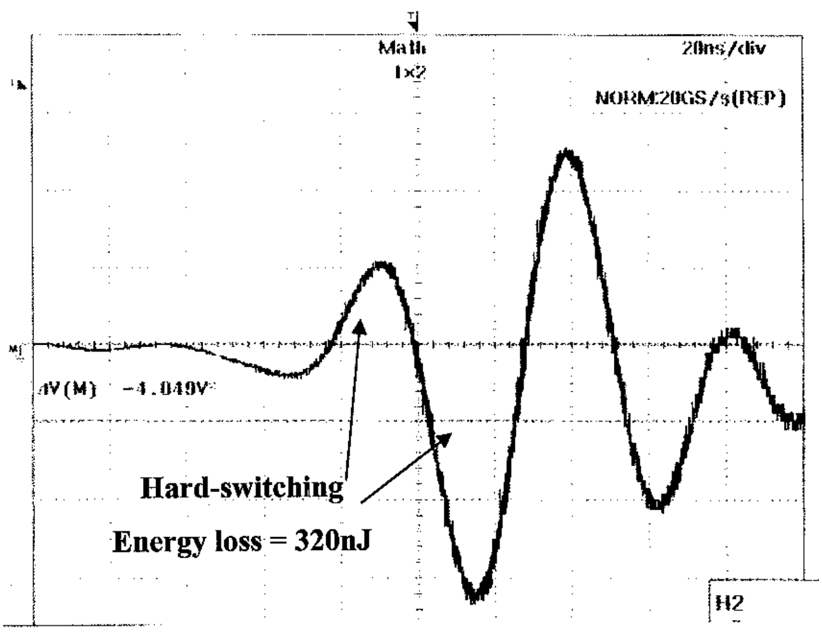



Figure 31: SiC diode turn-off Power loss in Hard-switching chopper

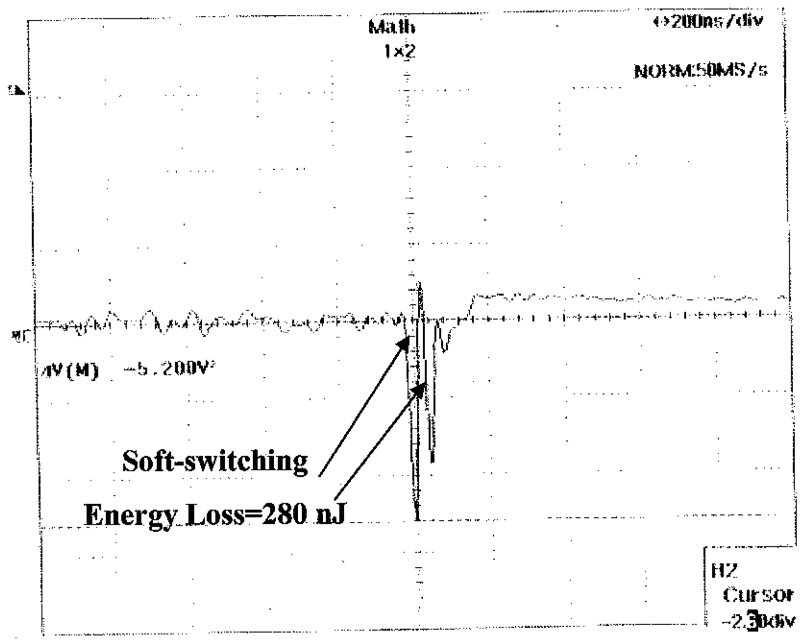



Figure 32: SiC diode turn-off Power loss in soft-switching chopper

### 4.3.4 Summary and Comparison between Soft and Hard switching chopper

| | Characteristics | Hard-switching | Soft-switching |
|---|---|---|---|
| **Simulation** | Recovery Current | - 400mA | - 310mA |
| **Experimentation** | Recovery Current | - 330mA | - 260mA |
| **Simulation** | SiC diode Turn-Off Loss | 410nJ | 290nJ |
| **Experimentation** | SiC diode Turn-Off Loss | 320nJ | 280nJ |

Table 5: Summary and Comparison between simulation and experimentation results

### 4.3.5 Discussion of Experimentation Results

Referring to Table 5;

i) Experimentation values (- 400 mA) are quite close to Simulation values (- 330 mA).

ii) The slight difference may occur because of:

a) Resistance and inductance of bus tracks of PCB.

b) Resistance and inductance of digital oscilloscope probe

iii) The SiC reverse recovery current and power loss waveform obtained using 1 Ω resistance (for further detailed setup, please refer to page 18).

iv) The voltage supply trips (short circuited) when probe is connected across the resistor on the emitter output line of IGBT. So, IGBT current waveform across CE obtained using two channels (for further detailed setup, please refer to page 20 – page 21).

v) To get IGBT power loss waveform, we should multiply (using MATH function of digital oscilloscope) current through IGBT and voltage $V_{CE}$. The digital oscilloscope has two channels only. Both of those channels were used to obtain IGBT current. So, the IGBT power loss waveform can not be obtained, because there is no empty channel for voltage across $V_{CE}$.

# CHAPTER 5
# CONCLUSION AND RECOMMENDATION

Two types of buck converters, hard switching and soft switching buck converters (choppers) are compared in term of power loss and reverse recovery current of SiC diode in a DC applications. Both simulation and experimentation results are obtained and compared. From the observations of the results following conclusions were made.

Hard switching chopper has more energy losses (4424 nJ) compared Soft switching chopper (519 nJ). Reverse recovery current of SiC diode in hard switching chopper is higher compared to soft switching chopper. (HARD: simulation: -400 mA, experiment= - 310 mA) (SOFT: simulation: -330 mA, experiment= - 260 mA)

The main losses occur during SiC diode turn-off (simulation= 410 nJ, experiment =320 nJ) (caused by reverse recovery current), IGBT turn-on (900 nJ) (caused by $I_{CE}$ current spike) and the highest main loss is IGBT turn-off (3080 nJ) (caused by tailing time, tailing current). The highest losses which are occurred in IGBT are significantly decreased during soft switching, which proves the theory statement (IGBT turn-on: from 900 nJ to 75 nJ and IGBT turn-off: from 3080 nJ to 154 nJ).

SiC diode turn-off loss is much higher than SiC diode turn-on loss (simulation: hard sw. turn-off = 410 nJ, turn-on= 34 nJ ). These losses are not drastically affected by soft switching chopper. These values are quite close compared to hard switching chopper (simulation: soft sw. turn-off = 290 nJ, turn-on= 14 nJ).

IGBT transistors have high turn-off switching loss (3080 nJ) due to the current tail and turn-on switching loss (900 nJ) due to current spike. Reducing the turn-off and turn-on switching losses of the IGBT would imply decreasing of the total loss of the system. That could be done by implementing zero voltage switching across the IGBT transistor which would decrease IGBT turn-on and turn-off losses (IGBT turn-on: from 900 nJ to 75 nJ and IGBT turn-off: from 3080 nJ to 154 nJ).

Soft switching chopper circuit is comparably easy to implement. The only difference with hard switching chopper is resonant capacitor, resonant inductor and inversely connected diode. This makes it inexpensive to implement in industry.

The study of the power loss of hard and soft switching chopper circuits can be expanded by studying temperature, EMI (Electro Magnetic Interference) effects on them.

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## APPENDIX

Table 2: Suggested Milestone for the First Semester of 2 Semester Final Year Project

| No. | Detail/ Week | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Selection of Project Topic | ■ | | | | | | | | | | | | | |
| | -Propose Topic | | | | | | | | | | | | | | |
| | -Topic assigned to students | | | | | | | | | | | | | | |
| 2 | Preliminary Research Work | | ■ | ■ | | | | | | | | | | | |
| | -Introduction | | | | | | | | | | | | | | |
| | -Objective | | | | | | | | | | | | | | |
| | -List of references/literature | | | | | | | | | | | | | | |
| | -Project planning | | | | | | | | | | | | | | |
| 3 | Submission of Preliminary Report | | | ● | | | | | | | | | | | |
| 4 | Project Work | | | | ■ | ■ | ■ | ■ | | | | | | | |
| | -Reference/Literature | | | | | | | | | | | | | | |
| | -Practical/Laboratory Work | | | | | | | | | | | | | | |
| 5 | Submission of Progress Report | | | | | | | | ● | | | | | | |
| 6 | Project work continue | | | | | | | | ■ | ■ | ■ | ■ | | | |
| | -Practical/Laboratory Work | | | | | | | | | | | | | | |
| 7 | Submission of Interim Report Final Draft | | | | | | | | | | | | ● | | |
| 8 | Oral Presentation | | | | | | | | | | | | | ● | |
| 9 | Submission of Interim Report | | | | | | | | | | | | | | ● |

● Suggested milestone

Table 3: Suggested Milestone for the Second Semester of 2 Semester Final Year Project

| No. | Detail/ Week | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| 1 | Project Work Continue | | ■ | ■ | | | | | | | | | | | |
| | -Practical/Laboratory Work | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| 2 | Submission of Progress Report 1 | | | ● | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| 3 | Project Work Continue | | | | ■ | ■ | ■ | ■ | | | | | | | |
| | -Practical/Laboratory Work | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| 4 | Submission of Progress Report 2 | | | | | | | | ● | | | | | | |
| | | | | | | | | | | | | | | | |
| 5 | Project work continue | | | | | | | | ■ | ■ | ■ | ■ | | | |
| | -Practical/Laboratory Work | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| 6 | Submission of Dissertation Final Draft | | | | | | | | | | | | ● | | |
| | | | | | | | | | | | | | | | |
| 7 | Oral Presentation | | | | | | | | | | | | | ● | |
| | | | | | | | | | | | | | | | |
| 8 | Submission of Project Dissertation | | | | | | | | | | | | | | ● |

● Suggested milestone
■ Process