A detailed analysis on BUCK Converter in different conduction mode

By

Md Shaidul Islam Shakil

Thesis Supervisor: Dr. Amina Hasan Abedin

A Thesis submitted to the Department of Electrical and Electronics Engineering

BRAC University

Declaration

I hereby declare that this thesis paper title “A detailed analysis on BUCK Converter in different conduction mode” is done only by my research along with the research’s implementation results found by me. Every material of research or thesis used from other sources has been mentioned along with their references. This thesis report is being submitted to the Department of Electrical and Electronics Engineering of BRAC University.

………………………………..

Dr. Amina Hasan Abedin

(Thesis Supervisor)

…………………………………

Md. Shaidul Islam Shakil

09220173

Acknowledgement

Although it has just been just four years studying in BRAC University, it is an experience that will stay with me forever. My stay in BRAC University has given me a lot to cherish, good friendships, an excellent studying environment to name a few.

First of all, I would like to thank my thesis supervisor Dr. Amina Hasan Abedin, Assistant Professor, Department of Electrical and Electronics Engineering, BRAC University, Bangladesh, for assisting and helping me on numerous occasions. I consider myself fortunate enough to work with her. I would like to thank her for believing in me.

I would like to thank all of them who helped and supported me through my completion of the thesis. Finally, I would like to thank the Department of Electrical and Electronics Engineering for supporting me during my thesis and BRAC University for giving me the opportunity to complete my research.

Thank You.

Abstract

A DC-DC BUCK Converter is a basic type of switch mode power converter. It has variety of application. It behaves differently in different conduction mode. In this thesis a buck converter is designed first considering the design parameters. Then the designed circuit is driven to boundary, continuous and discontinuous mode to analyze the circuit. The gain and efficiency of the circuit has also been found out. A clear picture is drawn for the theoretical and simulated circuit. For continuous mode the circuit simulation shows exact behavior but in discontinuous mode there is some discrepancies. All of these issues are covered in the thesis.

Table of Content **Page No**

List of Figures **Page No**

List of Tables **Page No**

Chapter - 01

Introduction

1.1 Introduction

Due to space constraints in portable equipment's the DC/DC converter is internally compensated. When the converter needs to be optimized for specific application conditions the inductor, output capacitor and the feedback divider are the only components that can be changed. The simplest way to reduce the voltage of a DC supply is to use a linear regulator (such as a 7805), but linear regulators waste energy as they operate by dissipating excess power as heat. Buck converters, on the other hand, can be remarkably efficient (95% or higher for integrated circuits), making them useful for tasks such as converting the main voltage in a computer (12 V in a desktop, 12-24 V in a laptop) down to the 0.8-1.8 volts needed by the processor.

My thesis is about a detailed analysis on BUCK Converter in various conduction mode by studying component's behavior using simulator.

1.2 Basic DC/DC analysis signals

Regardless of the converter topology (step down, boost, or buck-boost, etc.) the three basic waveforms that need to be measured are shown in Fig. 1 using a step down converter as the example. Fig. 1 shows the basic topology of a step down converter with its most important waveforms. V_L is measured with the oscilloscope at the switch pin and should show a stable square wave signal. The inductor current I_L is measured with a current probe. The best way to measure the inductor current is to use a small wire for the current probe in series to the inductor.

The wire does not change the circuit parameter since it adds only a small parasitic inductance in series to the normal inductor. The output voltage Vo is measured directly across the output capacitor of the device. To further minimize noise coupling into the probe, the ground clip must be removed and replaced with a short and direct ground connection across the output capacitor. Special probe connectors are usually the most convenient way to measure the output voltage ripple if they are populated on the PCB.

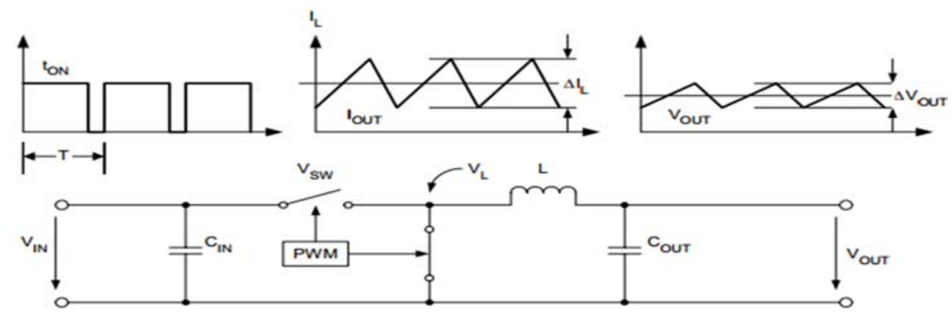


Fig1.1: Basic signal waveforms.

In the following figure it shows the square wave switching signal, output ripple voltage and inductor current.

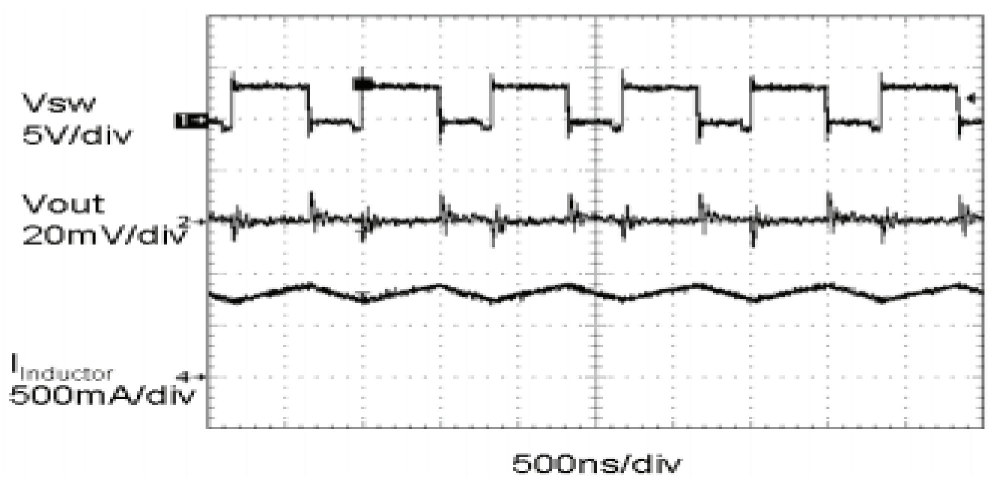


Fig 1.2: Basic oscilloscope signals used to evaluate a switching DC/DC converter

1.3 Component Selection

Inductor

The magnitude of switching ripple in the output voltage in a properly designed DC supply is much less than the dc component. As a result, the output voltage is approximated by its dc component. The ripple requirement in inductor current sets the inductor value. Typically, ΔIL lies in the range of 10-20% of the full load or maximum value of the dc component of Io. The peak inductor current which is equal to the DC component plus the peak to average ripple Δ I L/2, flows through the semiconductor switches and is necessary when specifying device ratings. To reduce the peak current a larger value of inductor is required. A secondary benefit in lowering the ripple current is that it reduces core/inductor, ESR and load losses.

Capacitor

In a BUCK converter the only steady state component of output capacitor current is that arising from the inductor current ripple. Hence inductor current cannot be neglected when calculating the output voltage ripple. The inductor current contains both a DC and ripple current component. The DC component must flow entirely through the load resistance R. While the ac switching ripple divides between the load resistance R and the filter capacitor C.

Power MOSFETs selection

MOSFETs are used as power switches for their near zero DC gate current and fast switching times. It is a requirement to have delay time much less than switching period. MOSFETs power dissipation impacts converter efficiency. This includes Rdson conduction losses, leakage losses; turn on-off switching and gate transition losses. Rdson of the power MOSFET determines the current it can handle without excessive power dissipation. Rdson directly affects the converter efficiency. To minimize Rdson, the applied gate signal should be large enough to maintain operation in the linear, triode or ohmic region. MOSFETs positive temperature coefficients means conduction loss increases with temperature.

1.4 Advantages and disadvantages

It is desirable to combine the advantages & disadvantages of these basic converters**.** We have found that Output voltages can be controlled in an efficient way with the proper use of these converters. Voltage can either be greater or less than input voltage. Moreover, we can get greater efficiency as switching transistors dissipates less power when it is outside active region. These converters are smaller in size, lighter in weight and have less heat generation due to higher efficiency. In real life application, devices can be driven by Bucking or Boosting the input voltage. This eliminates the damage of the device or breakdown.

On the other hand, implementing these in real life have some drawbacks as well. The generation of high amplitude is one of them. Another key drawback is efficiency penalty. Higher switching frequency leads to greater power loss. The low pass filter must block High frequency energy to avoid electromagnetic interface (EMI). A final trade-off of a switching regulator with integrated inductor is that the choice of inductance can be limited, restricting the scope for the designer to optimize the regulator to suit the operational parameters of the end product.

Chapter 2

Analysis of BUCK Converter

2.1 **Introduction**

A BUCK converter is a step down converter because its output voltage is always less than the input voltage. It has got pulsed input current and it requires input filter. In a BUCK converter, the continuous output current results in lower output voltage ripple due to the presence of output inductor. In the following discussion we will analyze the BUCK circuit by varying different parameters of the circuit and observe the changes occurred. ORCAD Schematics is used for simulation purpose.

2.2 **Designing a BUCK Converter**

The circuit diagram of Buck converter is shown in Fig. 2.1. The design of various parameters depend upon the problem requirement. For the purpose of analysis we consider 12V as input and 5 Volt as output. Accordingly the duty cycle, inductor and capacitor values are designed. The designed parameters are shown in Table 2.1.

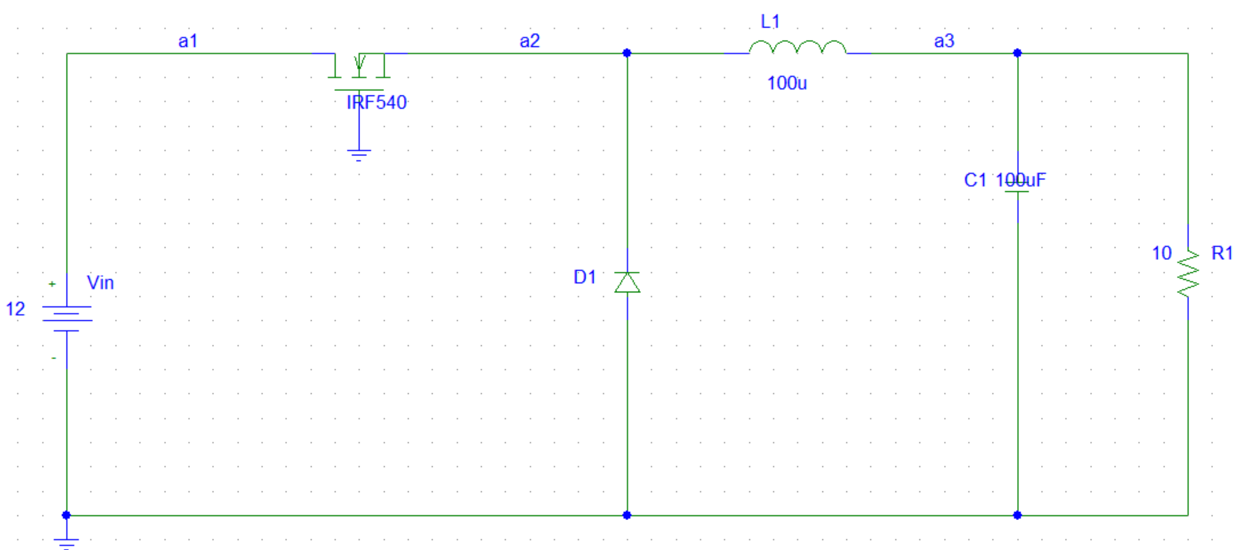


Fig-2.1: BUCK DC-DC Converter

Table 2.1: Different parameters

Input Voltage	Vin	12V
Output Voltage	Vo	5V
Inductor	L	140.62 uH
Capacitor	C	100uF
Frequency	f	40KHz
Resistor	R	10 Ω
Output Voltage Ripple	ΔVo	0.5%

2.2.1 **Inductor design**

For the circuit to operate in continuous conduction mode, the minimum value of inductor is required. We have obtained the inductor value by L = $\frac{(1-D)\times R}{2f}$ where frequency and resistor value was fixed at 40KHz and 10 Ω respectively. As a result the inductor values only depend upon D. A sample calculation id given below to show the design of L for different D. Once the design is fixed for a certain D we need to have some marzin to operate the circuit in continuous conduction mode (CCM). 125% extra value is taken for our design of the inductor in CCM operation.

$D = V_o/V_1 = 5/12 = 0.416$ or $D_1 = 0.1$ or $D_2 = 0.9$

$$L_{min} = \frac{(1-D)\times R}{2f} = 73uH$$

$$L_{min1} = \frac{(1-D_1)\times R}{2f} = 112.5\ uH$$

$$L_{min2} = \frac{(1-D_2)\times R}{2f} = 12.5\ uH$$

$L = 1.25 * L_{min1} = 140.62$ uH

2.2.2 **Capacitor design**

By circuit analysis it can be shown that the design of C depends upon, duty cycle, frequency and output voltage and deviation of output voltage. The formula is C = $\frac{(1-D)}{8L(\Delta Vo/Vo)f^2}$. This equation is determined in terms of specified voltage ripple.

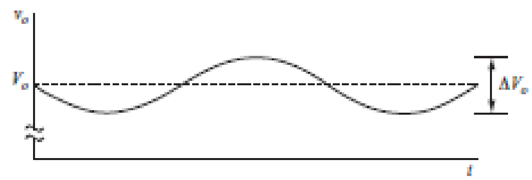


Fig-2.2: Output Voltage Ripple (Ref: from Daniel Hart Book)

From the equation, C = $\frac{(1-D)}{8L(\Delta Vo/Vo)f^2}$ = (1-0.416)/8*0.00009125*0.005*40000^2 = 100uF

2.3 **Analysis of the Buck Circuit with varying D**

The circuit is simulated for varying D ranging from 0.1 to 0.9 and found different values for Gain and Efficiency. With respect to duty cycle D, we have also changed the values for T = 1/f and **PW** = D*T. The following table shows a comparison of different values acquired from running the circuit simulation:

Table2.2: Analysis of the Buck Circuit with varying D

D	Output Voltage(V) Vo	Input Current(A) (AVG) I_{in}	Inductor Current(A) I_L	Gain = $\frac{Vo}{Vin}$	Pin = Vin*I	Pout= $\frac{Vo^2}{R}$	η = $\frac{Pout}{Pin}$
0.1	0.95	-0.01	100	0.08	-0.12	0.09	0.75
0.2	1.73	-0.04	200	0.14	-0.48	0.29	0.6
0.3	2.45	-0.07	300	0.20	-0.84	0.60	0.71
0.4	3.15	-0.13	375	0.26	-1.56	0.99	0.63
0.5	3.75	-0.18	400	0.31	-2.16	1.40	0.64
0.6	4.45	-0.25	450	0.37	-3	1.98	0.66
0.7	5.2	-0.28	475	0.43	-3.36	2.70	0.8
0.8	6	-0.38	550	0.5	-4.56	3.6	0.78
0.9	6.7	-0.5	600	0.55	-6	4.48	0.74

it can be observed from the table that as the duty cycle is increasing output voltage is also increasing.

Chapter 3

Performance Analysis of BUCK Converter in different conduction mode

3.1 **Performance Analysis of BUCK converters**:

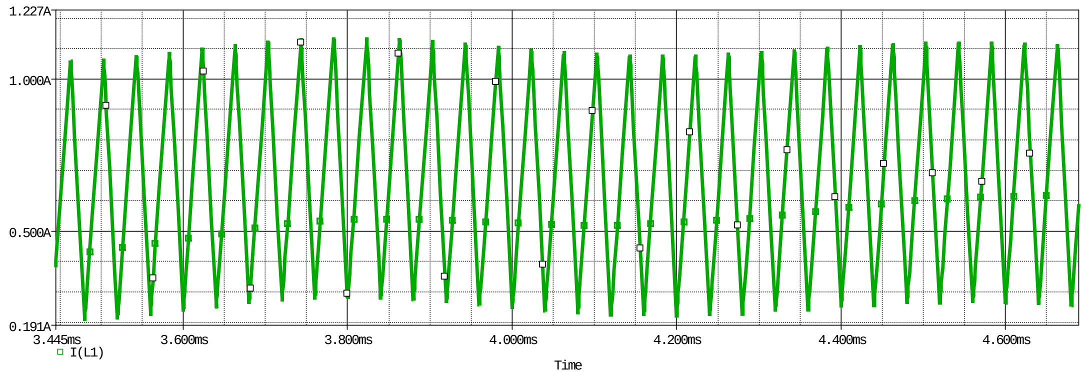


Fig 3.1- Inductor Current IL for D =0.9

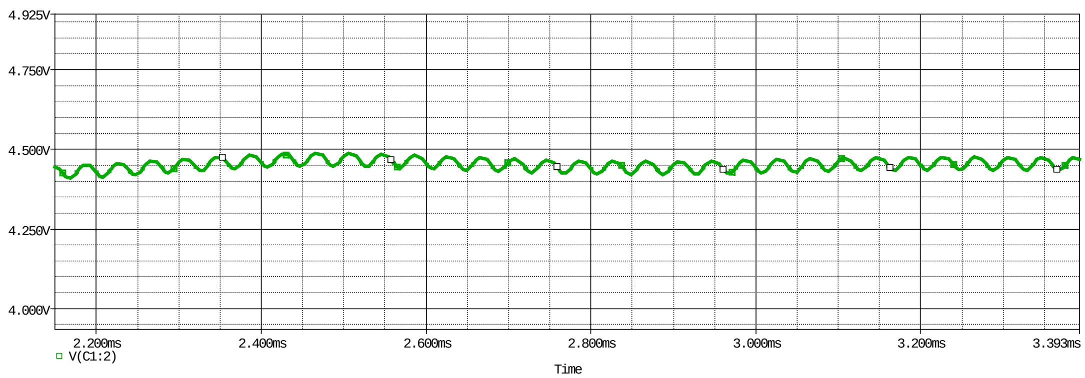


Fig 3.2- Output Voltage Vo for D =0.6

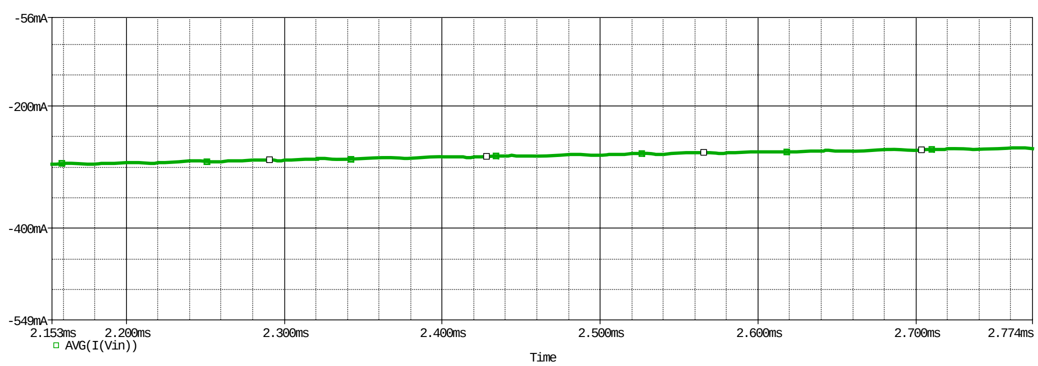


Fig 3.3- Average Input Current for D =0.6

3.2 **Analysis of Buck Converter in Continuous Conduction Mode**

For CCM operation the value of inductor is chosen to be 100uH. Simulation results are shown in figure 3.4 to 3.7. Observing Fig. 3.6 and 3.7 we can see that when the inductor voltage is fixed to a positive value the current is rising through the inductor and when it is fixed to a negative value the current is decreasing. For a full switching cycle average value of inductor voltage is zero.

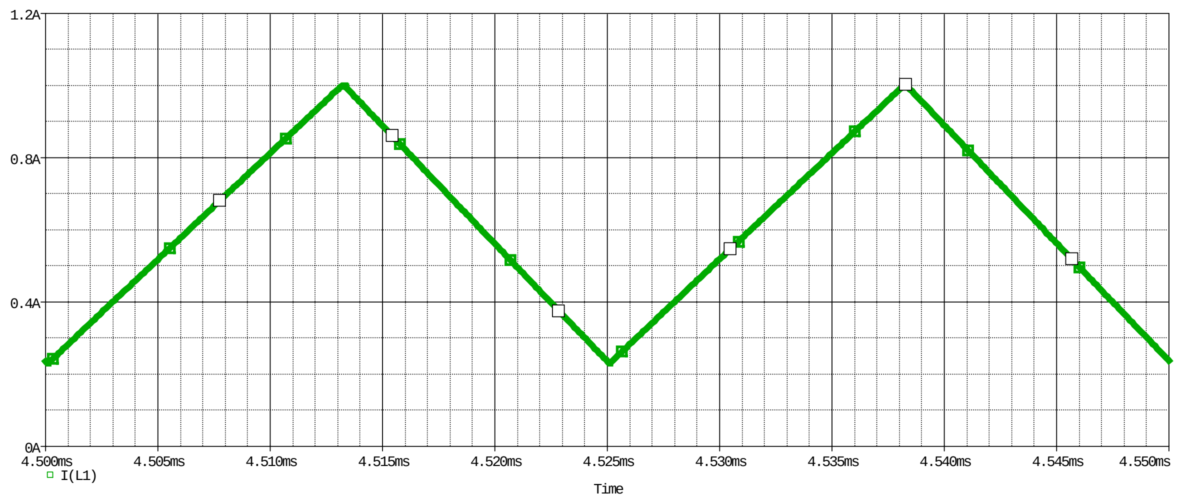


Fig 3.4- Current across Inductor I_{L1}

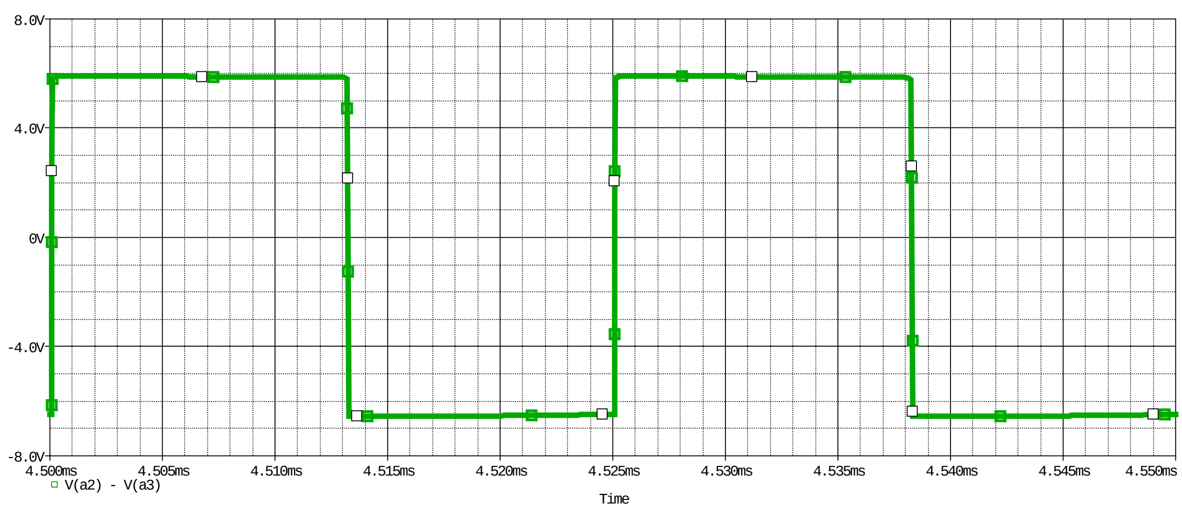


Fig 3.5- Voltage across Inductor V_{L1}

.

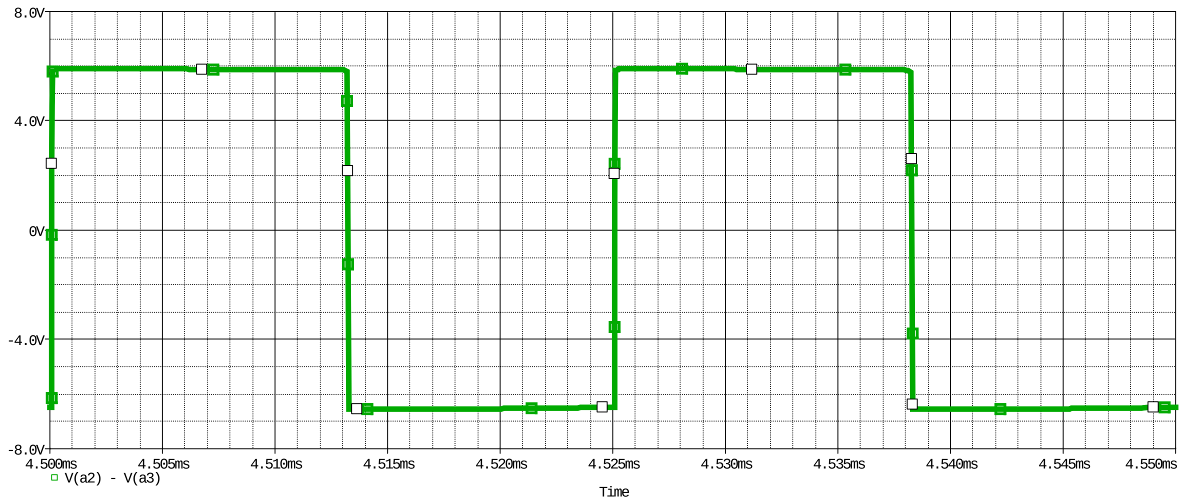


Fig 3.6- Voltage across inductor V_{L1}

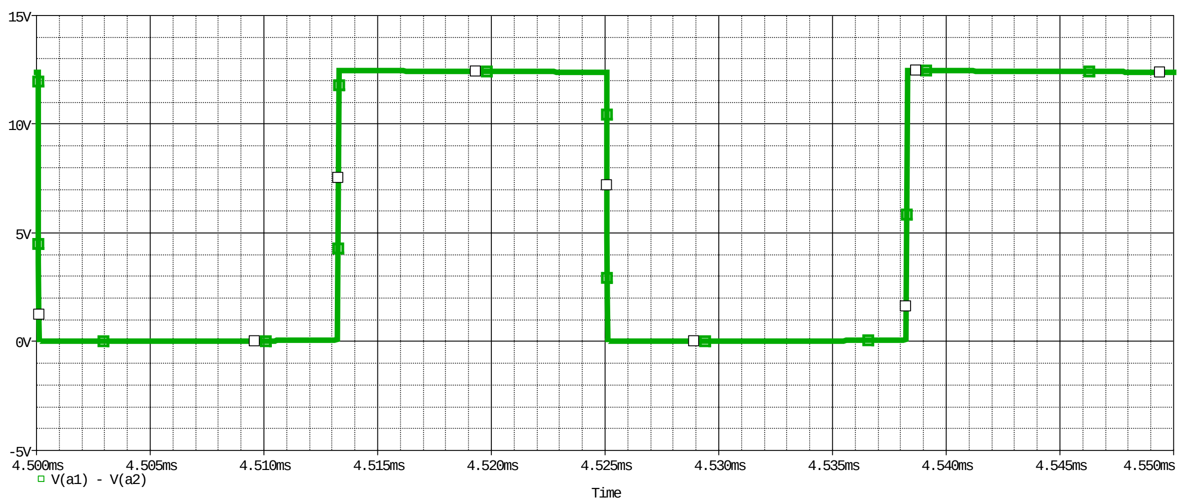
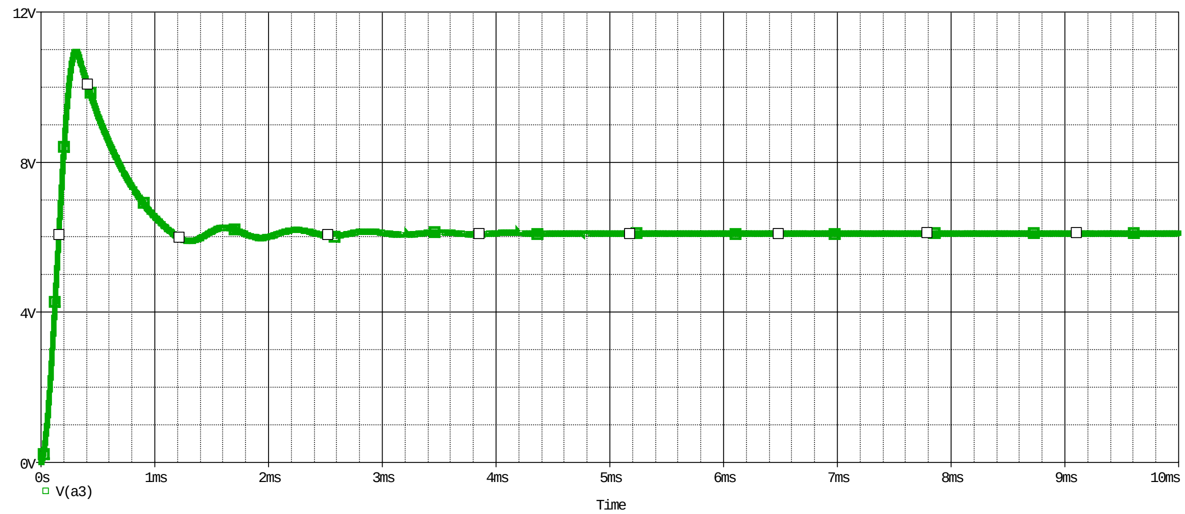


Fig 3.7- Voltage across Switch V_S

The voltage across inductor and switch are acting opposite as shown in Fig.3.6 and 3.7



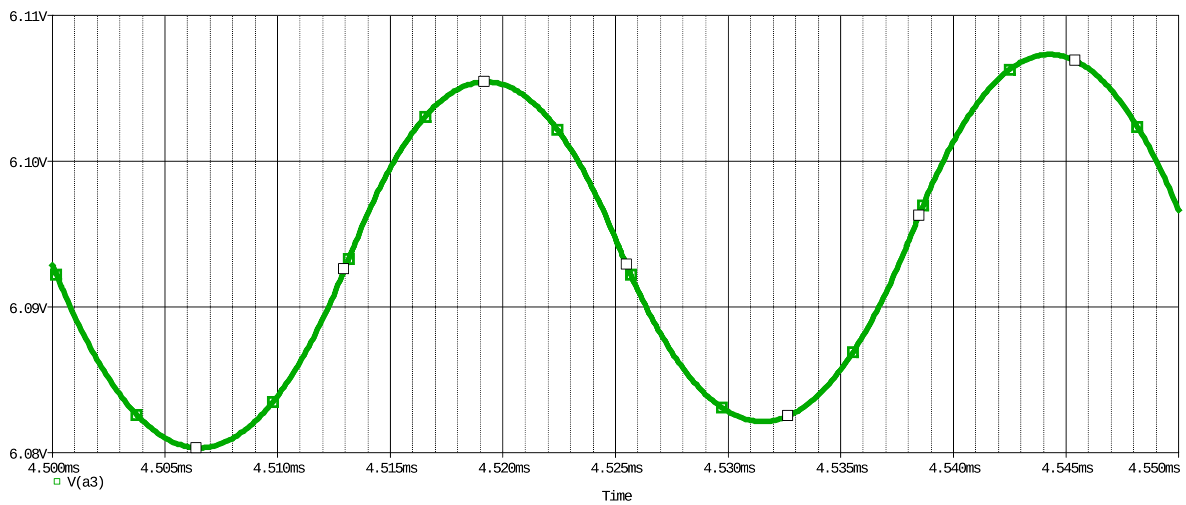


Fig 3.8 Voltage across Capacitor V_{a3}

Fig 3.8 shows the output voltage across the capacitor. There is a slight deviation around the set value because of the switching.

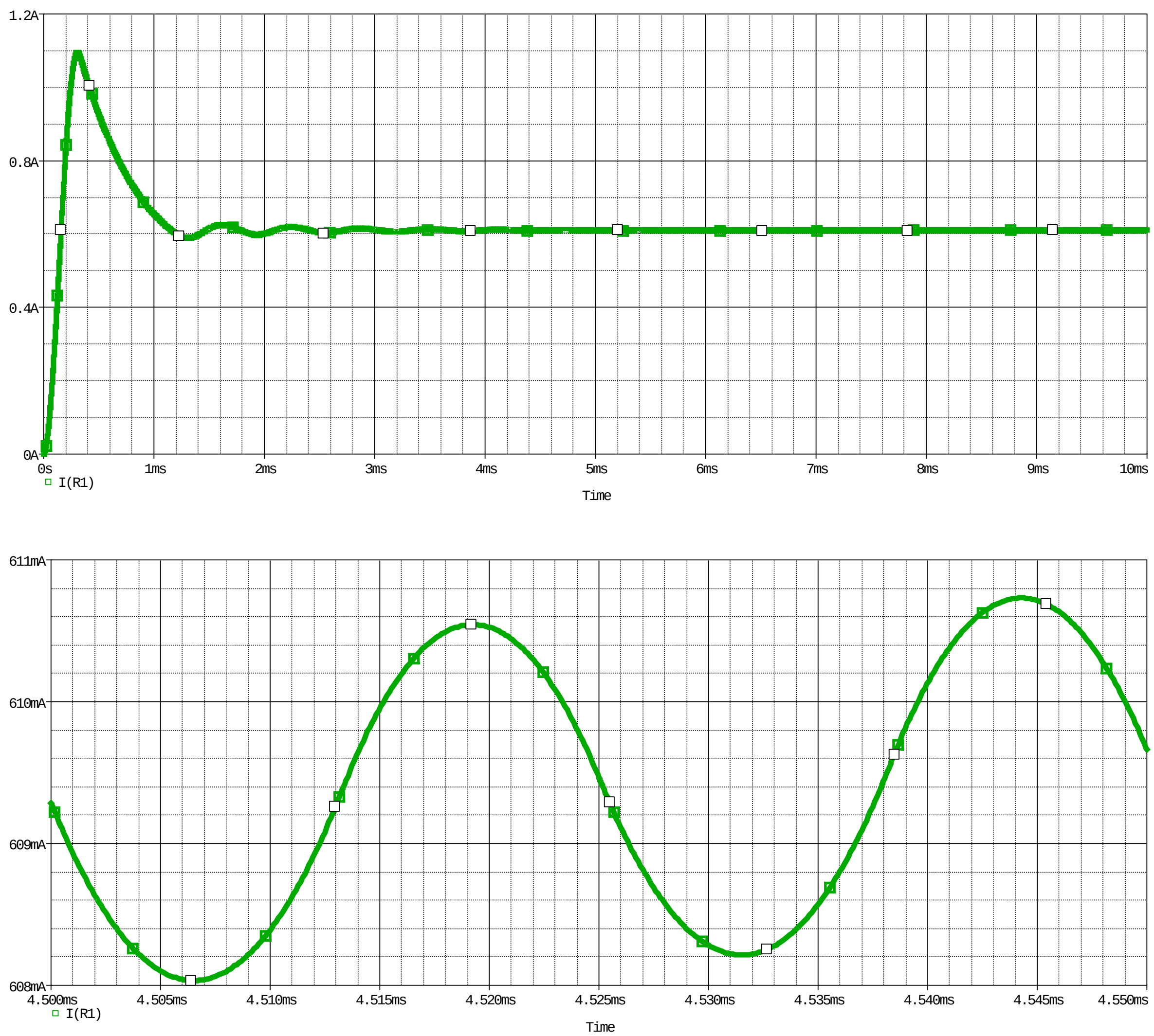


Fig 3.9 Current across Resistor I_{R1}

Fig. 3.9 shows the current through thr output resistor. It has the same shape of the output voltage.

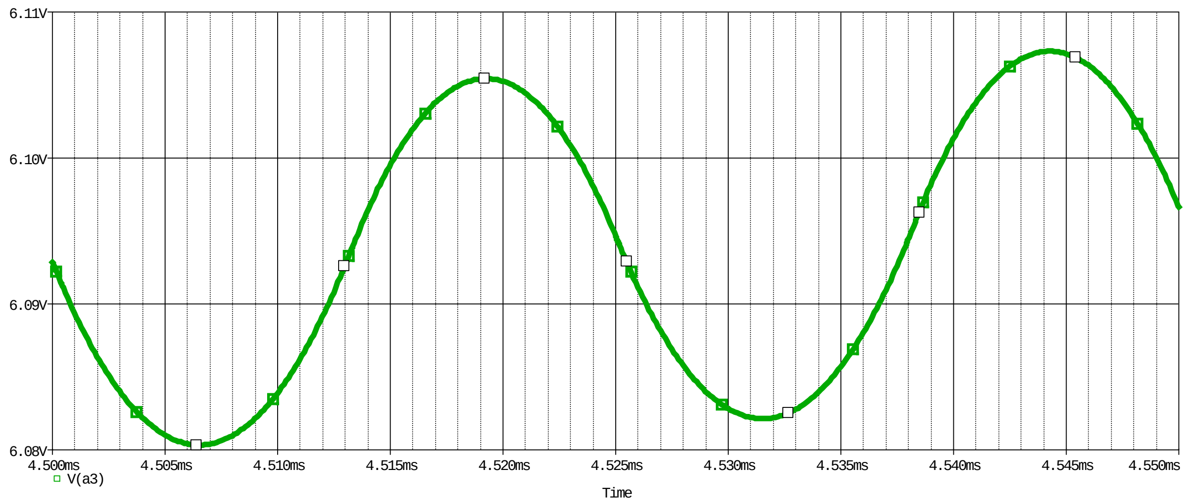


Fig 3.10- Voltage across Capacitor V_{a3}

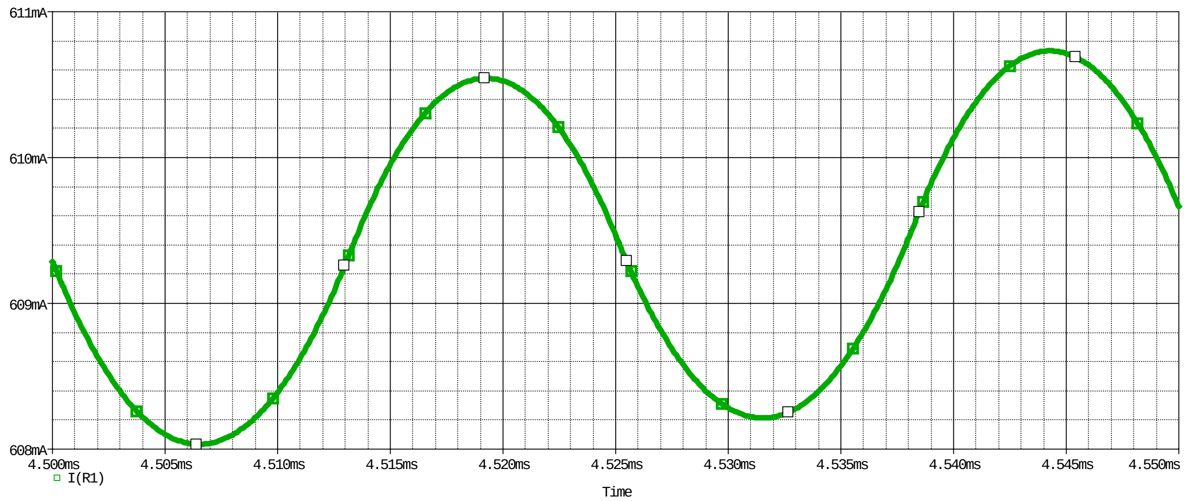


Fig 3.11- Current across Resistor I_{R1}

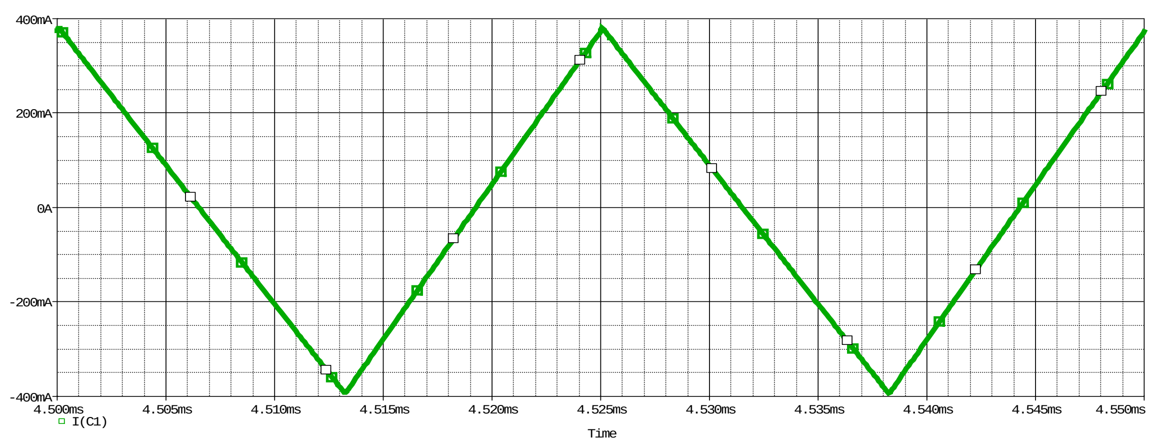


Fig 3.12- Current across Capacitor I_{C1}

Observing the capacitor current as in Fig 3.12, it is found that the average current is zero

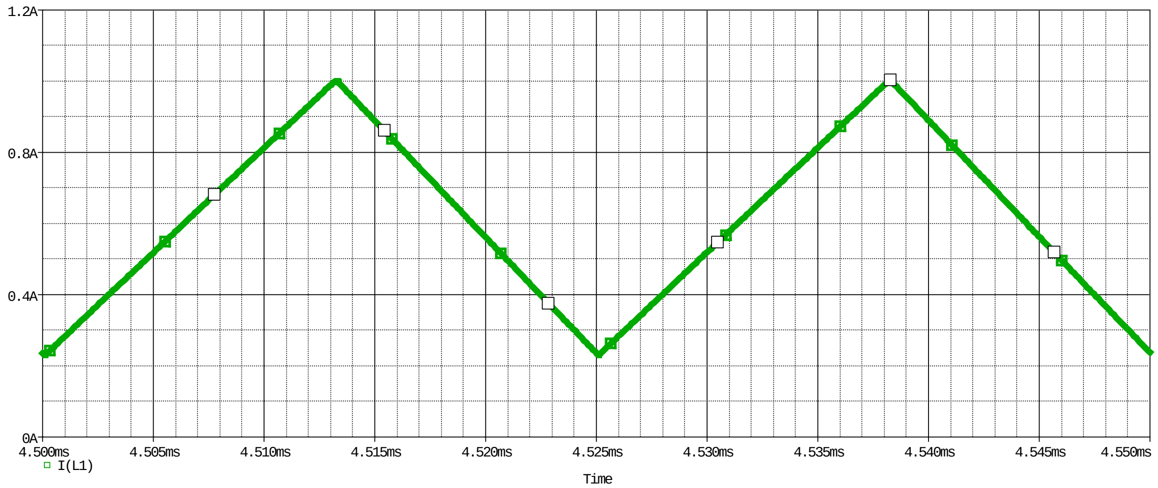


Fig 3.13- Current across Inductor I_{L1}

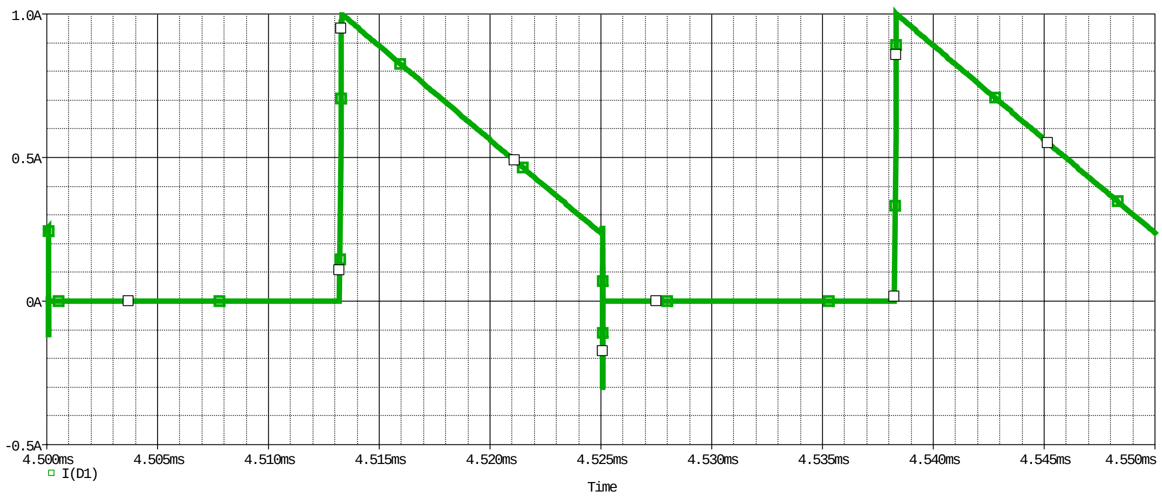


Fig 3.14- Current across Diode I_{D1}

From Fig. 3.13 and 3.14 it can be observed that the diode current is same as inductor current during the tome when the switch is off and during switch on diode is off as a result current is zero.

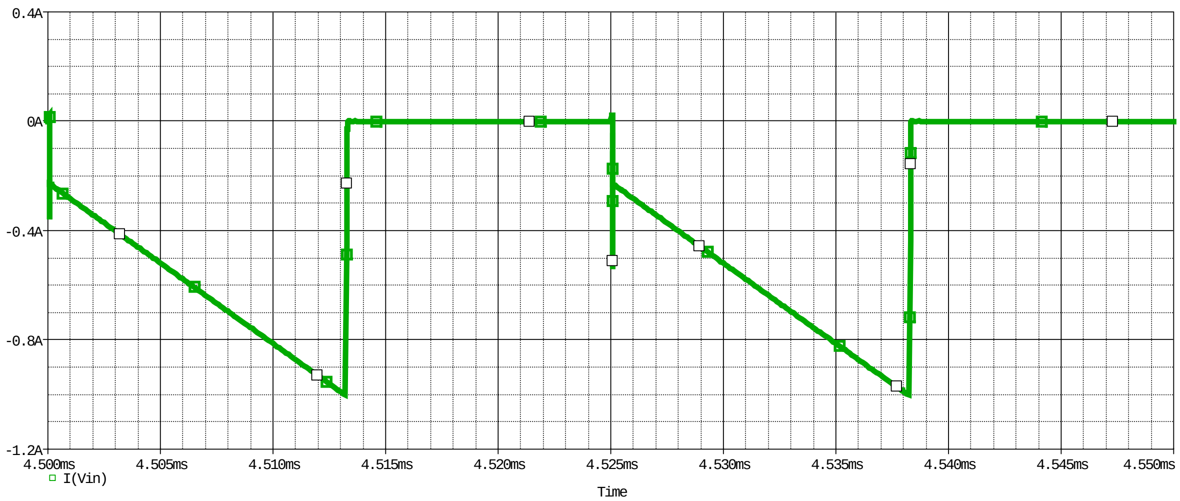


_Fig 3.15- Current across Source I_{Vin}

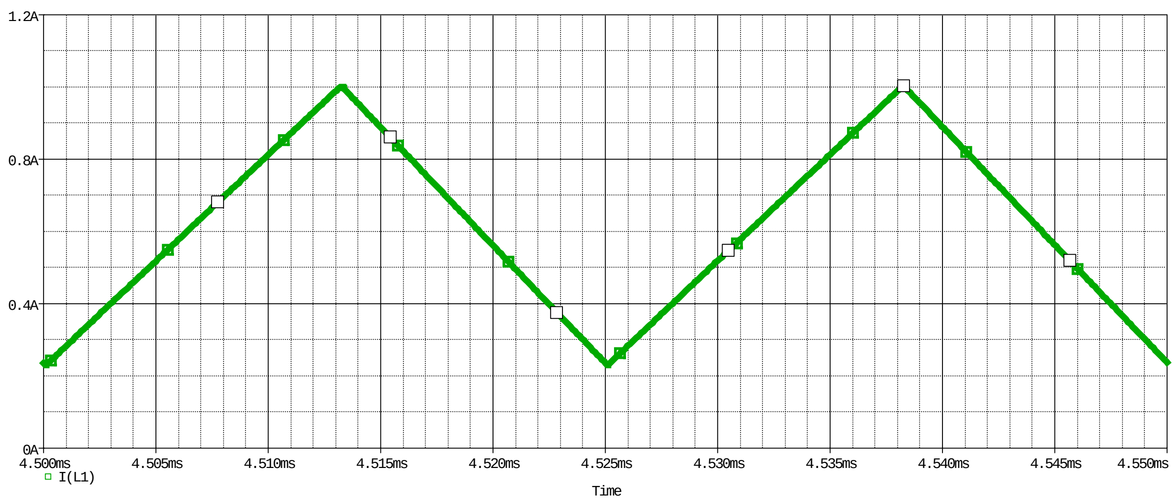


_Fig 3.16- Current across Inductor I_{L1}

Fig. 3.15 and 3.16 compares the input current with the inductor current. During switch on period they are same but during switch off input current is zero momentarily and current decreases across the inductor.

3.3 **Analysis of Buck Converter in Boundary Conduction Mode**

For boundary conduction mode the value of inductor is chosen to be 62.5uH and circuit performance is observed for D=0.5. Figure 3.17 to 3.29 shows different voltage and current for the designed BUCK converter. It can be observed that the wave-shapes has insignificant change over the CCM mode.

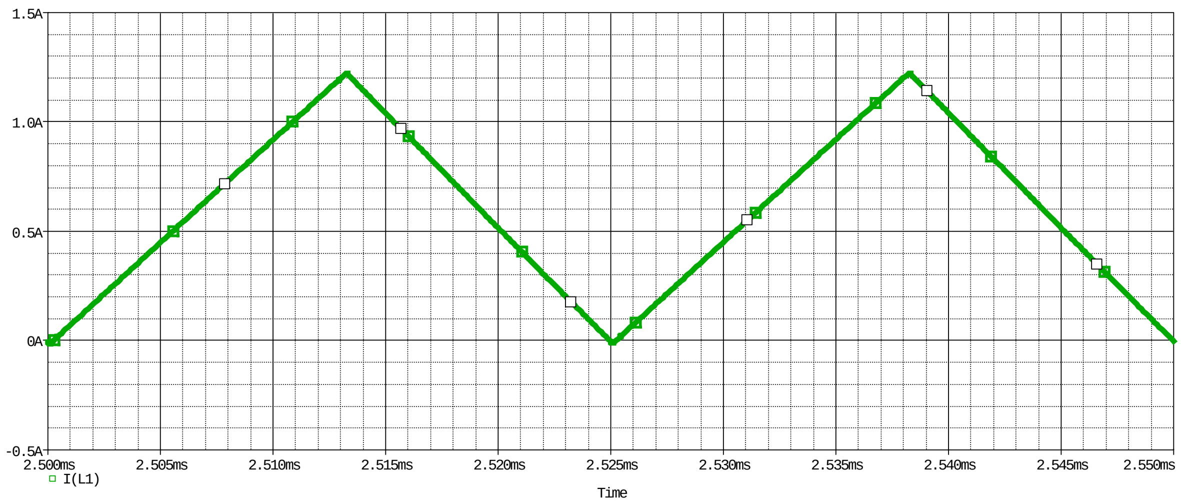


Fig 3.17- Current across Inductor I_{L1}

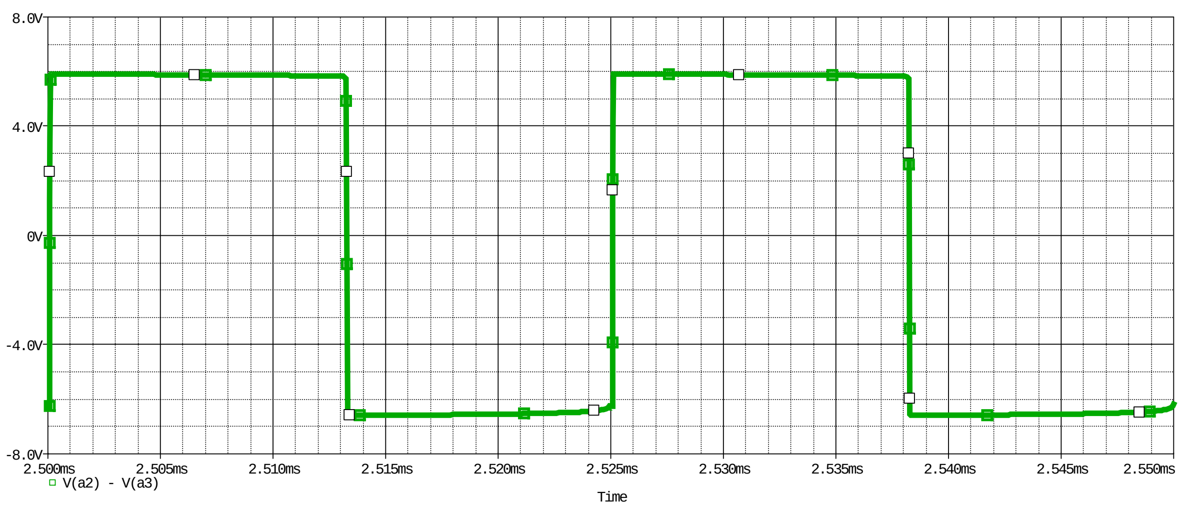


Fig 3.18- Voltage across Inductor V_{L1}

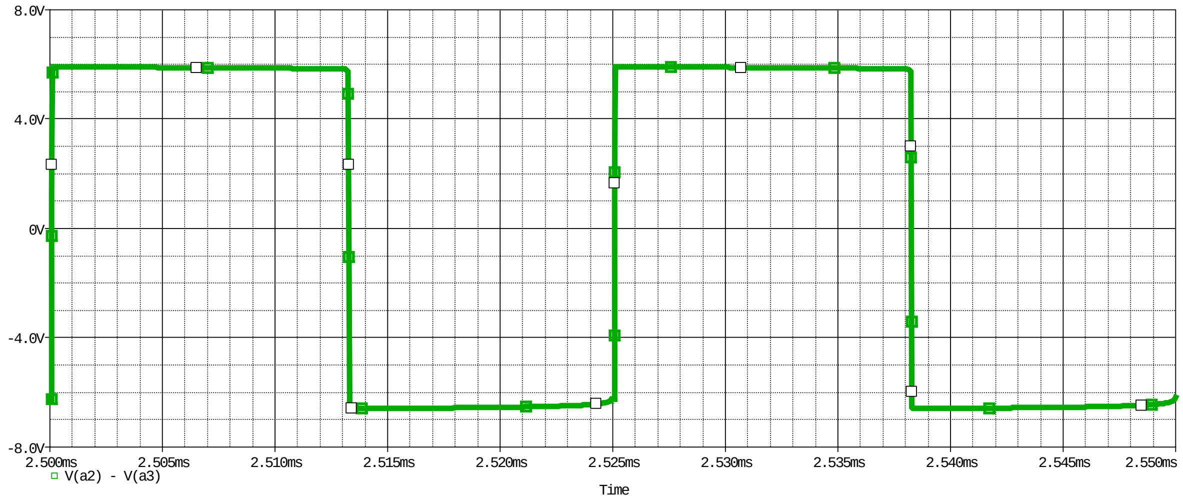


Fig 3.19- Voltage across inductor V_{L1}

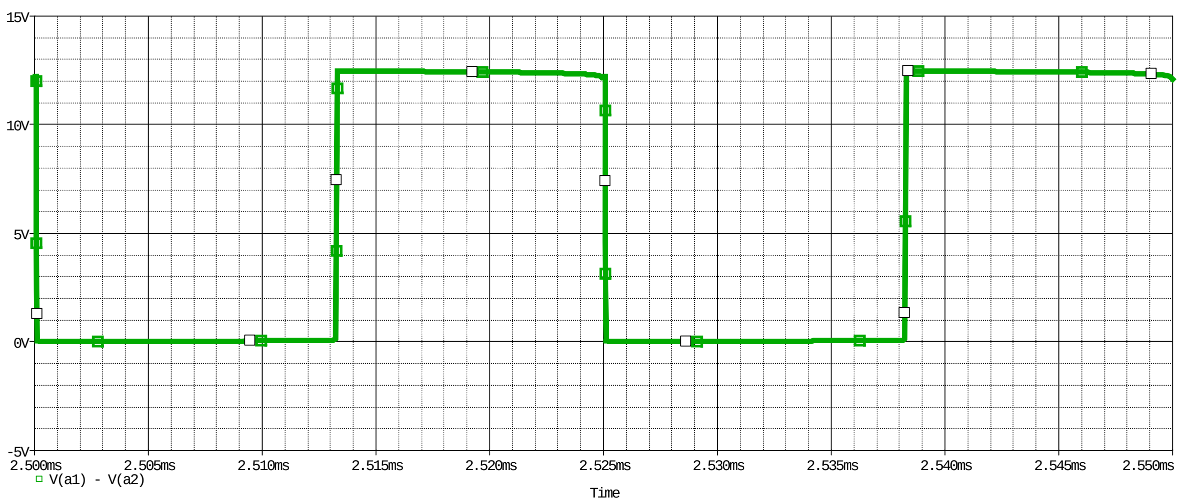


Fig 3.20- Voltage across Switch V_S

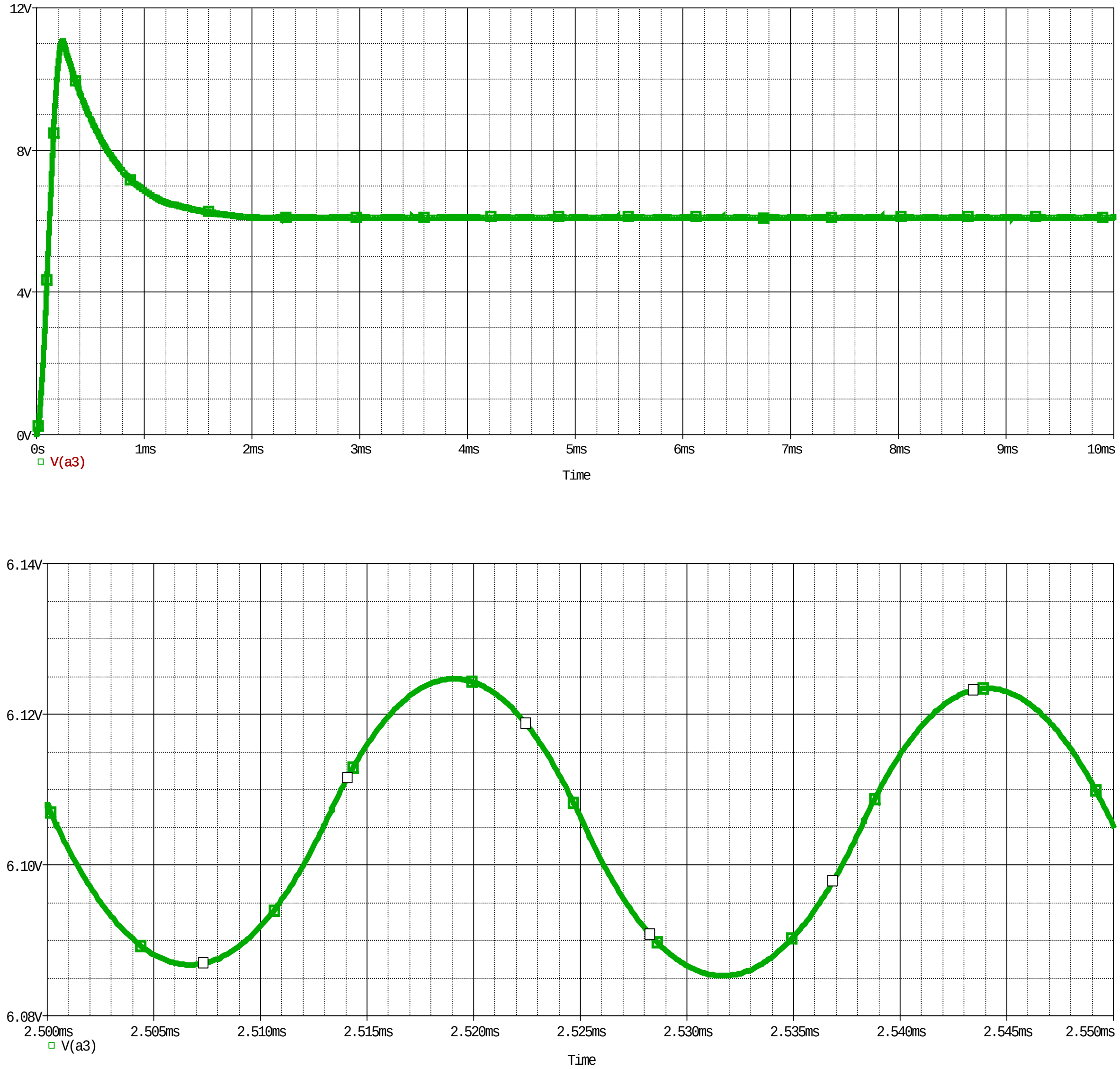


Fig 3.21- Voltage across Capacitor V_{a3}

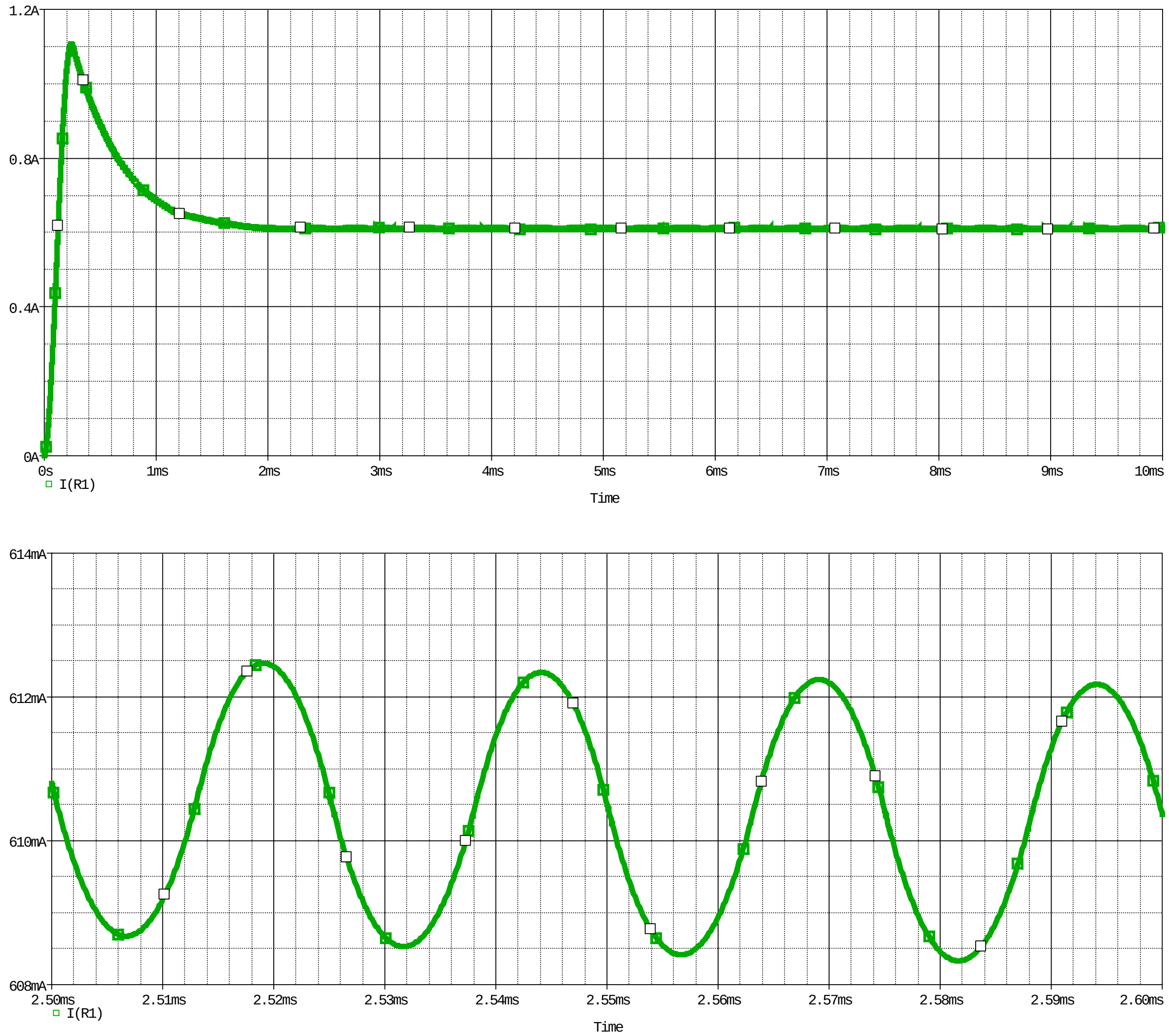


Fig 3.22- Current across Resistor I_{R1}

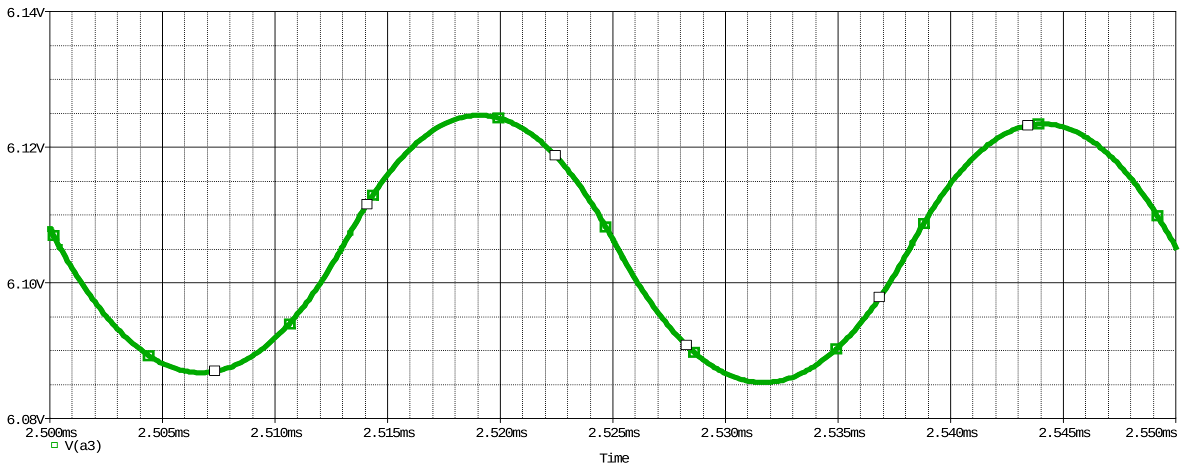


Fig 3.23- Voltage across Capacitor V_{a3}

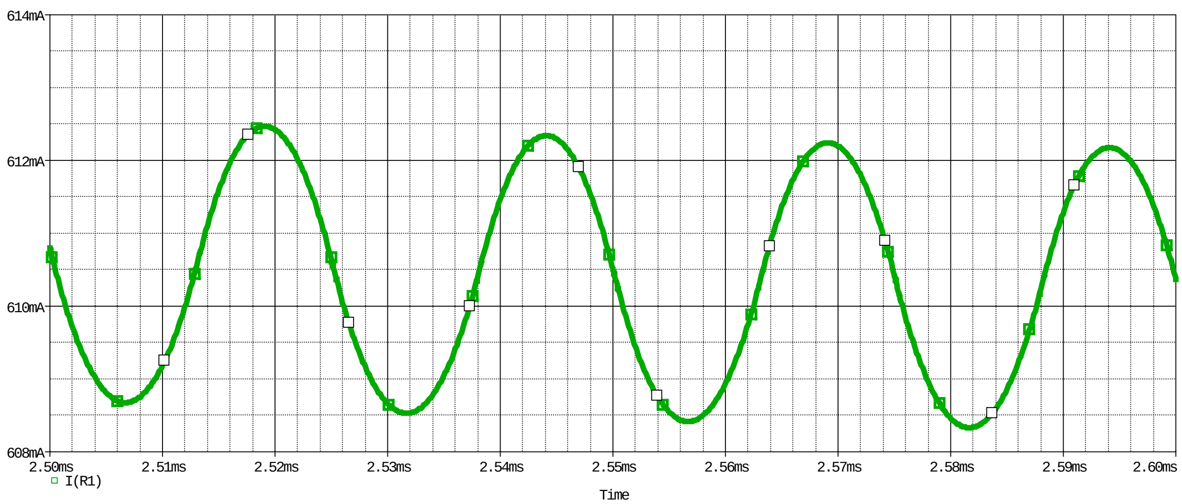


Fig 3.24- Current across Resistor I_{R1}

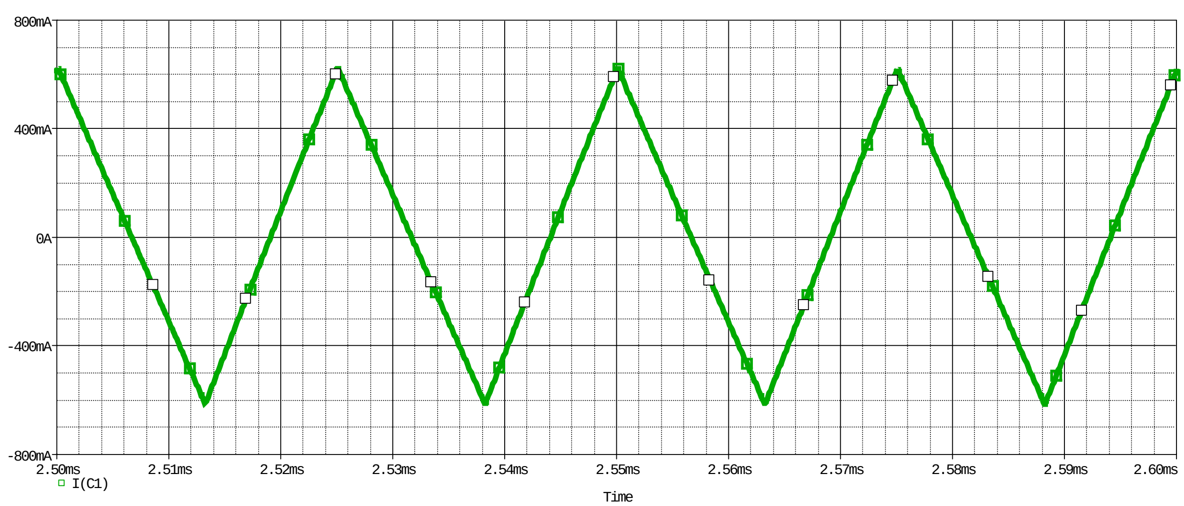


Fig 3.25- Current across Capacitor I_{C1}

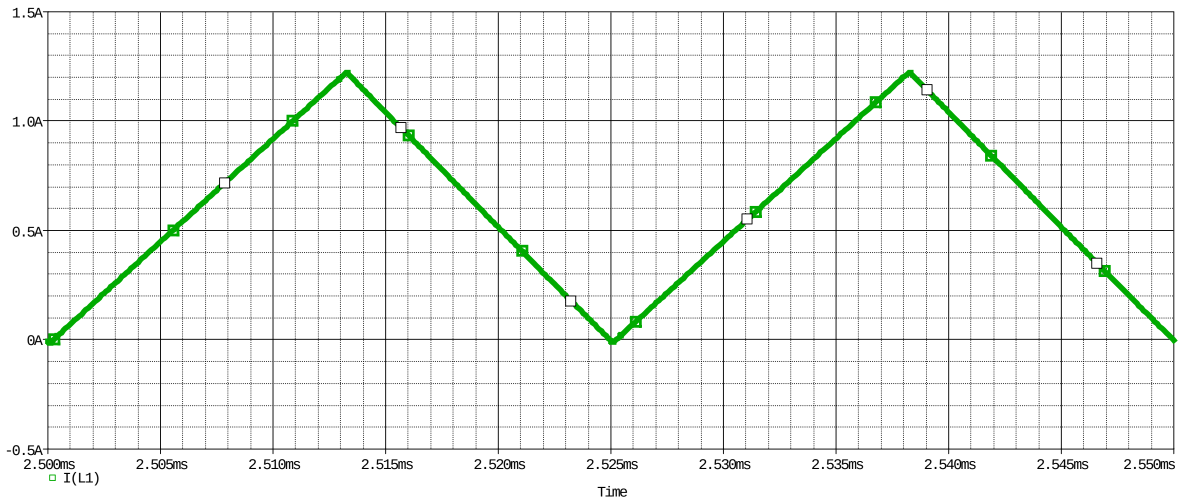


Fig 3.26- Current across Inductor I_{L1}

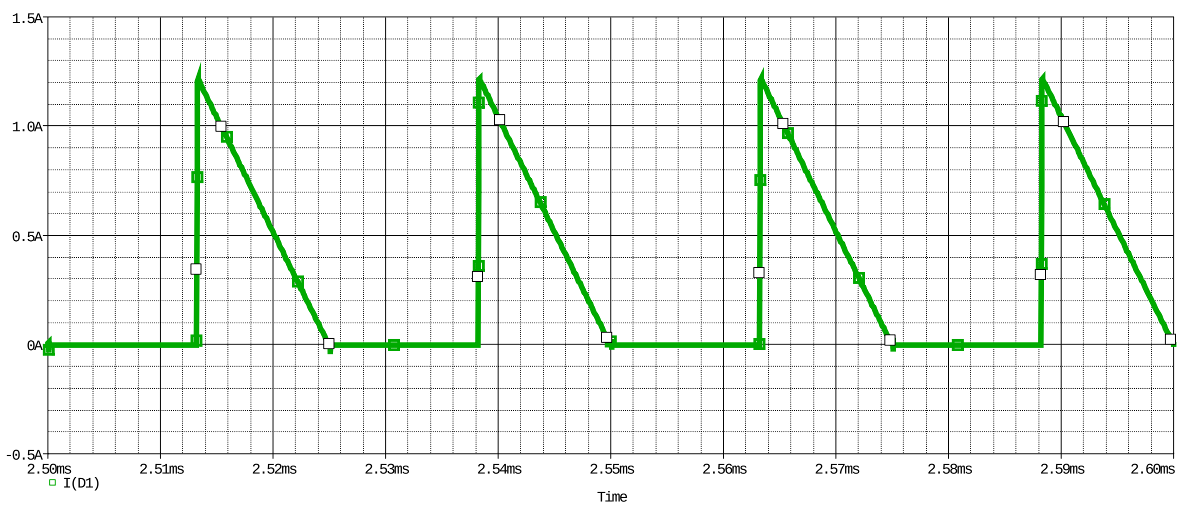


Fig 3.27- Current across Diode I_{D1}

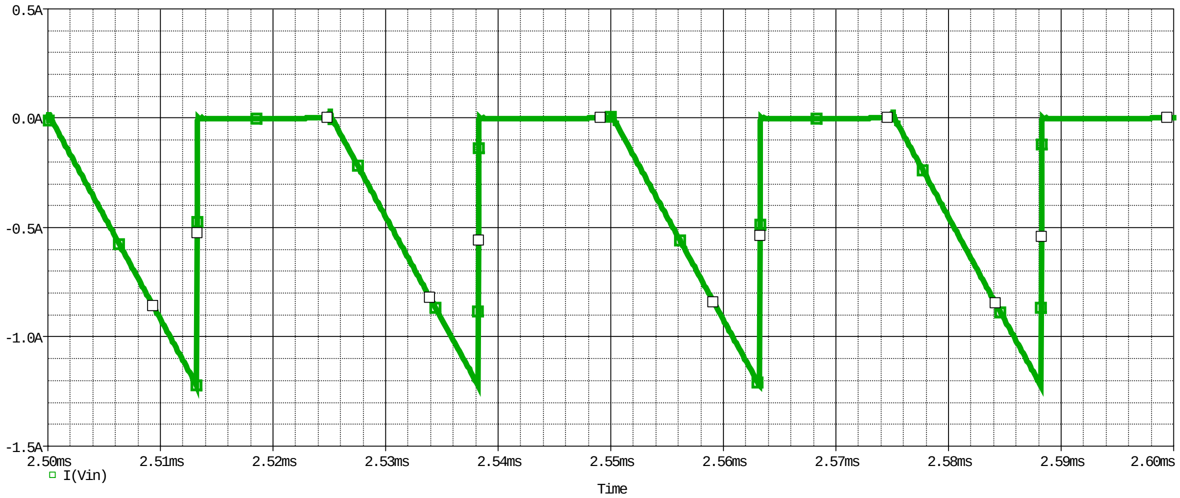


Fig 3.28- Current across Source I_{Vin}

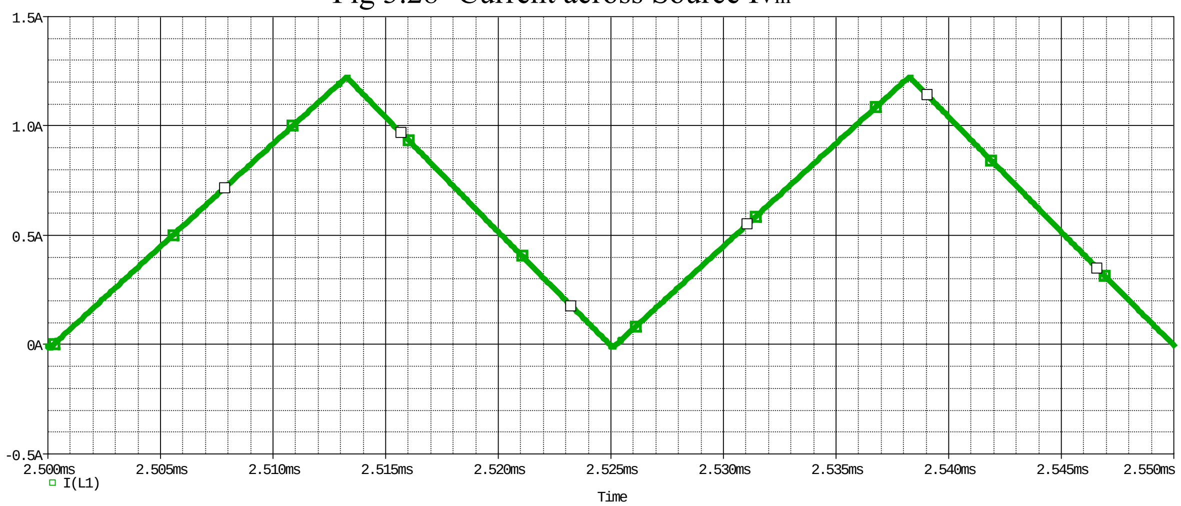


Fig 3.29- Current across Inductor I_{L1}

3.4 **Analysis of Buck Converter in Discontinuous Conduction Mode**

Fiuire 3.30 to 3.39 shows trhe waveshapes of different voltag and current when the designed BUCK circuit is driven in discontinuous mode for which the value of inducctor is chosen to be 25uH and observe the waveshapes for D=0.5. It can be observe that the non-conducting periods have some fluctuating values and some glitches aries. For practical circuit as the current is not possible to get negative these fluctuations will not take place.

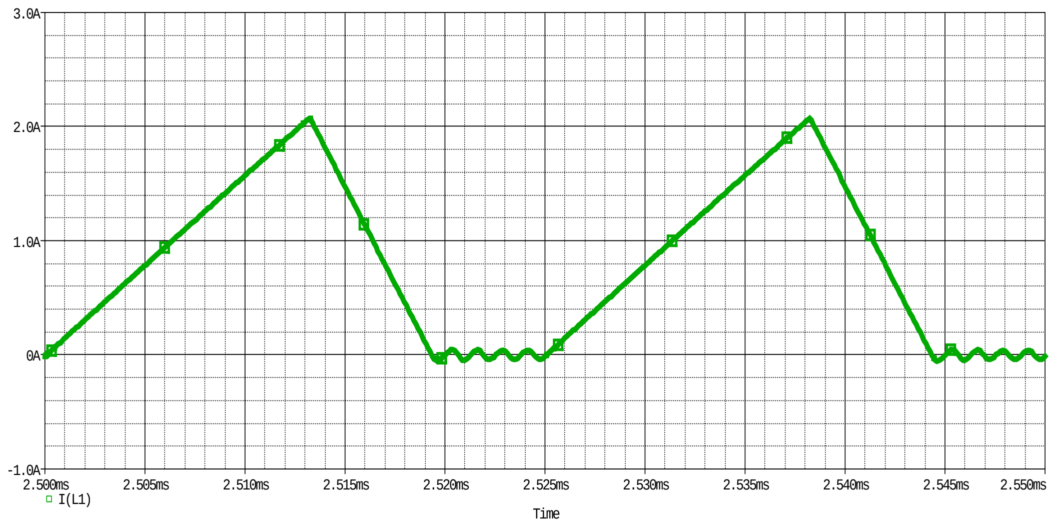


Fig 3.30- Current across Inductor I_{L1}

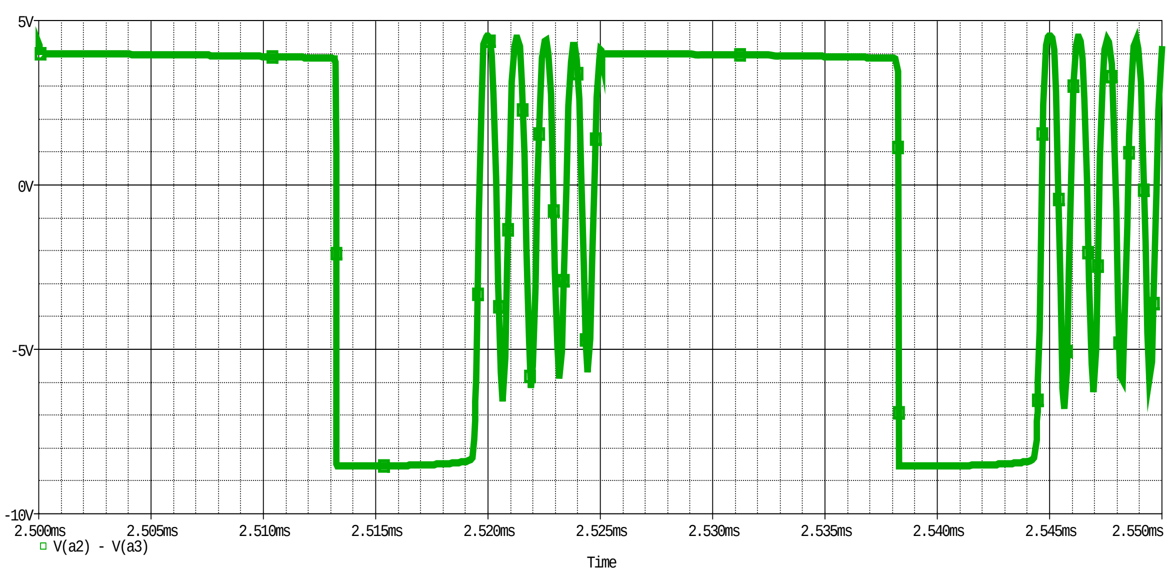


Fig 3.31- Voltage across Inductor V_{L1}

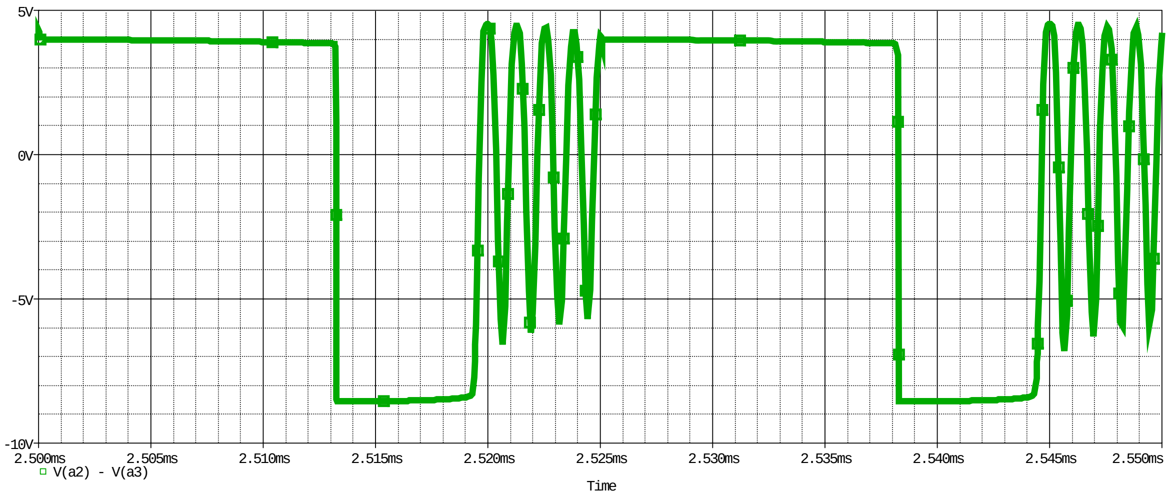


_Fig 3.32- Voltage across inductor V_{L1}

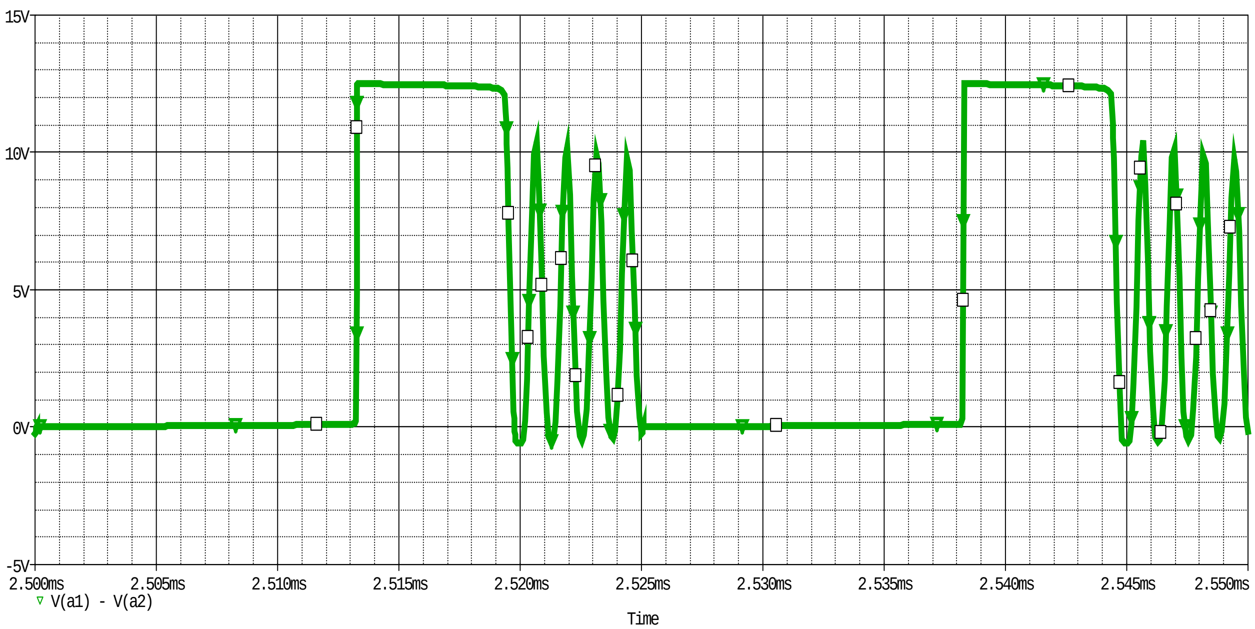


Fig 3.33- Voltage across Switch V_S

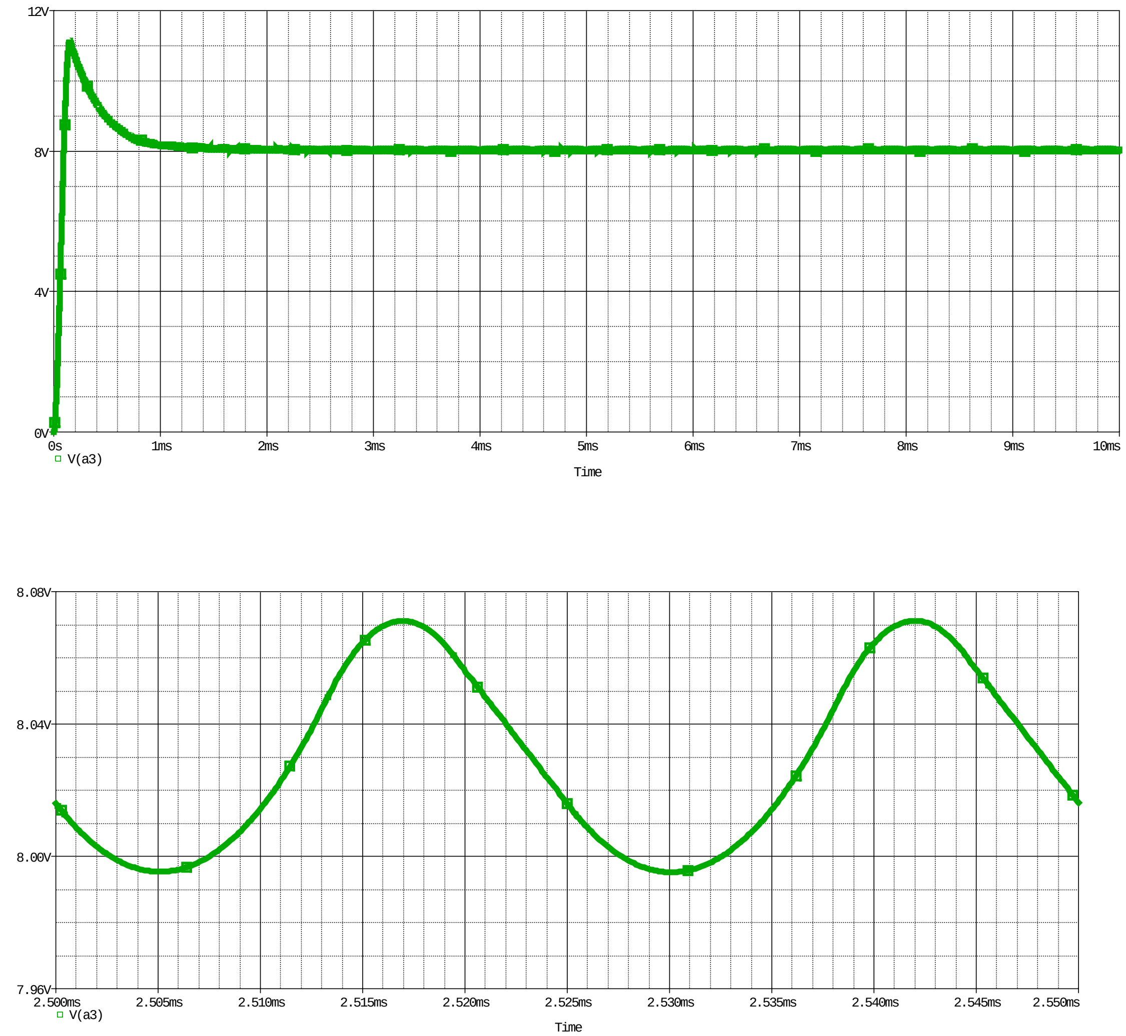


Fig 3.34- Voltage across Capacitor V_{a3}

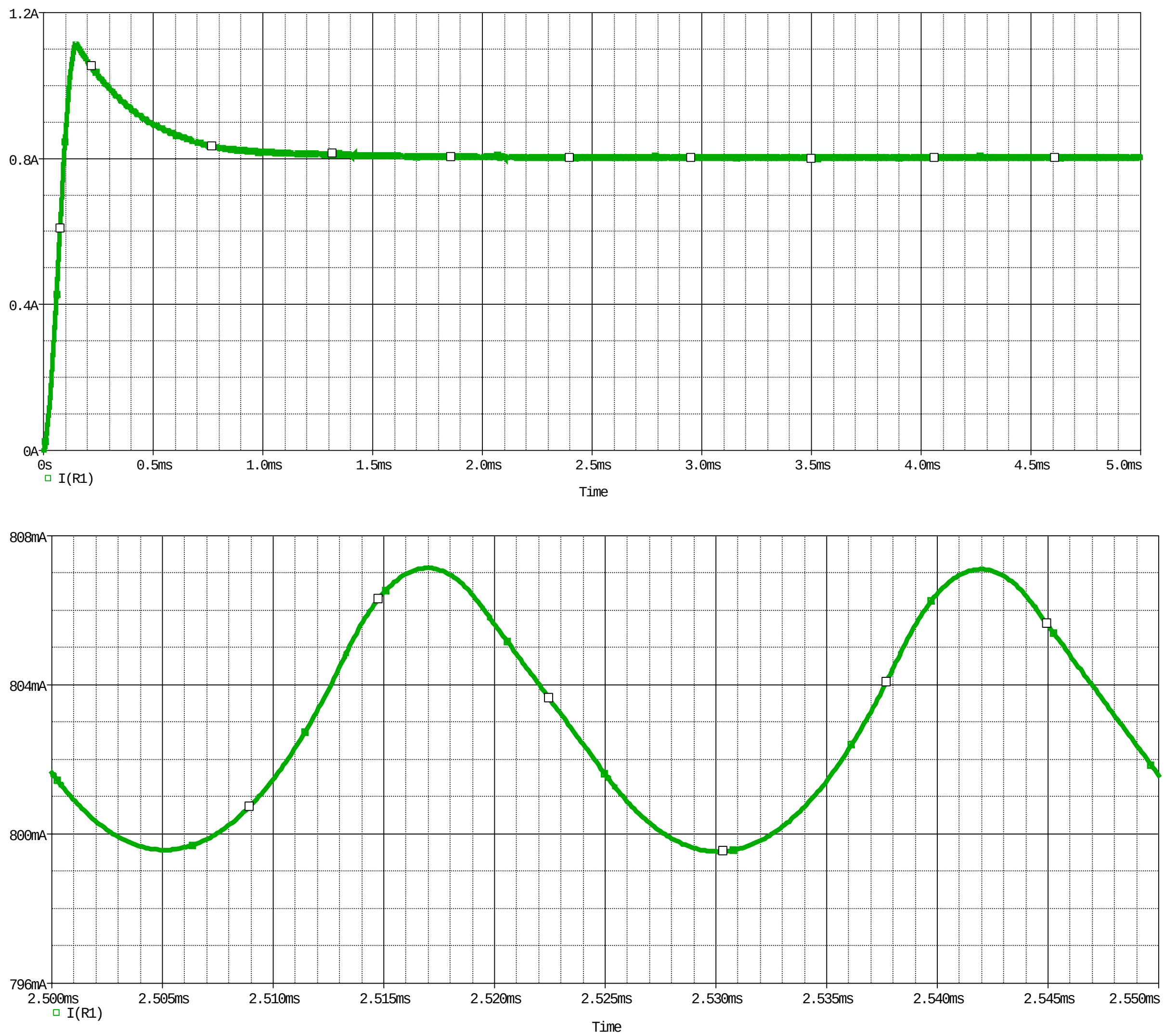


Fig 3.35- Current across Resistor I_{R1}

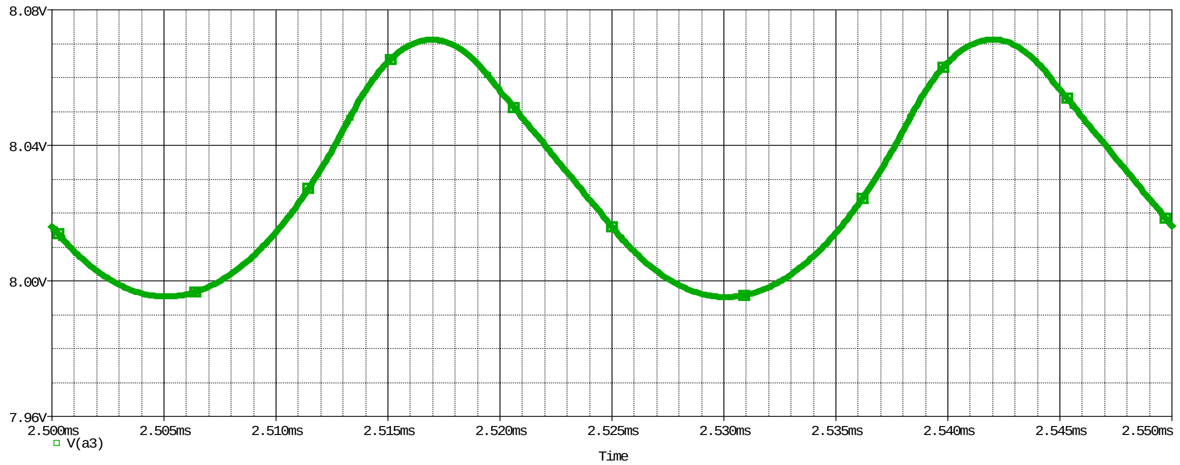


Fig 3.36- Voltage across Capacitor Va3

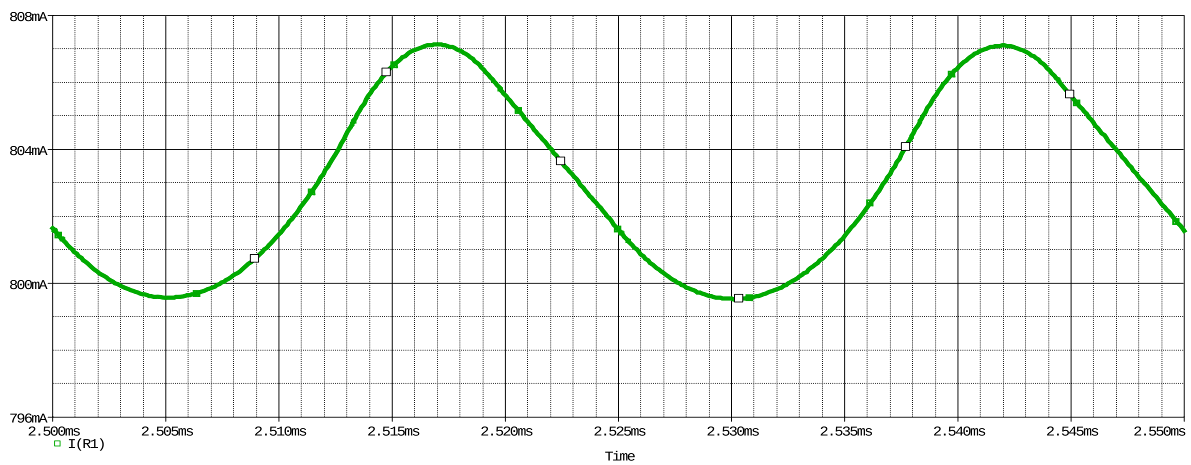


Fig 3.37- Current across Resistor IR1

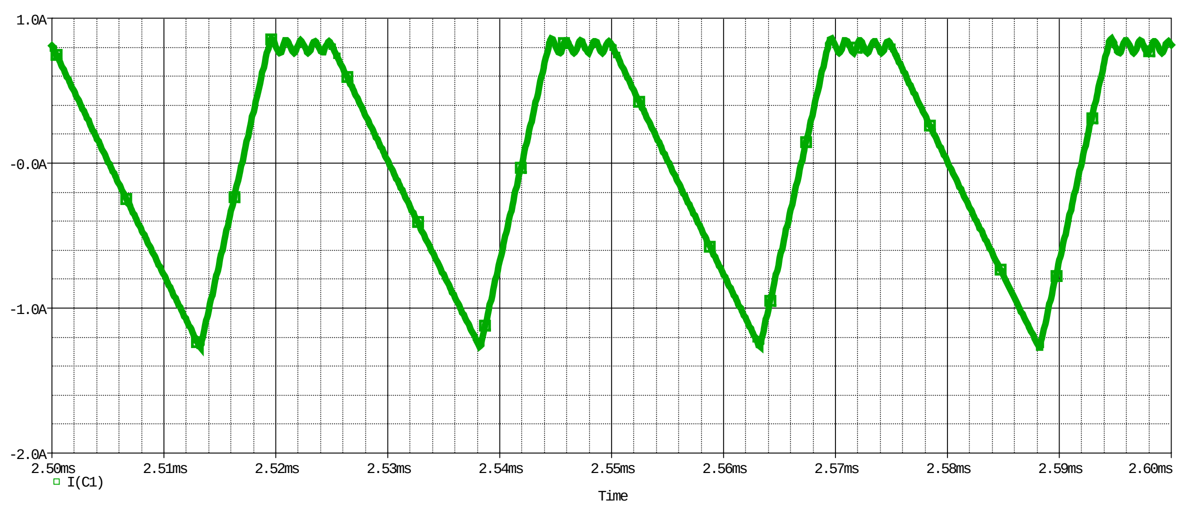


Fig 3.38- Current across Capacitor IC1

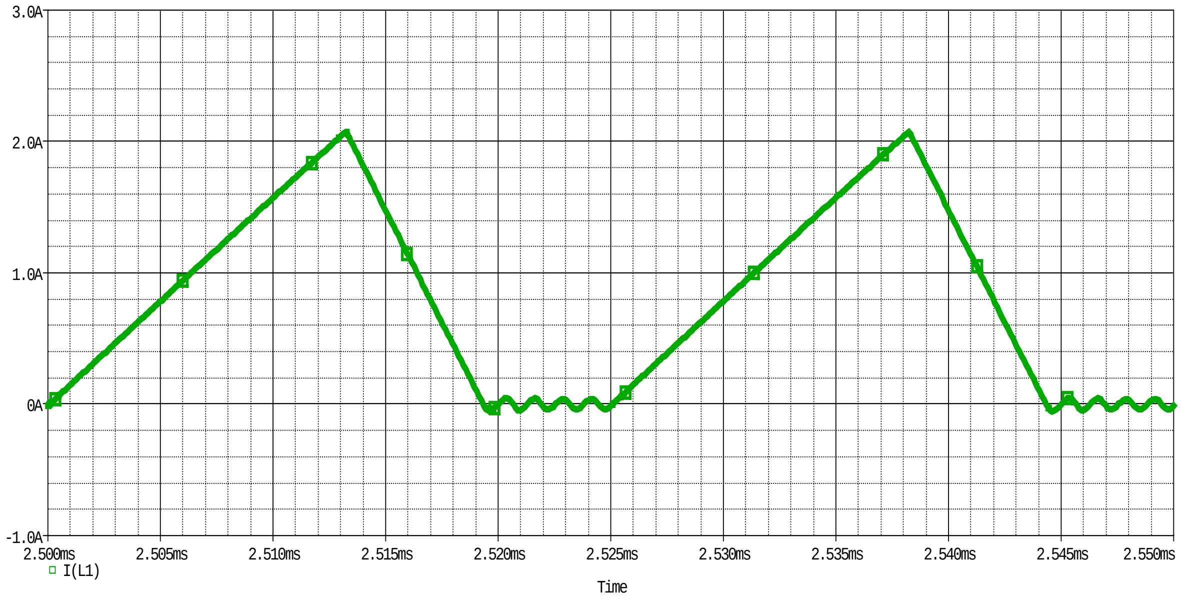


Fig 3.39- Current across Inductor I_{L1}

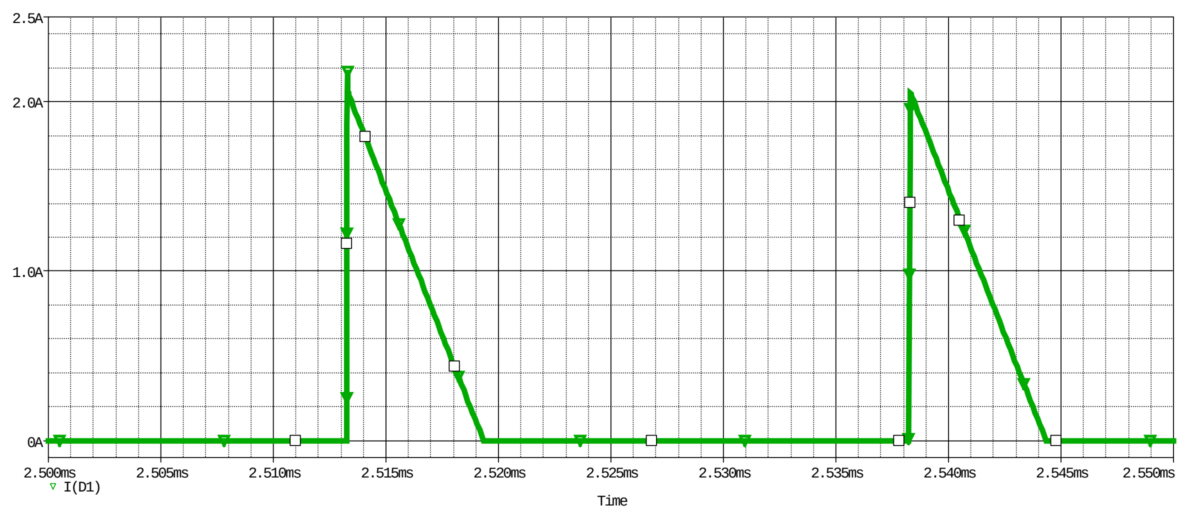


Fig 3.40- Current across Diode I_{D1}

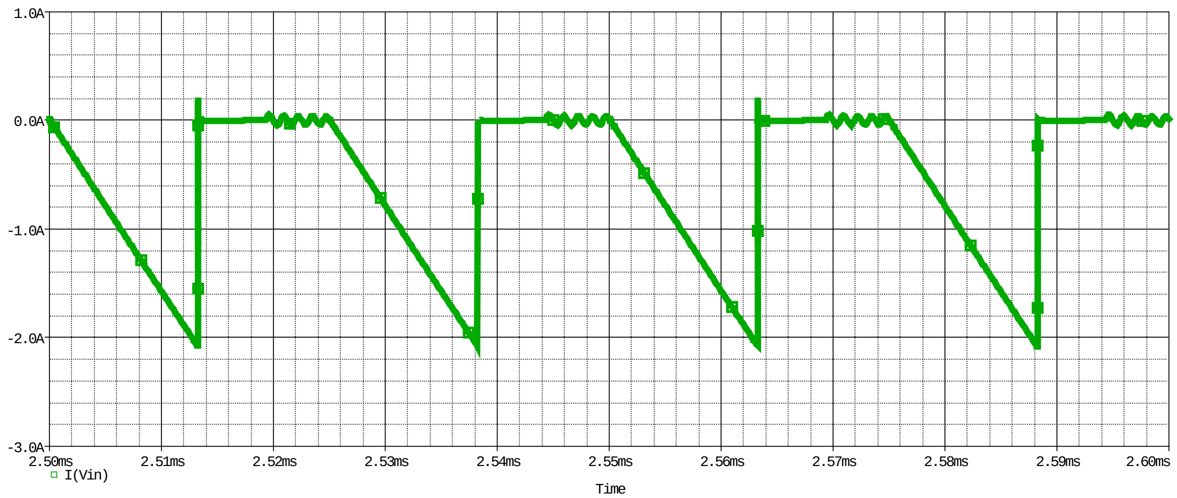


Fig 3.41- Current across Source I_{Vin}

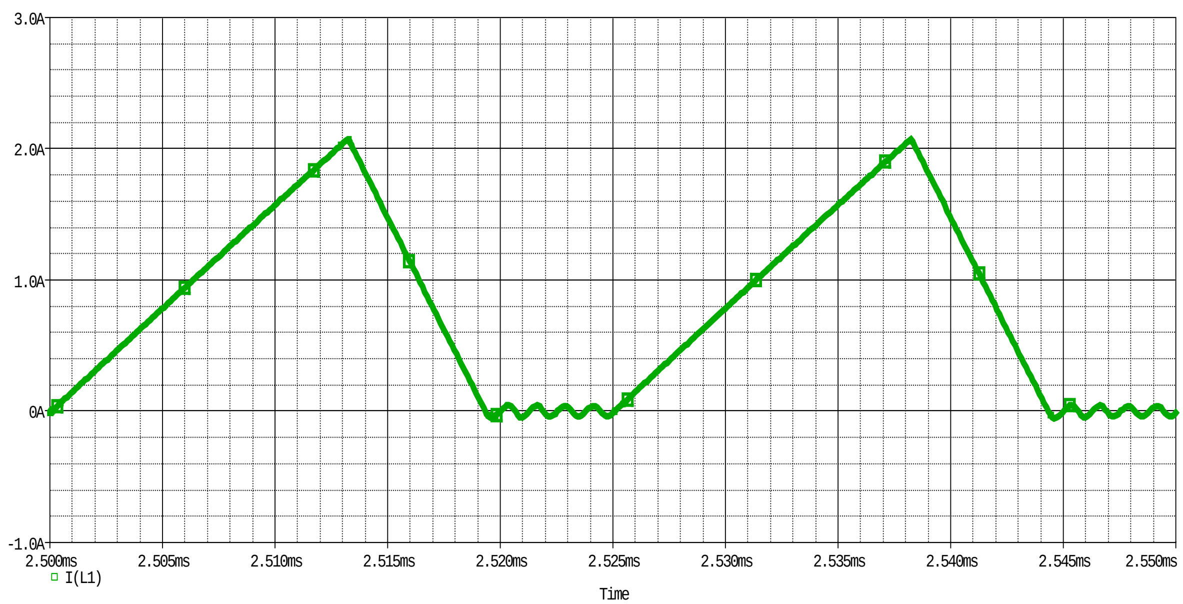


Fig 3.42- Current across Inductor I_{L1}

Chapter -04

Summary

4.1 Future Work

This report focuses on detailed analysis of a BUCK converter. Now-a-days, technology is becoming shorter to serve customers need of feasibility. Dc-Dc converters are demanded in modern technology and in devices such as smart phones, Tablets & laptops.

I have intention to work on BUCK converter because of their high demand in information technological devices. BUCK converters can be used in battery cells where demand is to convert a high voltage into low voltage for laboratory works.

4.2 Conclusion

In conclusion I am stating that I have described performance analysis of a BUCK Converter in different conduction mode in my thesis. I have also discussed about their advantages and disadvantages. I simulated BUCK converter with variable D where I have got different output voltages according to the characteristics of the converter. Finally, I have made a comparative study on the component's behavior in various conduction mode. I have done simulation in PSPICE for showing the output wave graph and experimental results. The simulation process of the software was highly effective for this thesis.

References:

[1] D.W. Hart "Power Elctronics" McGraw-Hill. Page no- 196

[2] N. Mohan, T.M.Undiland & W.P.Robbins "Power Electronics Converters Applications & Design" 2nd Edition, John Wiley & Sons, Inc.

[3] "Analysis of Synchronous and Interleaved Converter" thesis by Nahin, Fuad, Amin and Barua BRAC University EEE department