

Design of a Boost Converter

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Design of a Boost Converter

*A Thesis submitted in partial accomplishment for the degree of
Bachelor of Technology in “Electrical Engineering”*

By

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Under guidance of

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CERTIFICATE

This is to certify that the thesis entitled “**Design of a Boost Converter**”, submitted by **Abdul Fathah (Roll. No. 109EE0612)**, in partial fulfillment for the award of **Bachelor of Technology** in “**Electrical Engineering**” during session 2012-2013 at National Institute of Technology, Rourkela. An authentic record of research work carried out by him under my supervision and guidance.

The student has fulfilled all the recommended requirements.

The Thesis is based on candidate's own work, has not submitted elsewhere for a degree/diploma. In my opinion, this thesis is of standard required for the award of a bachelor of technology degree in Electrical Engineering.

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Abdul Fathah

B. Tech (Electrical Engineering)

Dedicated to
My beloved parents

ABSTRACT

The switching mode power supply market is flourishing quickly in today's world. Design engineers aren't always supplied with the desired amount of voltage they need in order to make their design function properly. Adding an extra voltage supply to a design is not always cost efficient. This thesis is proposed to provide the designer with a method of boosting DC voltage from 5 Volts to 15 Volts, by using a boost converter designed specifically for this task. All aim, calculations, tests, data and conclusions have been documented within this report. Results of simulation show that the switching converter will boost voltage from 5 volts to 15 volts with power conversion efficiency of 94.16 percent.

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Chapter 1

INTRODUCTION

1.1 RATIONALE

In many technical applications, it is required to convert a set voltage DC source into a variable-voltage DC output. A DC-DC switching converter converts voltage directly from DC to DC and is simply known as a DC Converter. A DC converter is equivalent to an AC transformer with a continuously variable turns ratio. It can be used to step down or step up a DC voltage source, as a transformer.

DC converters are widely used for traction motor control in electric automobiles, trolley cars, marine hoists, forklifts trucks, and mine haulers. They provide high efficiency, good acceleration control and fast dynamic response. They can be used in regenerative braking of DC motors to return energy back into the supply. This attribute results in energy savings for transportation systems with frequent stops. DC converters are used in DC voltage regulators; and also are used, with an inductor in conjunction, to generate a DC current source, specifically for the current source inverter. [1]

1.2 PURPOSE OF THE PROJECT

Efficiency, size, and cost are the primary advantages of switching power converters when compared to linear converters. The switching power converter efficiencies can run between 70-80%, whereas linear converters are usually 30% efficient. The DC-DC Switching Boost Converter is designed to provide an efficient method of taking a given DC voltage supply and boosting it to a desired value.

Chapter 2

BACKGROUND AND LITERATURE OVERVIEW

2.1 OVERVIEW

Power for the boost converter can come from any suitable DC sources, such as DC generators, batteries, solar panels and rectifiers. The method that changes one DC voltage to a different DC voltage is called DC to DC conversion. Generally, a boost converter is a DC to DC converter with an output voltage greater than the source voltage. It is sometimes called a step-up converter since it “steps up” the source voltage. [2]

2.2 HISTORY

For high efficiency, the SMPS switch must turn on and off quickly and have very less losses. The coming of a commercial semiconductor switch such as the boost converter in the 1950s represented a major milestone that made SMPSs possible. The main DC to DC converters were developed in the early 1960s when semiconductor switches were available.

Switched systems such as SMPS are a challenge to design since its model depends on whether a switch is opened or closed. R. D. Middlebrook from Caltech in 1977 published the models for DC to DC converters in market today. He averaged the circuit configurations for each switch state in a technique called state-space average modelling. This simplification resulted in reduction of two systems into one. This model led to insightful design equations which helped SMPS growth. [2]

2.3 APPLICATIONS

Battery powered systems often stack cells in series to obtain higher voltage. However, sufficient heaping of cells is not possible in many high voltage applications due to insufficient space. Boost converters can increase the voltage and reduce the cell numbers. Two battery-powered applications that use boost converters are hybrid electric vehicles (HEV) and lighting systems.

The NHW20 model Toyota Prius HEV utilizes 500 V. If there is no boost converter, the HEV would need nearly 417 cells to power its motor. In reality, a Prius actually uses only 168 cells and boosts the battery voltage from 202 V to 500 V. On a smaller scale application, boost converters also power devices such as portable lighting systems and emergency lights. A white LED typically

requires 3.3 V to function, and a boost converter can step up the voltage from a single 1.5 V alkaline cell to power the light. It can also produce higher voltages to operate cold cathode fluorescent tubes (CCFL) in devices such as LCD backlights and some flashlights.

A boost converter is used as the voltage increase mechanism in the circuit known as the 'Joule thief', which is a circuit topology used with low power battery applications, and is purposed at the ability of a boost converter to 'steal' the remaining energy in a battery. The energy remaining would otherwise be wasted since the low voltage of a nearly depleted battery makes it unusable for a load. The remaining energy would otherwise remain untapped because many applications do not allow enough current to flow through a load when voltage degrades. This occurs as batteries are degraded, and is a characteristic of a normal battery. [2][3]

There are a range of uses for a DC-DC boost converter. Travelers need to carry such devices when they want to bring electronics from home and the supply of current in a foreign country differs from that which is present at their home. Sometimes only a plug converter is required, but in other cases, plugging electronics directly into the power supply could damage the devices. A boost converter provides a bridge to allow travelers to access electricity safely.

Such devices are also used with systems that require high voltage, ranging from theatrical lighting to scientific apparatus. The boost converter may in some cases be wired directly into the electrical supply because of a permanent requirement. In other instances, it becomes necessary to plug the device in as required, especially in the case of traveling equipment like that used by bands on the concerts. As with other electrical devices, it is advisable to inspect a boost converter before use to confirm it is in good working condition and to check for any issues that might impair functionality or safety. [4]

Chapter 3

METHODOLOGY

3.1 GENERAL BOOST CONVERTER CONFIGURATION

In a boost converter, the output voltage is greater than the input voltage – hence the name “boost”. A boost converter using a power MOSFET is shown below.

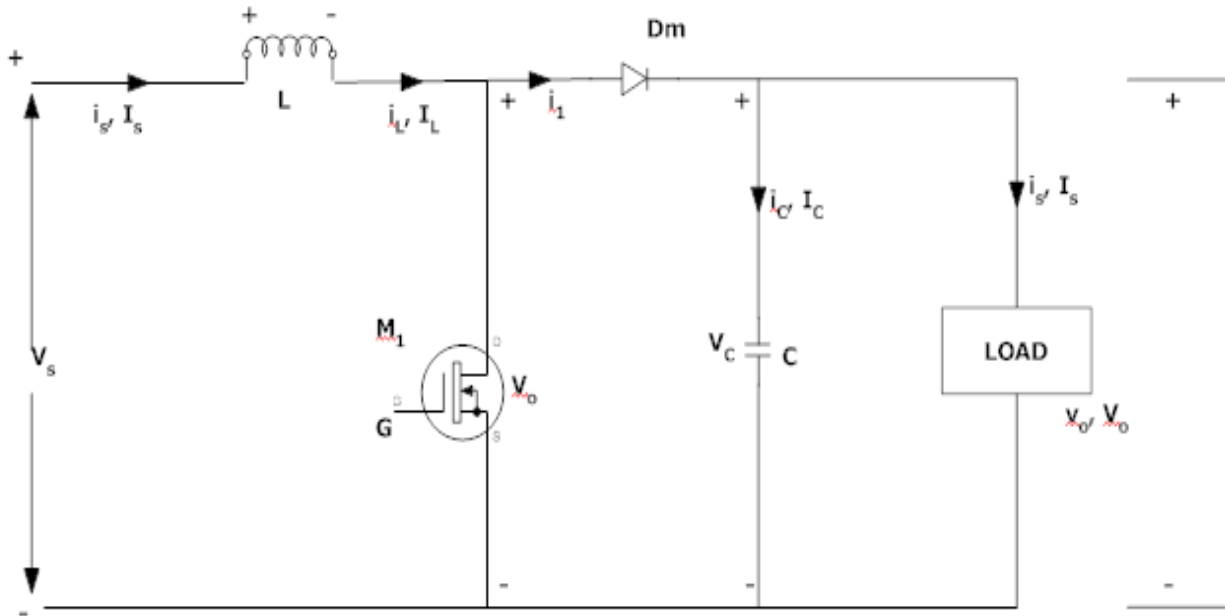
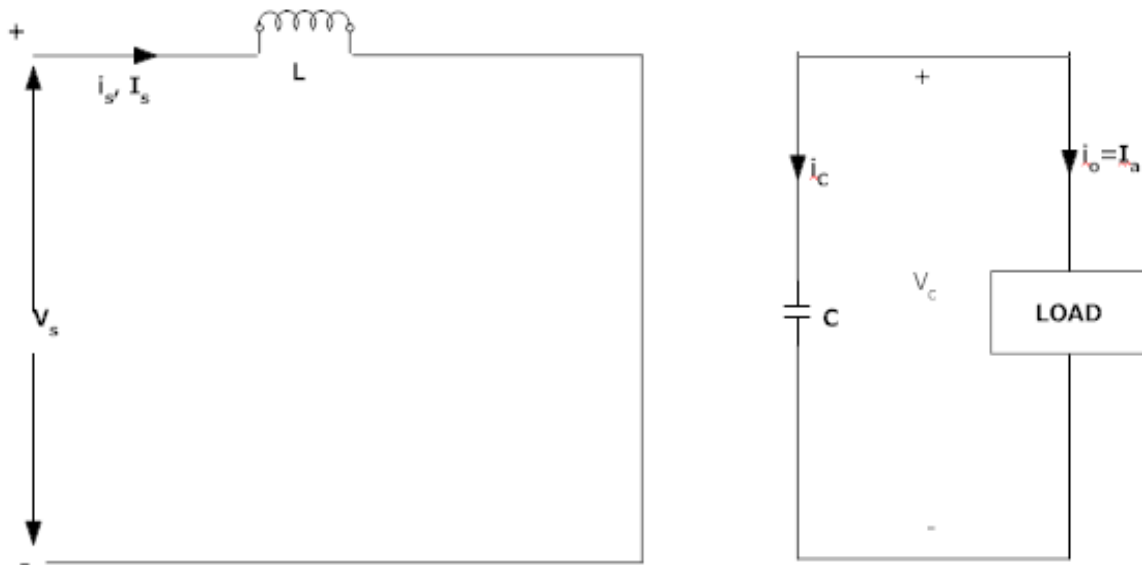


Fig. 3.1.1 Circuit diagram of Boost Converter. [1]

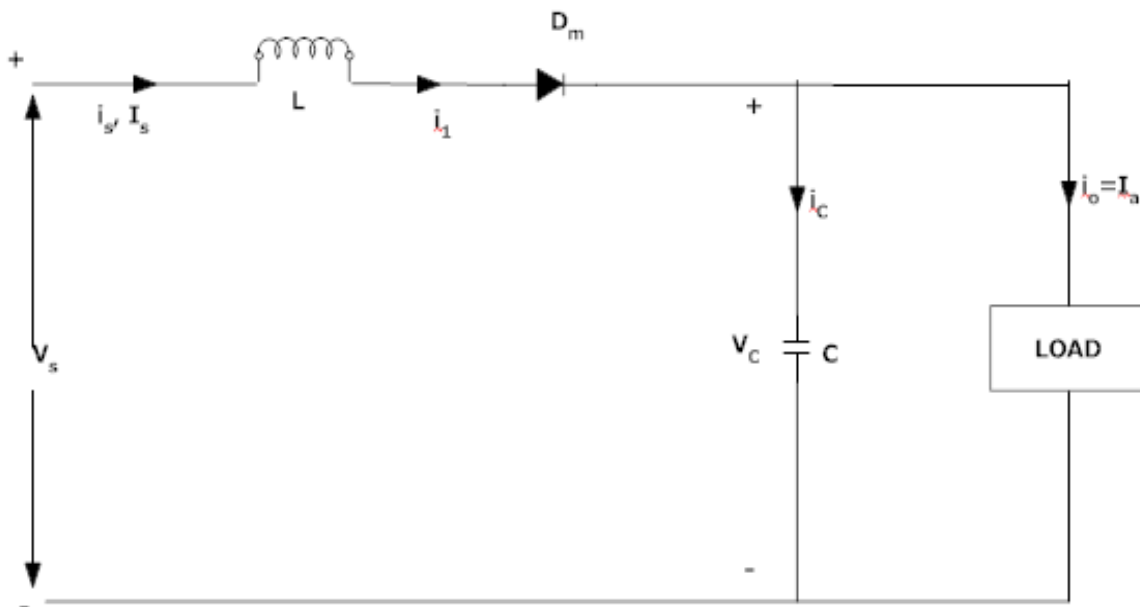
The function of boost converter can be divided into two modes, Mode 1 and Mode 2. Mode 1 begins when transistor M_1 is switched on at time $t=0$. The input current rises and flows through inductor L and transistor M_1 .

Mode 2 begins when transistor M_1 is switched off at time $t=t_1$. The input current now flows through L , C , load, and diode D_m . The inductor current falls until the next cycle. The energy stored in inductor L flows through the load.

The circuits for the two modes of operation are shown below:



(a)



(b)

Fig. 3.1.2 Circuit operation (a) Mode 1 and (b) Mode 2. [1]

The waveforms for the voltages and currents are shown below

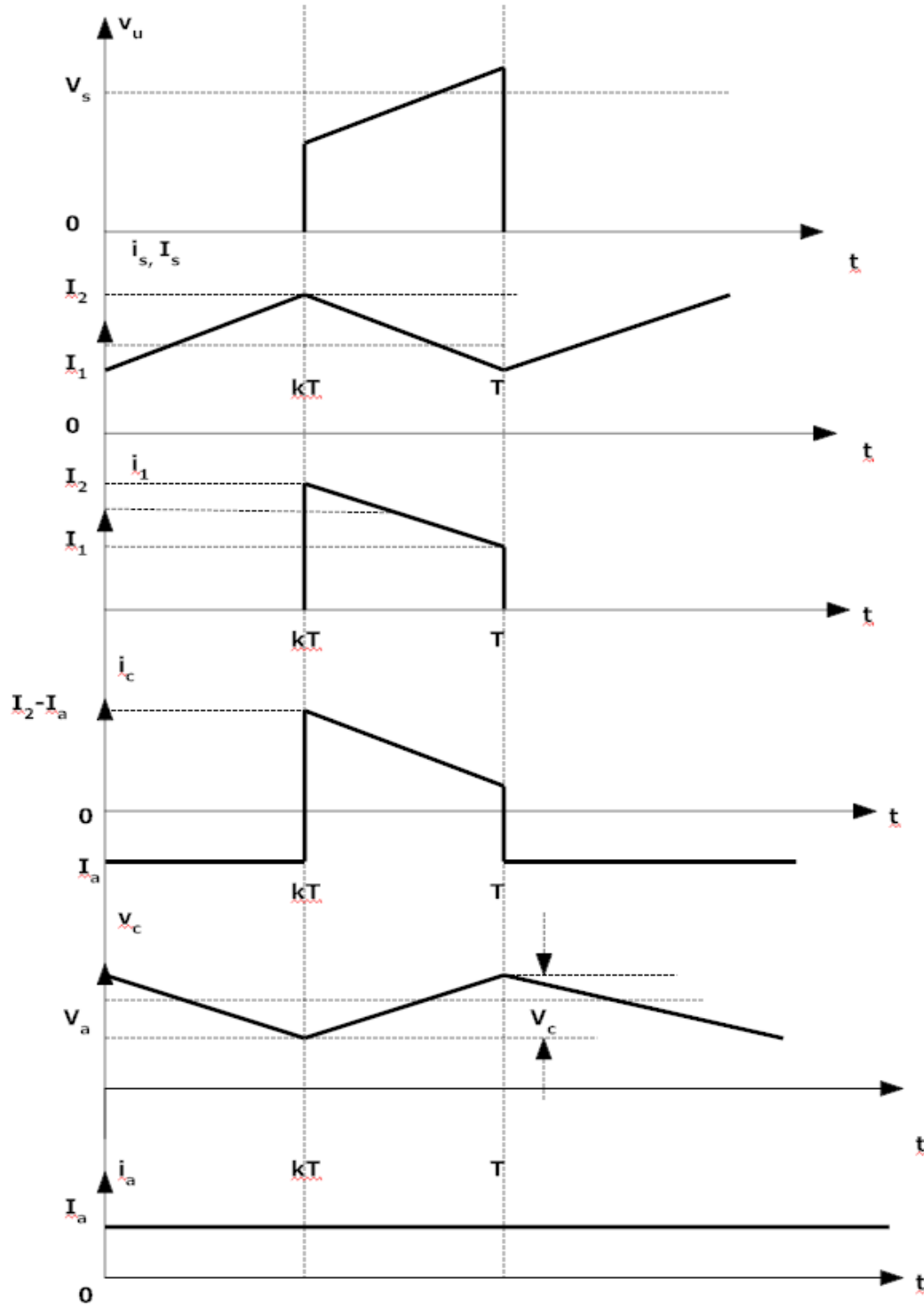


Fig. 3.1.3 Waveforms. [1]

The voltage-current relation for the inductor L is:

$$i = \frac{1}{L} \int_0^t V dt + i_0$$

Or

$$V = L \frac{di}{dt}$$

For a constant rectangular pulse:

$$i = \frac{Vt}{L} + i_0$$

When the transistor M₁ is switched:

$$i_{pk} = \frac{(V_{in} - V_{Trans})T_{on}}{L} + i_0$$

Or

$$\Delta i = \frac{(V_{in} - V_{Trans})T_{on}}{L}$$

And when the transistor is switched off the current is:

$$i_0 = i_{pk} - \frac{(V_{out} - V_{in} + V_D)T_{off}}{L}$$

Or

$$\Delta i = \frac{(V_{out} - V_{in} + V_D)T_{off}}{L}$$

Here V_D is the voltage drop across the diode D_m, and V_{Trans} is the voltage drop across the transistor M₁.

By equating through delta i, we can solve for V_{out}:

$$\frac{(V_{in} - V_{Trans})T_{on}}{L} = \frac{(V_{out} - V_{in} + V_D)T_{off}}{L}$$

$$V_{in} - V_{Trans}D = (V_{out} + V_D)(1 - D)$$

$$V_{out} = \frac{V_{in} - V_{Trans}D}{(1 - D)} - V_D$$

Neglecting the voltage drops across the diode and the transistor:

$$V_{out} = \frac{V_{in}}{1 - D}$$

So it is clear that the output voltage is related directly to the duty cycle. The main challenge when designing a converter is the sort of inductor to be used. From above equations, it can be seen that the inductance is inversely proportional to the ripple current. So, to reduce the ripple, a larger inductor should be used. [5]

3.2 BLOCK DIAGRM

Fig. 3.2.1 shows the basic blocks of building a boost converter circuit:

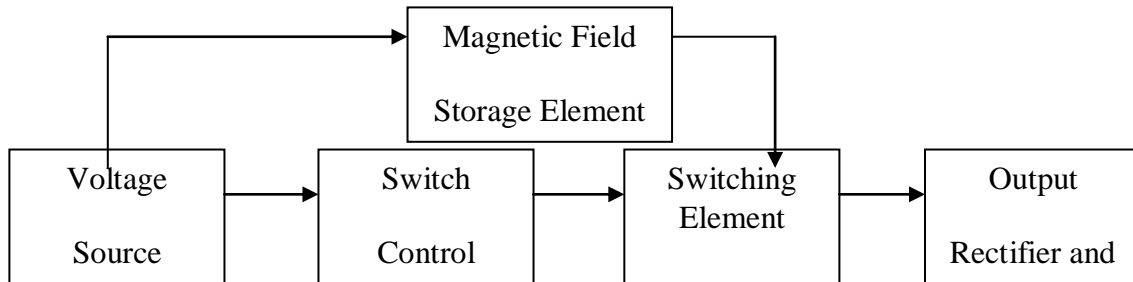


Fig. 3.2.1 Block diagram. [6]

The voltage source provides the input DC voltage to the switch control, and also to the magnetic field storage element. The block which contains switch control directs the action of the switching element, whereas the output rectifier and filter deliver an acceptable DC voltage to the output. [6]

3.3 SPECIFICATIONS

Engineers working in today's high tech environment have to deal with a rapidly changing market of electronic products and equipments. As new technologies are invented, integrated circuits function faster and are smaller in size and shape. But, many integrated circuits still require a voltage of 15 volts to function. The DC-DC Switching Boost Converter will take a 5 Volt DC voltage supply with $\pm 10\%$ tolerance and deliver 15 Volts to the load. The maximum current delivered to the load will be 0.4 A. The circuit will operate with a minimum efficiency of 94.16%. [7]

3.4 COMPONENT FUNCTIONS

The inductor shown in Fig. 3.1.1 acts as the magnetic field storage element shown in Fig. 3.2.1. It stores energy in its core material. The ideal PWM functions as the switch control and the transistor acts as the switch element. The diode and the capacitor are used to perform the function of the output rectifier and filter block.

3.5 COMPONENT CALCULATIONS

3.5.1 LOAD RESISTANCE

$$\text{Load Resistance} = \frac{V_o}{I_o}$$

Assuming I_o to be 0.4A

$$\text{Load Resistance} = \frac{15V}{0.4A} = 37.5\Omega$$

3.5.2 DUTY CYCLE

$$\text{Duty Cycle} = 1 - \frac{V_{in}}{V_o}$$

$$= 0.67$$

3.5.3 CAPACITOR

$$\Delta V = ESR \left(\frac{I_o}{1-D} + \frac{\Delta I L_{new}}{2} \right) = 2.622 \times 10^{-3} V$$

$$C = \frac{I_o \times D}{f_s \times \Delta V_o}$$
$$= \frac{0.4 \times 2}{3 \times 50 \times 2.622}$$

$$C = 2.034 \times 10^{-3} F$$

$$\text{New Ripple Voltage} = \frac{I_o \times D}{f_s \times C} = 2.424 \times 10^{-3} V$$

Capacitor Specifications -

Low ESR Tantanum Capacitor

No. - TRSE 22006K050R002

Capacitance - 2.2mF

Maximum O/P Voltage - 50V

Tolerance - $\pm 10\%$

3.5.4 INDUCTOR

$$L = \frac{V_s \times D}{f_s \times \Delta I_o}$$

Ripple current $\Delta I_o = 10\%$ of I_o

$$L = 870 \mu H$$

Inductor Specifications –

Family – 54z

Minimum Quality Factor – 27 at 8MHz

Test Frequency – 8MHz

Tolerance – 10%

Lead Style – Axial

Type – Lower Choke

Product Length – 19mm

Diameter – 0.8mm

Technology- Wire Wound

Inductance – 1mH

3.5.5 DIODE

Diode Specifications –

No. - IN5820

Maximum voltage – 30V

Maximum Current – 5A

Schottky Diode

Forward voltage drop at peak current = 0.4V

3.5.6 MOSFET

MOSFET Specifications –

Output Voltage – 30V

Load Current – 5A

$R_{DS} = 0.002\Omega$

$F = 50 \text{ KHz}$

N Channel MOSFET. [5]

3.6 LOSS CALCULATION

3.6.1 DIODE LOSS

$$\text{Diode loss} = V_d \times I_o (1-D)$$

$$= 0.07 \text{ W}$$

3.6.2 SWITCHING LOSS

$$V_{GS} = V_{Threshold}$$

$$E_1 = t_1 \frac{V_s I_o}{2}$$

$$E_2 = t_2 \frac{V_s I_o}{2}$$

$$P_{sw} = (t_1 + t_2) \frac{V_s I_o}{2} f_s$$

3.6.3 GATE CIRCUIT LOSS

Assuming

$$R_{driver\ pull\ up} = 5\Omega$$

$$R_{driver\ pull\ down} = 2\Omega$$

$$R_{gate} = 1.5\Omega$$

$$V_{DD} = 10V$$

When gate signal is rising

$$I = \frac{V_{DD} - V_{SP}}{R_{driver} + R_{gate}} = 0.31A$$

$$t_1 = \frac{Q}{I} = 168.8ns$$

$$t_2 = \frac{Q}{I} = 22.8ns$$

So,

$$P_{sw} = (t_1 + t_2) \frac{V_s I_o}{2} f_s$$

$$= 0.3\ W$$

3.6.4 CONDUCTION LOSS

$$I_o^2 \times D \times R = 0.21mW$$

3.7 EFFICIENCY

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

$$= \frac{6}{6 + 0.3 + 0.07 + 0.0021}$$

$$= \frac{6}{6 + 0.3721}$$

$$\text{Efficiency} = 94.16\%$$

3.8 TRANSFER FUNCTION

State Space Average Model

Switch ON equivalent circuit

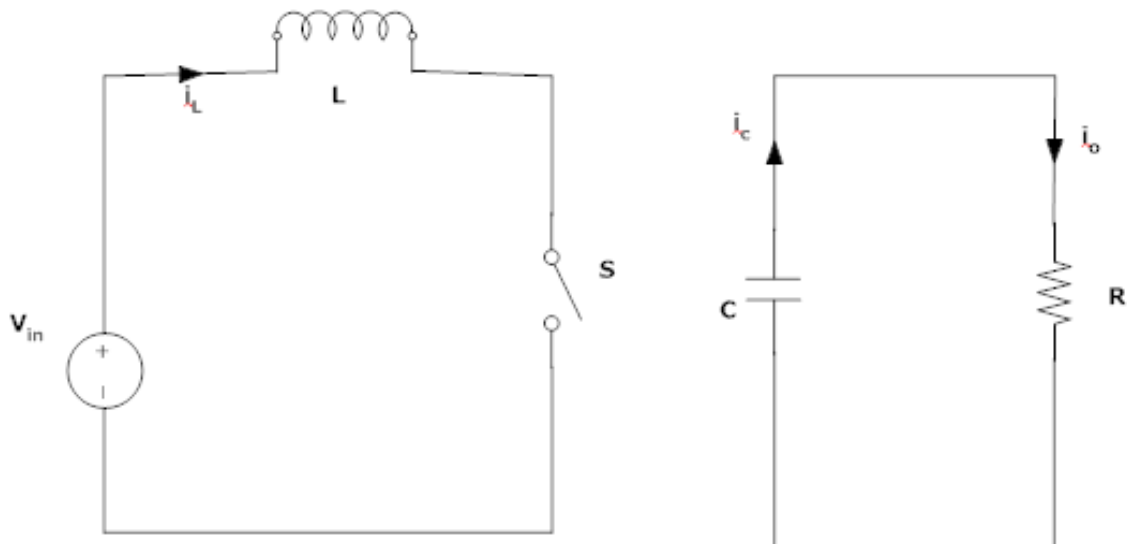


Fig. 3.8.1 Switch ON equivalent Circuit.

Applying KVL & KCL

$$L \frac{di}{dt} = V_{in} - R_{ON} \times i_L - R_L \times i_L$$

$$V_{out} = i_o \times R$$

$$C \frac{dV_c}{dt} + \frac{V_{out}}{R} = 0$$

And

$$V_{out} = V_c + i_c \times R_c$$

$$V_{out} = V_c \left[\frac{R}{R_c} \right]$$

From above,

$$C \frac{dV_c}{dt} = \frac{-V_c}{R + R_c}$$

$$i_{in} = i_L$$

State equation matrices are given as:

$$\begin{bmatrix} di_L/dt \\ dV_c/dt \end{bmatrix} = \begin{bmatrix} -(R_{on} + R_L)/L & 0 \\ 0 & -1/C(R + R_c) \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_{in}$$

And

$$V_{out} = \begin{bmatrix} 0 & R/R + R_c \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix}$$

So, A, B, C, D parameters are

$$A_{ON} = \begin{bmatrix} -(R_{on} + R_L)/L & 0 \\ 0 & -1/C(R + R_c) \end{bmatrix}$$

$$B_{ON} = \begin{bmatrix} 1/L \\ 0 \end{bmatrix}$$

$$C_{ON} = \begin{bmatrix} 0 & R/R + R_C \end{bmatrix}$$

$$D_{ON} = \begin{bmatrix} 0 \end{bmatrix}$$

Now for the circuit

$$A_{ON} = \begin{bmatrix} -459.7 & 0 \\ 0 & -12.12 \end{bmatrix}$$

$$B_{ON} = \begin{bmatrix} 11492.5 \\ 0 \end{bmatrix}$$

$$C_{ON} = \begin{bmatrix} 0 & 0.999 \end{bmatrix}$$

$$L \frac{di_L}{dt} = V_{in} - R_{ON} \times i_L - R_L \times i_L - V_{out} = R_D \times i_L$$

$$i_c = i_L - i_R$$

And

$$V_{out} = V_c + i_c \times R_c$$

$$V_{out} = V_c \left[\frac{R}{R+R_C} \right] + i_L \times R_c \left\{ \frac{R}{R+R_C} \right\}$$

Or

$$V_{out} = V_c \left[\frac{R}{R+R_C} \right] + i_L \left[\frac{R}{R+R_C} \right]$$

From above equation

$$L \frac{di_L}{dt} = V_{in} - \left[RD + Ron + RL + \left(\frac{R \times RD}{R+R_C} \right) \right] i_L - V_c \left[\frac{R}{R+R_C} \right]$$

Also,

$$i_c = i_L - i_R$$

$$C \frac{dV_c}{dt} = \frac{R}{R+R_c} \times i_L - \frac{V_c}{R+R_c}$$

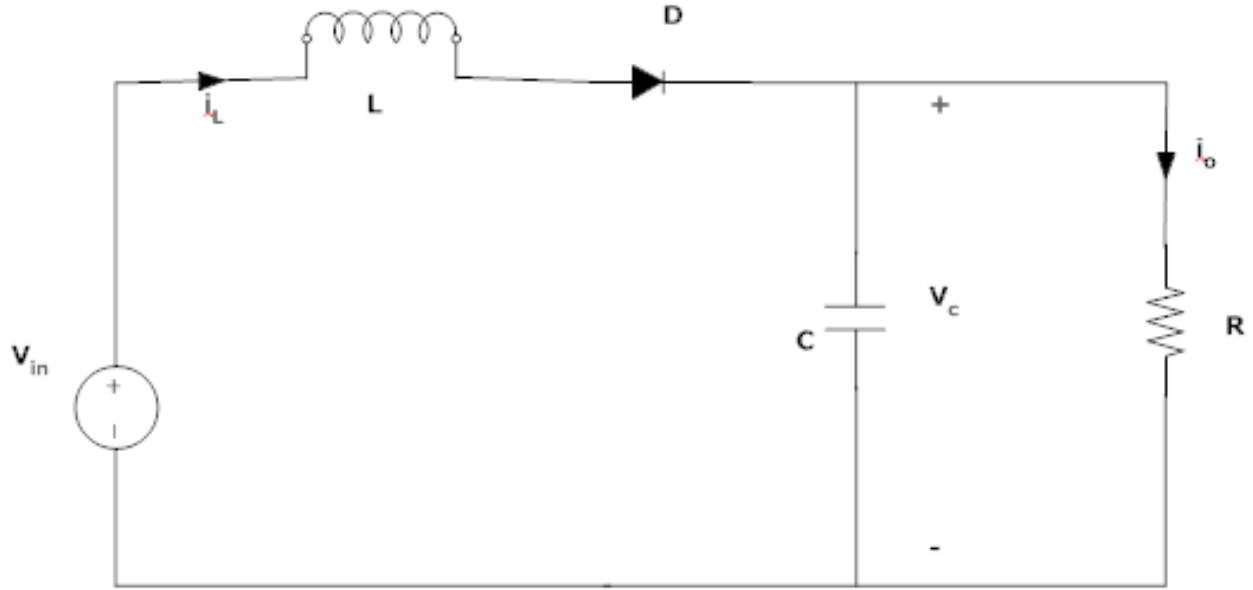


Fig. 3.8.2 Switch OFF equivalent circuit.

State equation matrices are given as-

$$\begin{bmatrix} di_L/dt \\ dV_c/dt \end{bmatrix} = \begin{bmatrix} -R_{ON} + RL + (R \times R_c/R + R_c) + RD/L & -R/(R + R_c)L \\ R/(R + R_c)C & -1/(R + R_c)V \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_{in}$$

$$V_{out} = \begin{bmatrix} R \times R_c/R + R_c & R/R + R_c \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix}$$

Parameters are

$$A_{off} = \begin{bmatrix} -3132.5 & -120475.6 \\ 454.1 & -12.12 \end{bmatrix}$$

$$B_{off} = \begin{bmatrix} 114942.5 \\ 0 \end{bmatrix}$$

$$C_{off} = [2 \times 10^{-3} \quad 0.999]$$

$$D_{off} = [0]$$

Now adding the weighted average of parameters

$$A_{avg} = A_{ON} \times d + (1 - d) \times A_{off}$$

$$A_{avg} = \begin{bmatrix} -1350.64 & -40158.0 \\ 151.36 & -12.12 \end{bmatrix}$$

$$B_{avg} = \begin{bmatrix} 114942.5 \\ 0 \end{bmatrix}$$

$$C_{avg} = [6.67 \times 10^{-9} \quad 0.999]$$

$$D_{avg} = [0]$$

$$\text{Transfer Function} = \frac{76.67s + 1.738 \times 10^7}{s^2 + 1363s + 6.095 \times 10^6}$$

Chapter 4

RESULTS AND OBSERVATIONS

4.1 MATLAB SIMULATION RESULTS:

Given below is a circuit diagram used for MATLAB simulation of boost converter. The purpose of this circuit is to measure output voltage and current waveform

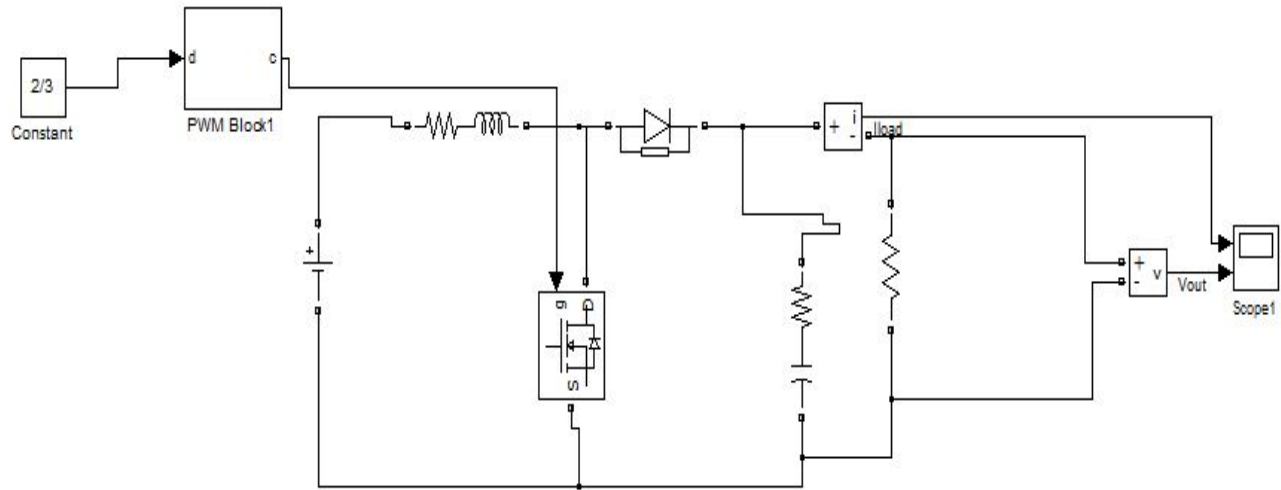


Fig. 4.1.1 Circuit Diagram of Boost Converter used in MATLAB.

Given below is the output current waveform obtained from MATLAB simulation

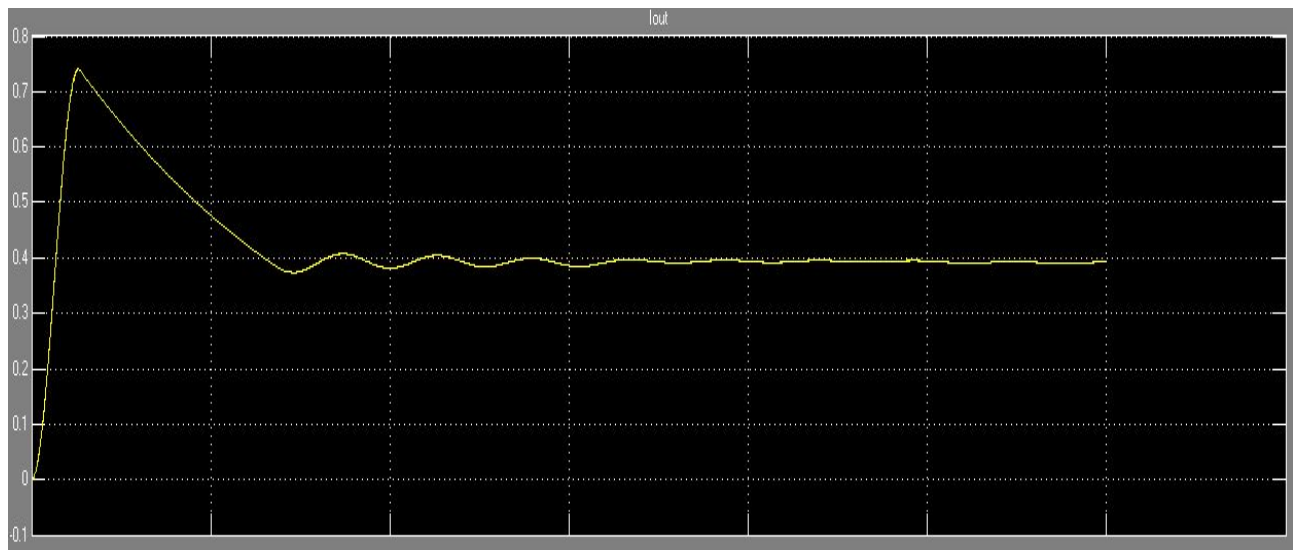


Fig.4.1.2 (I_o (output current) vs Time) in MATLAB.

Given below is the output voltage waveform obtained from MATLAB simulation

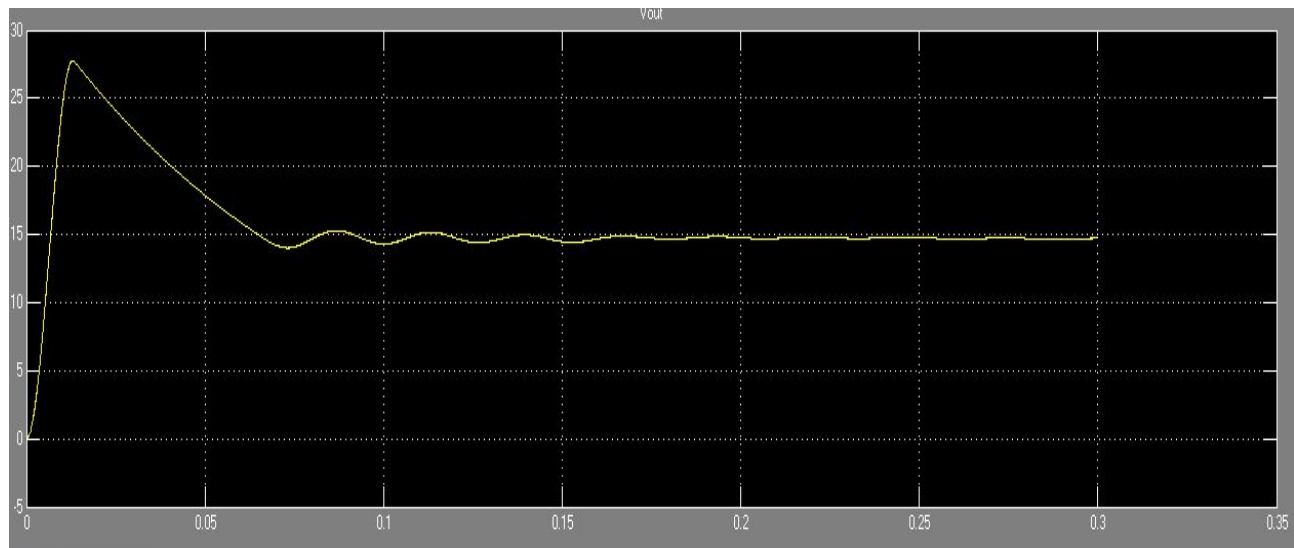


Fig. 4.1.3 (V_{OUT} (output voltage) vs Time) in MATLAB.

The frequency of operation is 50 kHz. Fig. 8 shows the output current obtained from simulation, which is 0.4 A. Fig. 9 shows the output voltage obtained from simulation, which is 15 V. Duty Cycle is maintained above 50%.

4.2 PSPICE SIMULATION RESULTS:

Given below is a circuit diagram used for PSPICE simulation of boost converter. The purpose of this circuit is to measure output voltage across the resistor R1

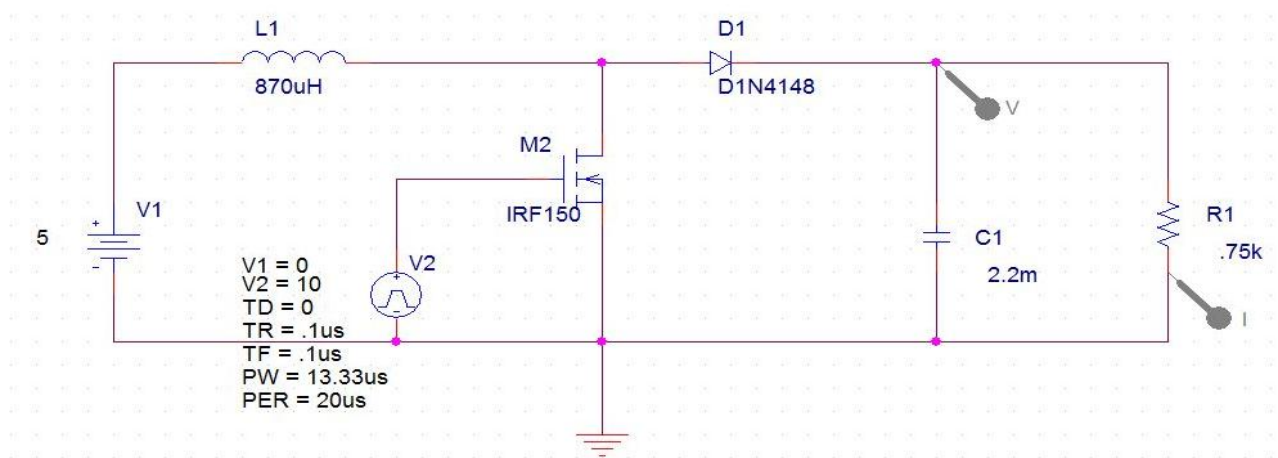


Fig. 4.2.1 Circuit Diagram of Boost Converter used in PSPICE.

Given below is the output voltage waveform obtained from PSPICE simulation

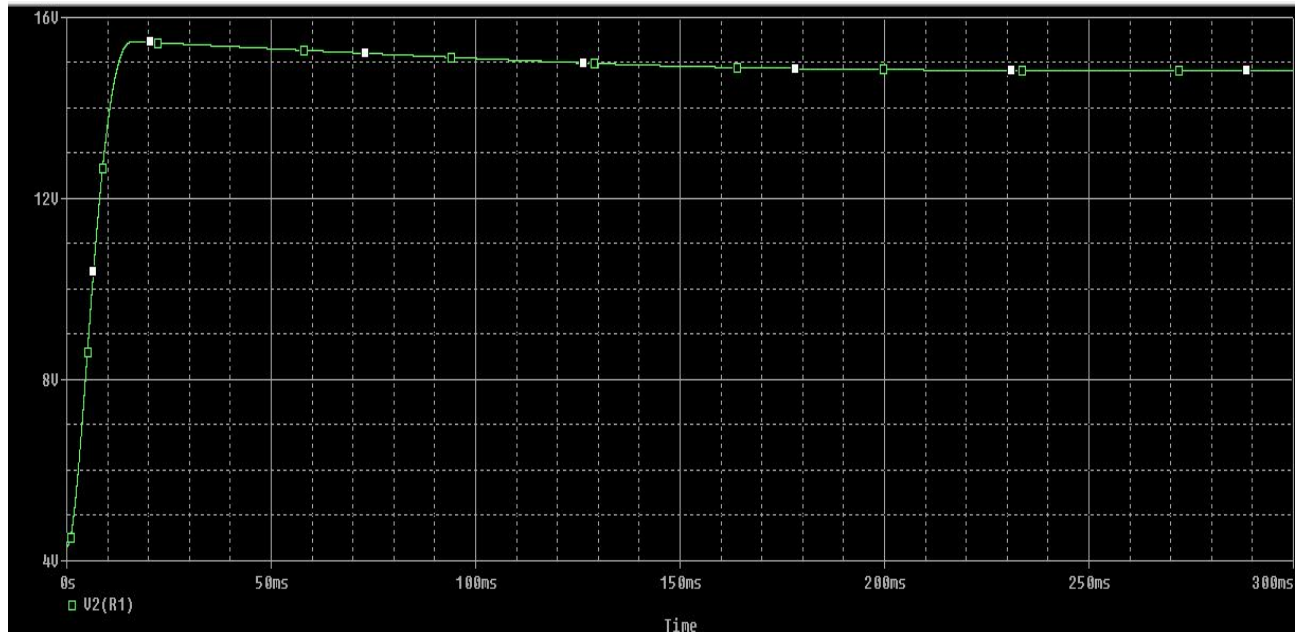


Fig. 4.2.2 V_{OUT} (output voltage) vs Time in PSPICE.

The above figure shows that the output voltage across the resistor R1 (37.5Ω) becomes stable after sometime, and remains at 15 V.

4.3 OBSERVATIONS:

From the results obtained, it is clearly observed that the boost converter steps up the voltage from 5 to 15 volt in accordance with the parameters derived earlier, fulfilling the desired conditions of output current being 0.4 A at frequency 50kHz. The efficiency of the boost converter is 94.16%.

Chapter 5

CONCLUSION

All of the specifications stated previously have been met by this boost converter design. MATLAB and PSPICE simulations using calculated parameters were performed and corresponding waveforms were obtained. The output voltage across the output capacitor is 15V with a maximum output ripple of 1.6%. The power efficiency of the circuit exceeds 94 %. However an additional constraint needs to be put on the load. The load must not exceed $0.75\text{k}\Omega$. This will cause the efficiency to fall below the specified value of 94.16%. Hardware design of BOOST CONVERTER was done. It is observed, by varying duty cycle output voltage also changes.

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