EFFICIENT VOLTAGE REGULATION OF MODIFIED HYBRID DC-DC CONVERTER

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A thesis submitted
to
the Department of Electrical and Electronic Engineering in partial fulfillment for the degree of
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DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
DHAKA BANGLADESH

MAY 2014

Dedicated

to

My parents

The thesis title "**EFFICIENT VOLTAGE REGULATION OF MODIFIED HYBRID DC-DC CONVERTER**".

Submitted by

MD ALI AZAM KHAN

Roll no: 040406127P, Session: April 2004

has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Electrical and Electronic Engineering on May 14, 2014.

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Candidate's Declaration

I hereby declare that this thesis has been prepared in partial fulfillment of the requirement for the degree of **Master of Science in Electrical and Electronic Engineering** at the **Bangladesh University of Engineering and Technology (BUET),** Dhaka and has not been submitted anywhere else for any other degree.

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Abstract

Switch mode dc-dc converters are attractive for their small size, ease of control and efficient power conversion. Output voltage is regulated by duty cycle control of semiconductor switch of switch mode dc-dc converters. The voltage gain and efficiency of practical switching regulators deviate from ideal values at extreme duty cycles. Also, desired gain /attenuation is not achievable at high/low duty cycles. In applications where high gain or high attenuation of voltage is desired with acceptable energy conversion efficiency, hybrid dc-dc switching converters are used. Hybrid dc-dc converters are combination of voltage multiplier/division circuit with appropriate SMPS circuits. By incorporating voltage multiplier/division cell with conventional converters like Buck, Boost, Buck-Boost, Ĉuk and SEPIC converters, desired voltage gain (either very low or very high) may be achieved at acceptable energy conversion efficiency. In the present work with an aim to attain very high voltage gain by conventional Boost, Buck-Boost, Ĉuk, and SEPIC topologies, a new voltage multiplier cell consisting of multiple inductors and diodes is proposed. The proposed voltage multiplier cell can be duplicated in multiple number and attached at the input side of Boost, Ĉuk, and SEPIC converters for hybrid operation to attain very high voltage gain at acceptable energy conversion efficiencies. In the present work, proposed multi-inductor voltage multiplier cell is attached to input side of Boost, Ĉuk, SEPIC and Buck-Boost converters and the performance of the resulting hybrid converters are studied generically by simulation. The performances of proposed hybrid converters have been compared with the performance of a previously reported two inductor voltage multiplier cell based hybrid dc-dc converters. The performance results were almost similar for both hybrid high gain dc-dc converters. However, it has been shown that the voltage gain can be further enhanced by more than two inductor cell voltage multiplier in the proposed circuits. The inductor numbers are limited to two in previously reported high gain hybrid dc-dc converter. Hence, the investigation of this research has come up with a new proposed multiplier, which when attached to the front end of dc-dc Boost, Ĉuk and SEPIC converters may provide very high voltage gain at acceptable energy conversion efficiency.

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INTRODUCTION

The DC-DC converters are widely used in industrial applications and computer hardware circuits, DC-DC conversion techniques have been developed very quickly. Modern electronic systems require high-quality, small, lightweight, reliable, and efficient power supplies. Linear power regulators, whose principle of operation is based on a voltage or current divider, are inefficient. This is because they are limited to output voltages smaller than the input voltage, and also their power density is low because they require low frequency (50 or 60 Hz) line transformers and filters. Linear regulators can, however, provide a very high-quality output voltage. Their main area of application is at low power levels. Electronic devices in linear regulators operate in their active (linear) modes, but at higher power levels switching regulators are used. Switching regulators use power electronic semiconductor switches in on and off states. Because there is a small power loss in those states (low voltage across a switch in the on state, zero current through a switch in the off state), switching regulators can achieve high energy conversion efficiencies.

Modern power electronic switches can operate at high frequencies. The high frequency DC-DC chopper-converters are known as switch mode power supplies (SMPS). SMPS are extensively used as power supplies of computers and electronic equipment. According to the type of voltage regulation (step-down/step-up/step-up-down) SMPS has three basic (Buck, Boost and Buck-Boost/Ĉuk/Sepic) and many derived configurations. The voltage regulation is achieved by duty cycle (D) control of the switching signal of the semiconductor switch of the SMPS. In a practical SMPS, the efficiency and the voltage-gain are function of the duty cycle D. Each type of SMPS has high value of efficiency for limited range of voltage gain (within a range of duty cycle D). In case of extreme gains (either high or low), hybrid SMPS converters may be used to maintain high conversion efficiency. Hybrid SMPS converters are combination of voltage multiplier/divider circuits with appropriate

SMPS circuits. In this Thesis work the boost, the hybrid boost dc-dc converter with two inductors, the hybrid proposed boost converter with two inductors and the proposed hybrid boost dc-dc converter with three inductors are studied by simulation at variable duty cycles.

1.1STATE OF THE PROBLEM

Static power converters are used for controlled, efficient and clean use of electricity in various applications. These converters according conversion types are: AC-AC (Voltage Controllers and Cycloconverters), AC-DC (Rectifiers), DC-DC (Choppers) and DC-AC (Inverters). Among the four static power converters mentioned, high frequency dc-dc chopper-converters are known as switch mode power supplies (SMPS). SMPS are extensively used as power supplies of computers and electronic equipment. According to the type of voltage regulation (step-down/step-up/step-up-down) SMPS has three basic (Buck, Boost and Buck-Boost/Ĉuk/SEPIC) and many derived configurations. The voltage regulation is achieved by duty cycle (D) control of the switching signal of the semiconductor switch of the SMPS. In a practical SMPS, the efficiency and the voltage-gain are function of the duty cycle D. Each type of SMPS has high value of efficiency for limited range of voltage gain (within a range of duty cycle D). In case of extreme gains (either high or low), hybrid SMPS converters may be used [1-3] to maintain high conversion efficiency. Hybrid SMPS converters are combination of voltage multiplier/divider circuits with appropriate SMPS circuits. As per need, any of the conventional SMPS circuit may be modified in hybrid manner to achieve extreme duty cycle operation (for either very-low or very-high gain) at relatively high efficiency than its non hybrid counterpart.

1.2 REVIEW OF DC-DC CONVERTERS

There are four basic topologies of switching regulators:

a. Buck converter

b. Boost converter

c. Buck-Boost converter and

d. Ĉuk converter.

1.2.1 BUCK CONVERTER

In Buck converters, output voltage is regulated and is less than the input voltage, hence the name "Buck". The circuit diagram is shown in Figure-1.1. The ideal voltage gain, current gain and efficiency relationships of this converter are,

$$\frac{V_0}{V_{in}} = D \tag{1.1}$$

$$\frac{I_0}{I_{in}} = \frac{1}{D} \tag{1.2}$$

$$\eta = 1 \tag{1.3}$$

Where, D is the duty cycle of the gate/base pulse that controls the voltage and current gain of the converter. $D = T_{on}/T$, on time to period ratio of the gate /base pulse of the switch used to the buck converter.

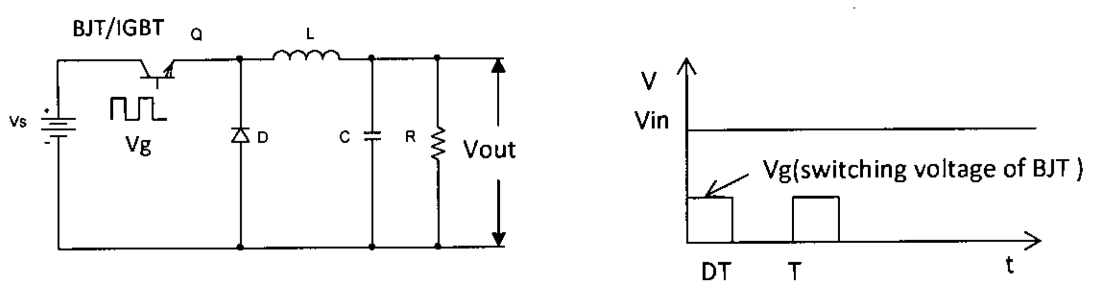


Figure 1.1 Buck DC-DC Converter

1.2.2 BOOST CONVERTER

In Boost converters, the output voltage is greater than the input voltage, hence the name "Boost". The circuit diagram is shown in Figure-1.2.

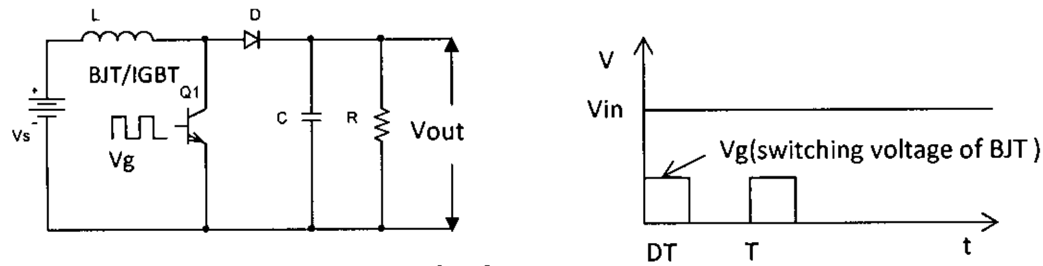


Figure 1.2 Boost DC-DC

The ideal voltage gain, current gain and efficiency relationships of this converter are,

$$\frac{V_0}{V_{in}} = \frac{1}{1-D} \tag{1.4}$$

$$\frac{I_0}{I_{in}} = (1-D) \tag{1.5}$$

$$\eta = 1 \tag{1.6}$$

Where, D is the duty cycle of the gate/base pulse that controls the voltage and current gain of the converter. $D = T_{on}/T$, on time to period ratio of the gate /base pulse of the switch used to the boost converter.

1.2.3 BUCK- BOOSTCONVERTER

Buck converters can step-down and boost converters can step-up dc voltages individually. The Buck-Boost converter in which the inductor is grounded can perform either of these two conversions. The output voltage polarity is opposite to input voltage and as a result the converter is also known as an *inverting* converter. The Buck Boost dc-dc converter circuit is shown in Figure 1.3

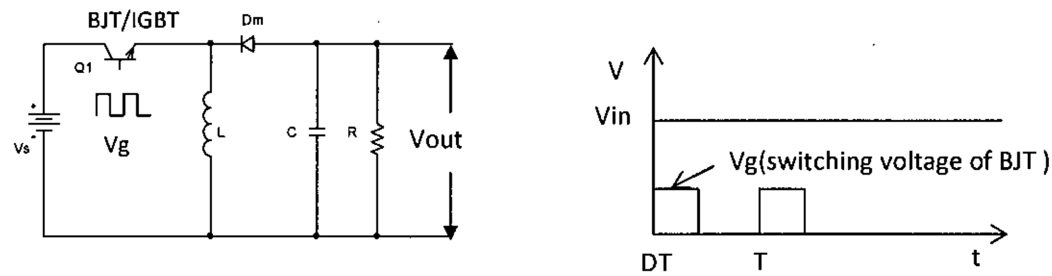


Figure 1.3 Buck Boost DC-DC Converter

The ideal voltage gain, current gain and efficiency relationships of this converter are,

$$\frac{V_0}{V_{in}} = -\frac{D}{1-D} \tag{1.7}$$

$$\frac{I_0}{I_{in}} = \frac{1-D}{D} \tag{1.8}$$

$$\eta = 1 \tag{1.9}$$

Where, D is the duty cycle of the gate/base pulse that controls the voltage and current gain of the converter. $D = T_{on}/T$, on time to period ratio of the gate /base pulse of the switch used to the Buck Boost converter.

1.2.4 ĈUK CONVERTER

It is the modified form of Boost-Buck converter having the capability to regulate input voltage in both buck and boost way. The circuit is shown in Figure 1.4.

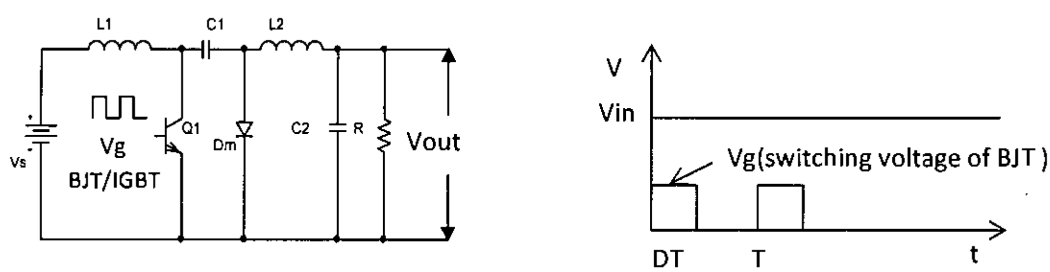


Figure 1.4 ĈUK CONVERTER

The ideal voltage gain, current gain and efficiency relationships of this converter are,

$$\frac{V_0}{V_{in}} = -\frac{D}{1-D} \tag{1.10}$$

$$\frac{I_0}{I_{in}} = \frac{(1-D)}{D} \tag{1.11}$$

$$\eta = 1 \tag{1.12}$$

Where, D is the duty cycle of the gate/base pulse that controls the voltage and current gain of the converter. $D = T_{on}/T$, on time to period ratio of the gate /base pulse of the switch used to the ĈuK converter.

1.2.4.1 SEPIC CONVERTER

SEPIC converter is a modified ĈuK converter with same ideal voltage gain and current gain characteristic. However the output of the sepic converter is non inverted. The circuit of the SEPIC dc-dc converter is shown in Figure 1.5

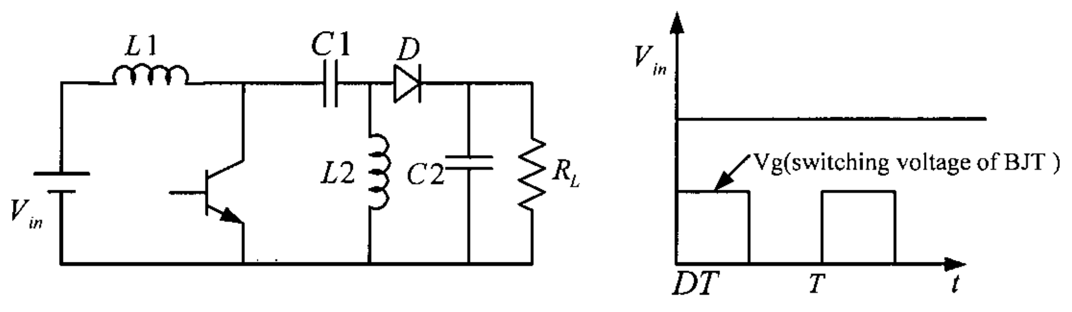


Figure: 1.5 SEPIC DC-DC Converter

The ideal voltage gain, current gain and efficiency relationships of this converter are,

$$\frac{V_0}{V_{in}} = \frac{D}{1-D} \tag{1.13}$$

$$\frac{I_0}{I_{in}} = \frac{(1-D)}{D} \tag{1.14}$$

$$\eta = 1 \tag{1.15}$$

Where, D is the duty cycle of the gate/base pulse that controls the voltage and current gain of the converter. $D = T_{on}/T$, on time to period ratio of the gate /base pulse of the switch used to the SEPIC converter.

1.3 NON IDEAL DC-DC CONVERTERS AND PROBLEM DEFINITION

In section1.2, the voltage gain, current gain and efficiency expressions of Buck, Boost, Buck-Boost, ĈuK and SEPIC converters are given for ideal conditions, where, the elements of the converter are assumed to be idea. But in practice, the switch closein the converters is non-ideal with conduction and switching losses in them during operation. Also, the inductors used in the converters have inherent resistance in there, the switch conduction, switching losses and inductors inherent resistance are neglected the deriving equations of the converters. When the non-idealities of switch and inductor is taken into considerations, the voltage gain and efficiency equations become dependent on duty cycle D of the switching pulses of switch of the converters. As a result the ideal high voltage gains and high efficiency are not attainable at extreme duty cycles. As an example non-ideal voltage gain and efficiency expression of Boost dc-dc converter is presented in section 13.1. In deriving the the non-ideal voltage gain and non ideal efficiency expression of the Boost converter voltage drop across the switch during conduction and the inherent resistance of the inductor of the converter are taken into consideration. 1.3.1 Boost DC-DC converter is shown in Figure 1.6-1.8

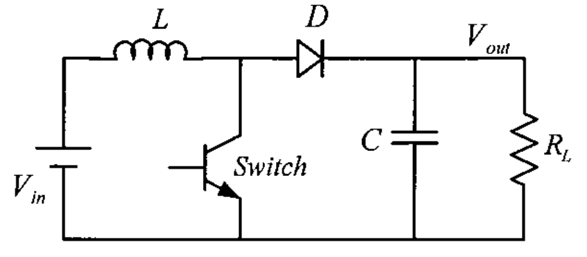


Figure: 1.6 Boost DC-DC Converter

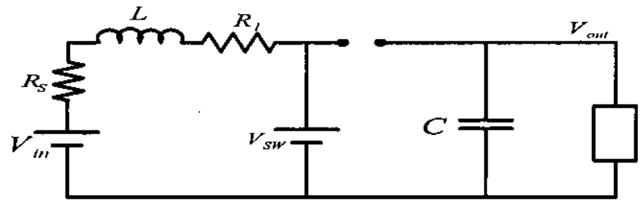


Figure: 1.7 Boost DC-DC Converter with Switch ON (Source Resistance R_S, Inductor Resistance R_l and voltage across Switch V_{SW} when switch is ON)

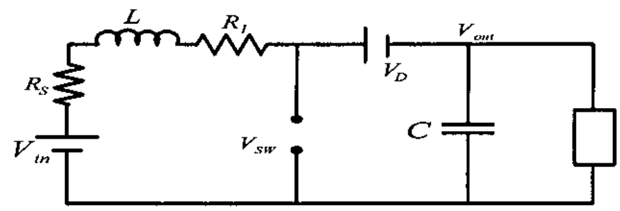


Figure: 1.8 Boost DC-DC Converter with Switch OFF (V_D is diode voltage drop when diode is conductors)

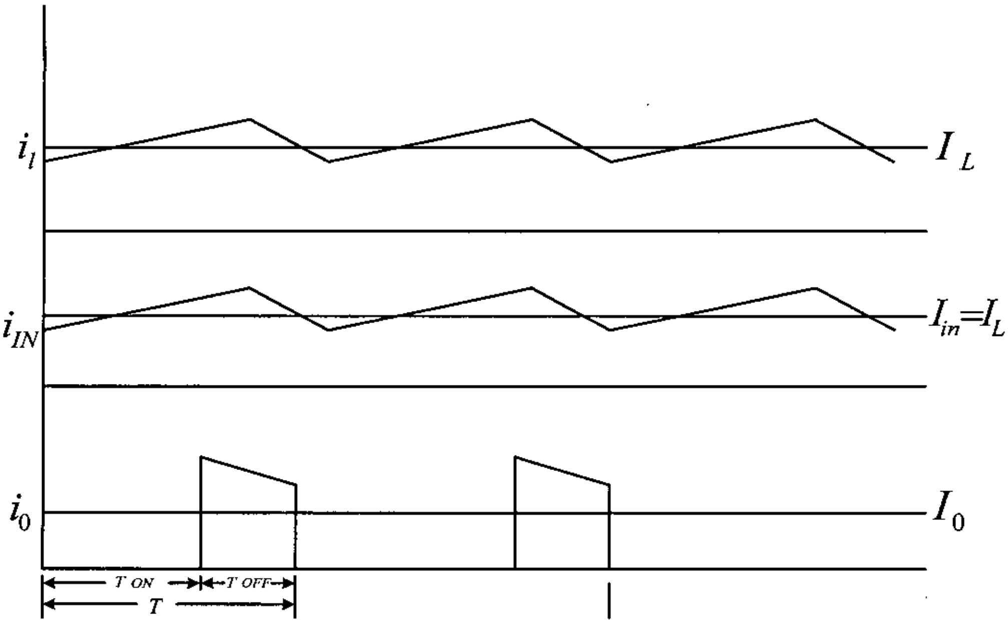


Figure 1.9 shows the current waveforms of Boost DC-DC converter (inductor current, input current and output current).

When the switch is ON, inductor current raises, while the current falls when the switch is OFF. From Figure 1.9 it is evident that,

$$I_{IN} = I_L \tag{1.16}$$

$$I_0 = (1-D)I_L \tag{1.17}$$

Hence,

$$\frac{I_0}{I_{IN}} = (1-D) \tag{1.18}$$

This is the same as ideal current gain relationship of Boost DC-DC converter. Efficiency of the DC-DC converter can be expressed as

$$\eta = \frac{V_0 I_0}{V_{in} I_{in}} \tag{1.19}$$

Where, η is the efficiency and V_0 , V_{in} , I_0, I_{in} have their usual meaning. From equation (1.19) Voltage gain $\frac{V_0}{V_{in}}$ can be expressed as

$$\frac{Vo}{V_{in}} = \eta \frac{I_{in}}{I_0} \tag{1.20}$$

Replacing (1.18) in (1.20) we get

$$\frac{V_0}{V_{in}} = (1-D)\eta \tag{1.21}$$

Efficiency of Boost DC-DC converter can also be obtained as,

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{Losses}} \tag{1.22}$$

Where, $P_{out} = I_0^2 R_{Load}$ and $P_{Losses} = I_{in}^2 (R_s + R_i) + I_{sw} V_{sw} + I_D V_D$ Where,

$$I_{SW} = DI_L \tag{1.23}$$

$$I_D = (1-D)I_L \tag{1.24}$$

$$I_{IN} = I_L \tag{1.25}$$

$$I_0 = (1-D)I_L \tag{1.26}$$

P_{out} and P_{Losses} can be expressed as,

$$P_{Losses} = I_L^2 (R_s + R_i) + DI_L V_{SW} + (1-D)I_L V_D \tag{1.27}$$

$$P_{out} = (1-D)^2 I_L^2 R_{out} \qquad (1.28)$$

$$\eta = \frac{1}{\left[1 + \frac{(R_s + R_l)}{(1-D)^2 R_{Load}} + \frac{D}{I_L (1-D)^2 R_{Load}} V_{SW} + \frac{1}{I_L (1-D) R_{Load}} V_D\right]} \qquad (1.29)$$

$$\eta = \frac{(1-D)^2}{\left[(1-D)^2 + \frac{(R_s + R_l)}{R_{Load}} + \frac{D}{I_L R_{Load}} V_{SW} + \frac{1}{(1-D) I_L R_{Load}} V_D\right]} \qquad (1.30)$$

and

$$\frac{v_o}{v_{in}} = \frac{1}{(1-D)} \eta$$

$$= \frac{1-D}{\left[(1-D)^2 + \frac{R_s + R_l}{R_{Load}} + \frac{D}{I_L R_{load}} V_{sw} + \frac{1}{(1-D) I_L R_{load}} V_D\right]} \qquad (1\text{-}31)$$

If

$\frac{v_{sw}}{I_L R_{Load}}$ and $\frac{v_D}{I_L R_{Load}}$ are considered to be very small, then 1-30 and 1-31 can be written as

$$\eta = \frac{(1-D)^2}{(1-D)^2 + \frac{R_s + R_l}{R_{load}}} \qquad (1\text{-}32)$$

And

$$\frac{v_0}{v_{in}} = \frac{1-D}{(1-D)^2 + \frac{R_s + R_l}{R_{load}}} \qquad (1\text{-}33)$$

Equations (1-32) and (1-33) can be written as,

$$\eta = \frac{(1-D)^2}{(1-D)^2 + \alpha} \quad (1\text{-}34)$$

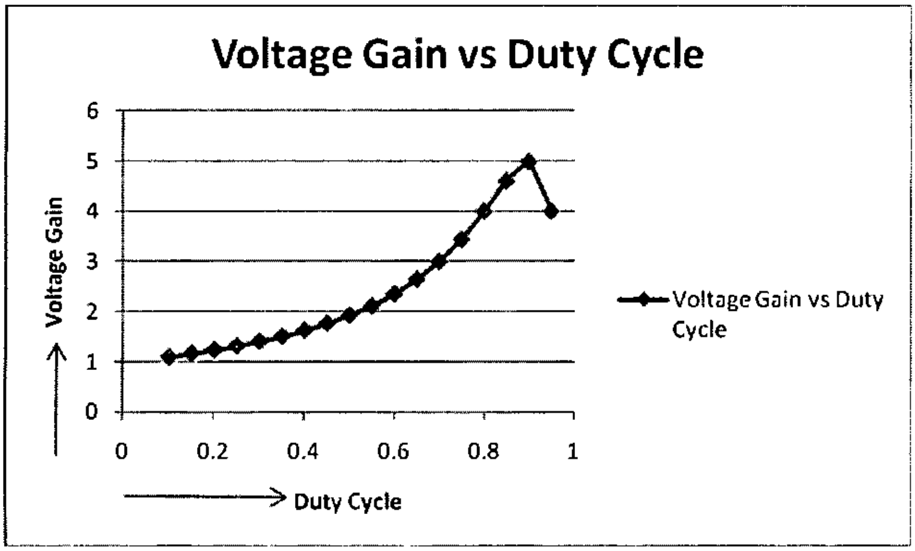
$$\frac{v_0}{v_{in}} = \frac{(1-D)}{(1-D)^2 + \alpha} \quad (1\text{-}35)$$

Where, $\alpha = \frac{R_s + R_l}{R_{load}}$

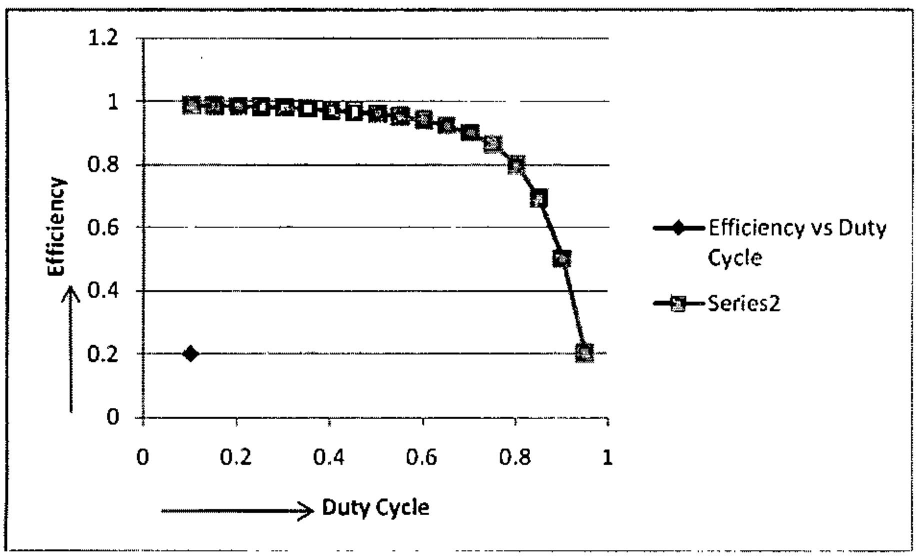
If $R_s = 1\Omega$, $R_l = 0.001\ \Omega$ and $R_{load} = 100\ \Omega$, then $\alpha = \frac{1.001}{100} \approx 0.01$ and the variation of efficiency η and $\frac{v_o}{v_{in}}$ with duty cycle can be plotted as shown in figure 1.10 (a) & (b) from the data of table 1A. The graph at the table show that though the boost converter theoretically has large gain and high efficiency, the practical converter in this case has maximum gain of 5 at efficiency 50% and the gain falls after duty cycle D>0.9. Hence for further gain, the boost converter of the example must have other means.

Table 1A practical boost DC-DC converter voltage gain and efficiency variation with Duty Cycle

α	D	η	V_0/V_{in}
≈ 0.01	0.10	0.987	1.09
	0.15	0.986	1.16
	0.20	0.984	1.23
	0.25	0.982	1.31
	0.30	0.980	1.40
	0.35	0.976	1.50
	0.40	0.972	1.62
	0.45	0.968	1.76
	0.50	0.961	1.92
	0.55	0.952	2.11
	0.60	0.941	2.35
	0.65	0.924	2.64
	0.70	0.900	3.00
	0.75	0.862	3.44
	0.80	0.800	4.00
	0.85	0.692	4.61
	0.90	0.500	5.00
	0.95	0.200	4.00



(a)



(b)

Figure-1.10 Voltage Gain and Efficiency Variation with Duty Cycle of a Boost DC-DC Converter with Non-ideal Elements.

Like hybrid configurations which would yield higher gains at better efficiency than reported in [1].

Similar analysis may be applied to other types of DC-DC converter like Ĉuk, SEPIC and Buck-Boost converter to show that for attaining high gain in single stage DC-DC converters, hybrid technique of voltage boost up prior to switch mode conversion (during switching) must be incorporated in conventional topologies.

1.4 LITERATURE REVIEW OF HIGH GAIN DC-DC CONVERTERS [1-3, 18-121]

In various energy applications high efficiency, high power, high voltage boost DC/DC converters are required as interface between low voltage source and the load, which operate at higher voltages. Energy storage components such as batteries, and ultra-capacitors which are used in the power trains of hybrid electric vehicles, electric vehicles, solar PV systems and fuel cell applications. In the modern power drive, the voltage levels of the energy storage devices are low and vehicle motors are driven higher voltages. In the computers and in the telecommunications batteries with low voltage levels are utilized as a back-up power source. Automotive headlamps which use high-intensity discharge lamp ballasts is another example of low voltage to high voltage dc dc converter application. The DC/DC converter is required to boost the low voltage of the car battery to much higher voltage during start-up and normal operation. In these and similar applications, non-isolated boost DC/DC converters can be used but they should operate at high efficiency while conducting high currents from low-voltage dc sources. The duty cycle of a conventional boost converter increases with the increase of the voltage gain.

Classical converters with magnetic coupling as flyback can achieve high step-up voltage gain. The power transformer volume is a problem in flyback magnetically coupled converters. The energy of the transformer leakage inductance, increased switching loss, electromagnetic interference and reduced converter efficiency are main draw backs of flyback converters. Active clamping soft-commutation techniques can be used to reduce the switching losses and the EMI generation of flyback type dc-dc converters. But the voltage stress is higher than in the hard-switching structures. Converters like classical boost, Cuk, Buck Boost, SEPIC and Inverse SEPIC (Zeta) can provide high step-up voltage gain, but with severe voltage and current stress and high duty-cycle. Non-isolated dc–dc converters operating with high gain known as quadratic boost converter are available, but with additional inductors and filter capacitors. Non-isolated dc–dc converter topologies were proposed in literature, high voltage gain is possible with low voltage stress and losses, improving the performance with relation the classical topologies.

To increase dc-dc converters' output voltage, pulse charging capacitors charging in parallel and discharging in a series has been used in the past and are being used in the present..To achieve high voltage gain it is necessary to charge and discharge them several times. This increases the number of components in the system. The advantage of this solution is the lack of magnetic components. Example of such solution is a switched capacitors converter which provides high voltage gain at a reasonable duty cycle and fairly high efficiency and adjustable output voltage. Converters with switched capacitors with principles of resonant energy transfer between switched capacitors were also reported in literature. Another approach is to introduce a family of coupled-inductor converters. The use of a coupled inductor converter can enable high voltage gain without the necessity to work at the highest duty cycle. Boost converter with capacitor voltage multiplier with gain up to 20 and high efficiency up to 97% was also reported in the past. In order to increase voltage gain the converter operation should be based on the use of a coupled-inductor with a series switched capacitor. Moreover, the clamp circuit recovers energy stored in leakage inductance ensuring high efficiency of this topology. Coupled-inductor boost converter with an output voltage doublers were also presented. In this topology the output voltage is the sum of the classical boost converter voltage and twice amplified output voltage. There are many known converter topologies and it is not an easy task to choose the one with the best performance. Selection should be carried out taking into account the complexity of the converter. A large number of alternative converter topologies and implementations have been proposed typically achieving high conversion efficiency at the medium to high input voltage range and at medium power levels.

An alternative for the implementation of high step-up structures was proposed in reference [1] with the use of the voltage multiplier cells integrated with conventional dc–dc converters. The use of the voltage multiplier in the conventional dc–dc converters added new operation characteristics with the resultant structure showing high voltage gain. The use of voltage multiplier in low frequency rectifiers was a classical solution for high dc output voltage. The voltage lift technique was utilized to implement a series of high voltage and wide conversion range applications dc-dc converters. It is possible to add more multiplier cells in order to achieve higher step-up ratios. "The voltage multiplier cell increases the static gain of the classical boost by a factor, where M is the number of multiplier cells. However, the maximum switch voltage is lower than the output voltage" [1].

1.5 OBJECTIVE OF THE RESEARCH

This research work aims at modifying conventional dc-dc switch mode converters with additional input stage inductive voltage multiplier stage so that the converters can operate at acceptable efficiency. Since a respective converter voltage will be stepped up as necessary, the desired gain of the converter will be attained at duty cycle smaller than required by the conventional dc-dc converters. In a practical dc-dc converter the efficiency is a function of the duty cycle D of the control signal of the static switch of the converter. Maximum efficiency of dc-dc converters happen within a certain range of duty cycle. By putting input stage voltage gain stage will keep the efficiency of a dc-dc converter within the maximum efficiency by attaining the desired gain at an early duty cycle before efficiency starts degrading.

1.6 OUTLINE OF THE THESIS

This thesis consists of three chapters. Chapter-1 deals with introduction to SMPS, State of the problem, review of DC-DC Converters. It incorporates Non ideal DC-DC Converters and problem Definitions. Literature Review, Objective of the research and outline of the research are also included in chapter-1.

Chapter-2 includes the high gain DC-DC Converters with multiple inductor multiplier cells. In this chapter the boost, the hybrid boost DC-DC Converter with two inductors [1],the hybrid proposed boost conductors with two inductors and the proposed hybrid DC-DC Converter with three inductor are studied by simulation. The proposed cell will provide higher boost voltage to the next stage of the DC-DC converter at a lower duty cycle than the conventional DC-DC Boost, Ĉuk or SEPIC converter.

Chapter-3 concludes the thesis with summary, achievements and suggestion on future works.

CHAPTER-2

HIGH GAIN HYBRID DC-DC CONVERTERS WITH MULTIPLE INDUCTOR MULTIPLIER CELL

INTRODUCTION

High gain topologies of various categories are constantly being investigated so as to obtain appropriate dc-dc converter for a particular applications. These converters are used in telecommunication industries, hybrid vehicles, solar PV systems, fuel cell application, UPS and reasonable source interconnection to grids etc. Hybrid dc-dc converters utilize voltage multiplier cells either at the front or at the load side of conventional dc-dc converters. By incorporating voltage multiplier cell with dc-dc converters like Boost, Ĉuk, SEPIC and Buck Boost converters the desired gain of the input to the load can be achieved at a lower duty cycle before the voltage gain and efficiency degradation start in these converters. With a aim to have high voltage gain at acceptable efficiency a new multi-inductor voltage multiplier cell is proposed in this thesis. The proposed cell is used to replace the front inductor of conventional Boost, Ĉuk, SEPIC and Buck-Boost dc-dc converter and the performance is studied by simulation.

2.1 MULTIPLE INDUCTOR MULTIPLIER CELL

Proposed two inductor cell for boost, Ĉuk and SEPIC dc-dc hybrid converter is shown in Figure 2.1. The circuit of Figure 2.1 takes the form of Figure 2.2 when the switch is ON. Currents flow through the inductors according to current division rule and rises with time. Instantaneous voltage across the inductor L_1 and L_2 are $v_{L1} = L_1 \frac{di_{L1}}{dt}$ and $v_{L2} = L_2 \frac{di_{l2}}{dt}$ respectively. If the two inductors have half the value of the inductor of single inductor conventional dc-dc converter, then i_{L_2} and i_{L_1} will be larger than i_L of the L of conventional dc-dc converter. As a result v_{l_2} and v_{l_1} will be higher than v_L of conventional dc-dc converter. When the switch of the proposed cell turns OFF, $V_{dc}+v_{l_1}$ or $V_{dc}+v_{l_2}$ appear across the switch providing the boost voltage to the next stage of the converter. Since v_{L_1} or v_{L_2} stage of the converter,

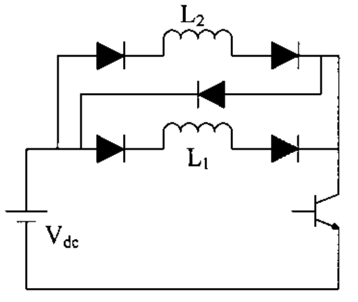
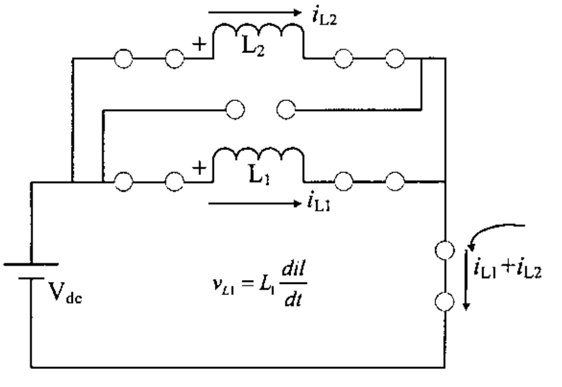
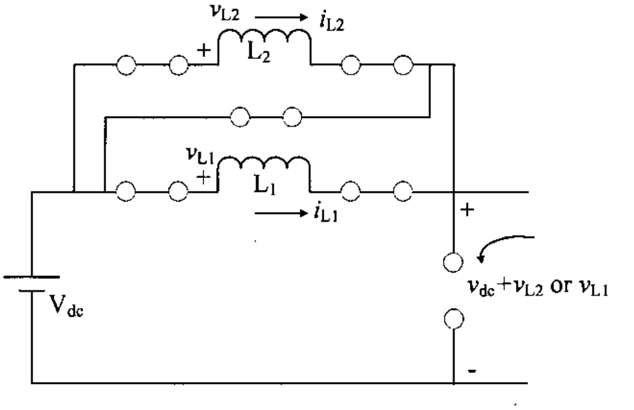


Figure 2.1 Proposed Inductor cell for Boost, Ĉuk, SEPIC converter



(a)Circuit for Figure 2, when switch is ON



(b) Circuit for Figure 2, when switch is OFF
Figure 2.2 Circuit of Figure 2.1 when is turns ON and OFF

is higher than v_l of conventional dc-dc converter, the proposed cell will provide higher Boost voltage to the next stage of the dc-dc converter at a lower duty cycle then the conventional dc-dc Boost, Ĉuk or SEPIC converter. The proposed cell is different than the Boost cell of Figure 2.3-2.4 made of two inductors of reference [1].It can be multiplied several times as shown in Figure 2.5.

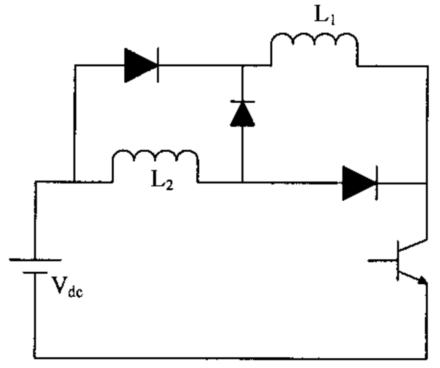
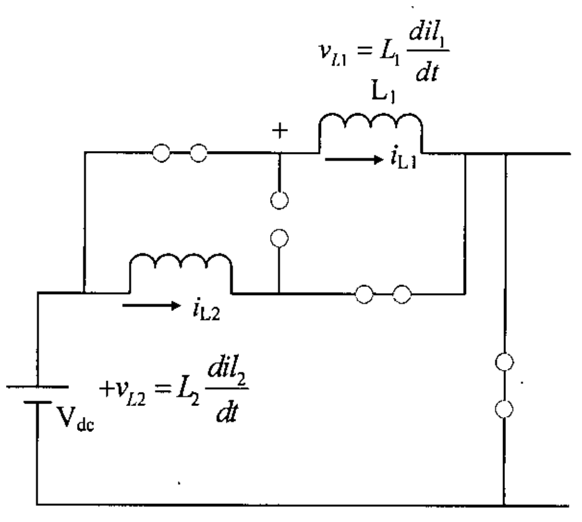
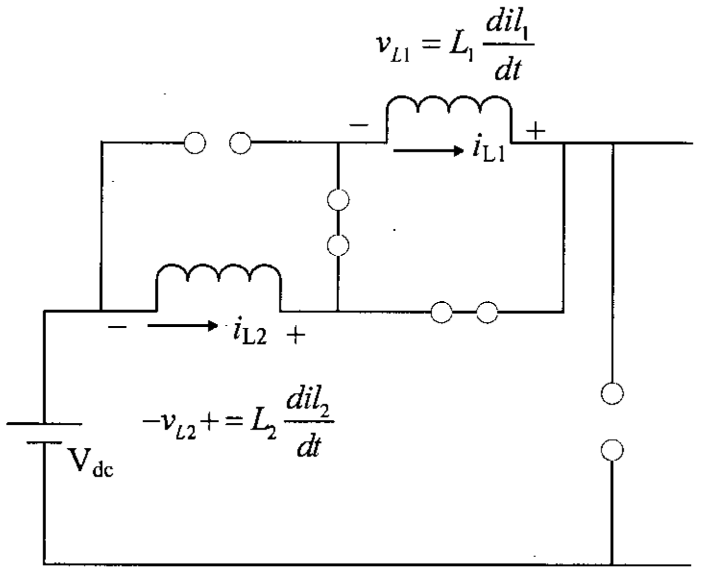


Figure-2.3 Boost cell made two inductors as reported in reference [1]



(a) Boost cell of Figure 2.3 when switch is ON



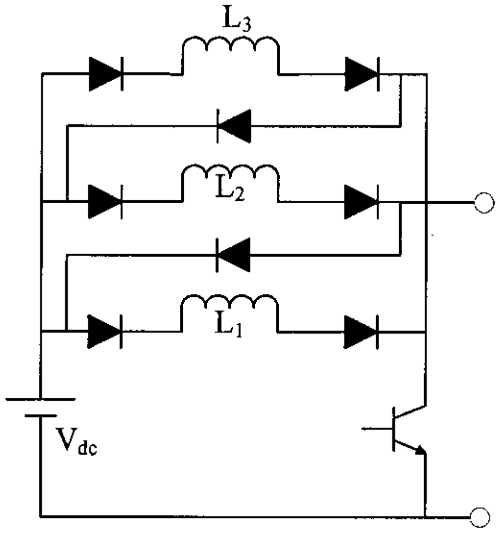
(b) Boost cell of Figure 2.3 when switch is OFF

Figure 2.4 Boost cell made of two inductors as reported in reference [1].

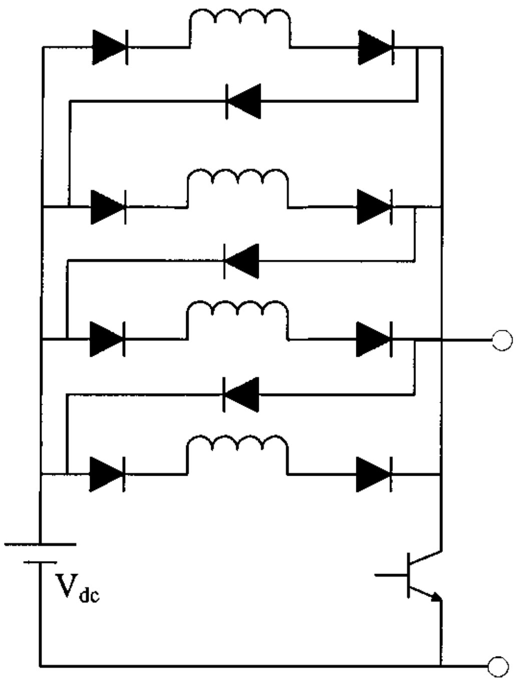
(a) The circuit of Figure 2.3 when switch is ON

(b) The circuit of Figure 2.3 when switch is OFF.

Three and four inductor cells for example



a) Proposed boost cell with three inductors

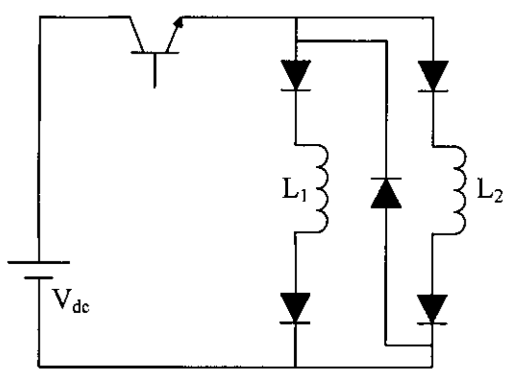


b) Proposed Boost cell with four inductors.

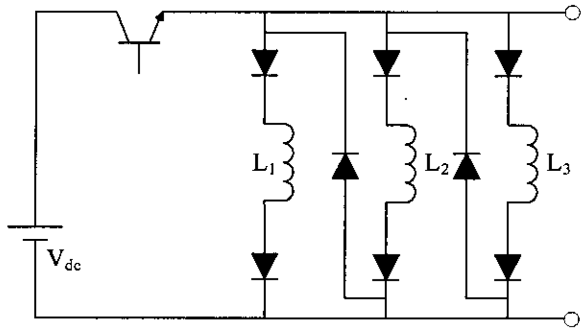
Figure 2.5 Proposed multi-inductor Boost cell for Boost, Ĉuk and SEPIC hybrid high gain dc-dc converter.

a) Proposed boost cell with three inductors
b) Proposed boost cell with four inductors.

Same proposed multi-inductor boost cell can be adopted for Buck-boost, high gain dc-dc converter as shown in Figure-2.6.



a) Two inductor Boost cell for Buck-Boost high gain hybrid dc-dc converter.



b) Three inductor boost cell for Buck-boost high gain hybrid dc-dc converter

Figure 2.6 Proposed multi-inductor boost cell for high gain hybrid buck-boost DC-DC converter.

a) Boost cell with two inductors

b) Boost cell with three inductors.

2.2 HYBRID DC-DC CONVERTER WITH NEW MULTIPLE INDUCTOR MULTIPLIER CELL

The proposed multiple inductor multiplier cell is used in Boost, Ĉuk, SEPIC and Buck-Boost dc-dc converters to operate them in hybrid mode to attain high voltage gain. The hybrid converter with two inductor multiplier cell are shown in Figure 2.7-2.10. The performance of three hybrid high gain converters are studied by simulation. The result of the performance, comparison with performance of hybrid high gain DC-DC converter of reference [1] are provided in sections 2.3-2.6.

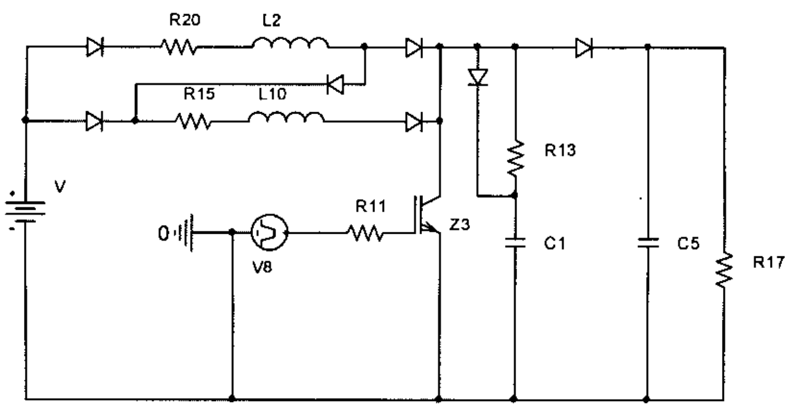


Figure 2.7 Proposed hybrid Boost converter with two inductor multiplier cell.

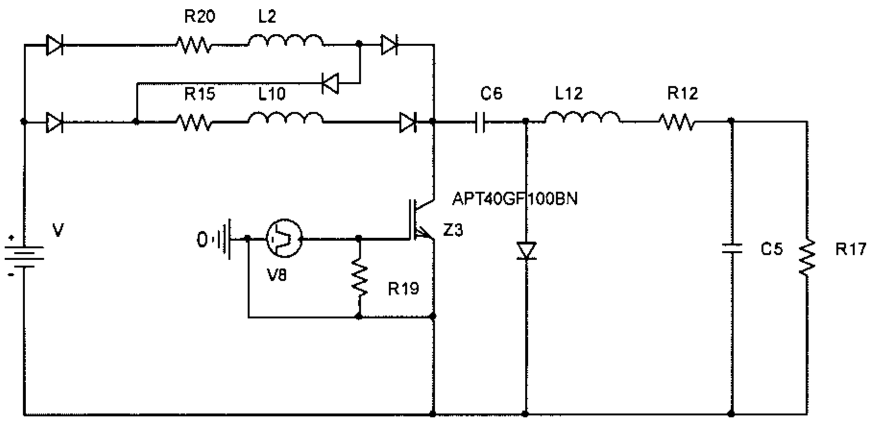


Figure 2.8 Proposed Cuk hybrid converter with two inductor multiplier cell.

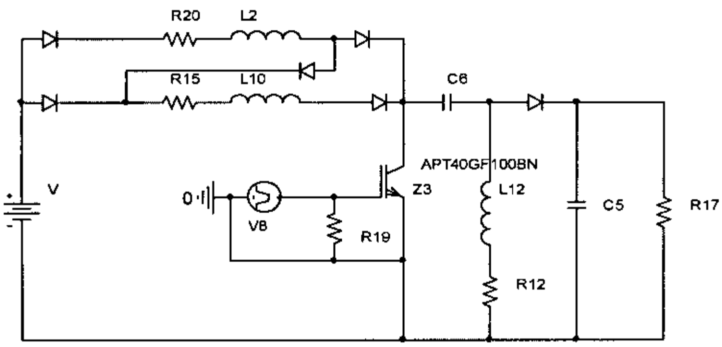


Figure 2.9 Proposed SEPIC hybrid converter with two inductor multiplier cell.

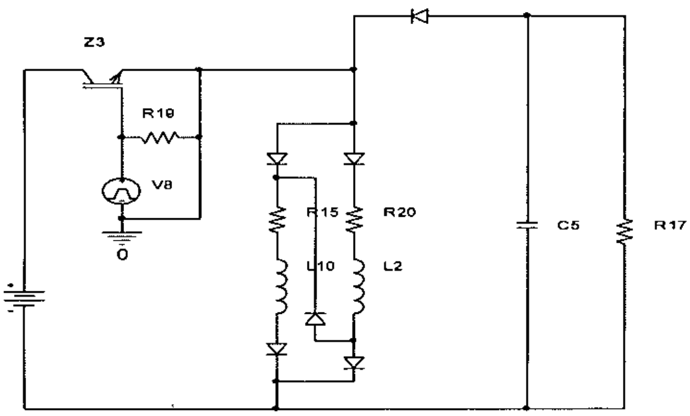


Figure 2.10 Proposed hybrid buck-boost converter with two inductor multiplier cell.

2.3 BOOST HYBRID CONVERTER WITH MULTIPLE INDUCTOR MULTIPLIER CELL

The boost, the hybrid boost dc-dc converter with two inductors [1], the hybrid proposed boost converter with two inductors and the proposed hybrid boost dc-dc converter with three inductors are studied by simulation at variable duty cycles. The total inductors in all the circuits are kept at 1 mH for the purpose of comparison on the same component value. The conventional Boost circuit is shown in figure 2.11and its typical waveforms are shown in figure 2.12. The hybrid boost circuit of reference [1] is shown in figure 2.15 and its typical waveforms is shown in Figure 2.16. The proposed boost hybrid circuit with two and three inductor cells are shown in Figures 2.19 and 2.23 respectively. Typical waveforms of Figures 2.19 and 2.23 are shown in Figures 2.20 and 2.24 respectively. The input voltage, output voltage, voltage gain, input power, output power and efficiency are tabulated in Tables 2.1-2.4 and depicted in graphs of Figure 2.13-2.14, Figure 2.17-2.18, Figure 2.21-2.22 and Figure 2.25-2.26 for circuits of Figure 2.11, Figure 2.15, Figure 2.19, Figure 2.23 respectively. Table 2.A compares the results of four configurations for voltage gain of 3.5 in the first row, which indicate that for 1mH total inductor the voltage gain 3.5 takes place at 0.7, 0.4, 0.4 and 0.2 duty cycle for normal, hybrid boost [1], proposed hybrid boost of 2 inductors and proposed hybrid boost converter of 3 inductor. The efficiency of the paper hybrid circuit is higher than normal and proposed hybrid circuit for two inductors. But for 3 inductor circuit the efficiency is better than normal and hybrid circuit of [1].

Also in the second row of the Table 2.A it is evident that voltage gain of the proposed multiple inductors can be made higher than any other topology. The increase of inductor number keeping the total inductor value same is not possible in the hybrid circuit of the paper [1].

Table 2.A Comparison of Normal Boost, Boost Topology of [1], Proposed Boost Topology, Proposed Topology with Three Inductor

Normal Boost			Hybrid Boost of [1] two Inductor		
Duty cycle	Voltage Gain	Efficiency %	Duty cycle	Voltage Gain	Efficiency %
0.7	3.5	80	0.4	3.5	85
0.875	7.77	70.11	0.875	11.82	55.84

Table 2.A (Continued)

Hybrid Boost of Proposed Topology with 2 Inductor			Hybrid Boost of Proposed Topology with 3 Inductor		
Duty cycle	Voltage Gain	Efficiency %	Duty cycle	Voltage Gain	Efficiency %
0.4	3.5	74	.2	3.5	85.84
0.875	10.55	49.64	0.875	13.358	52.56

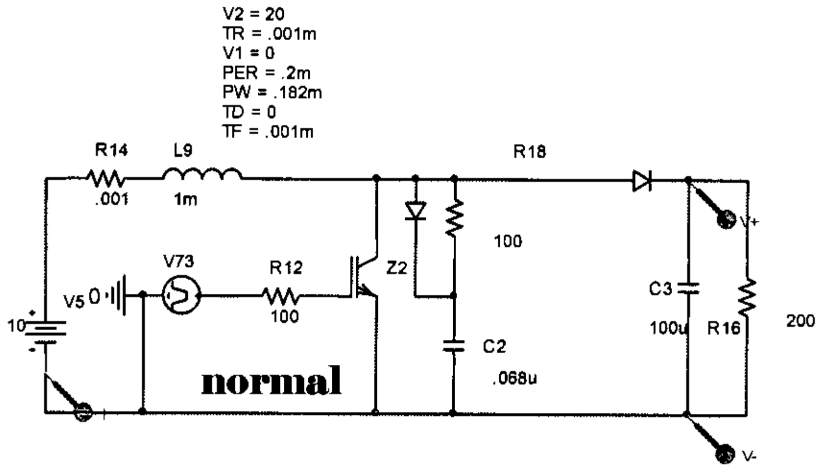


Figure-2.11: Boost DC-DC Converter

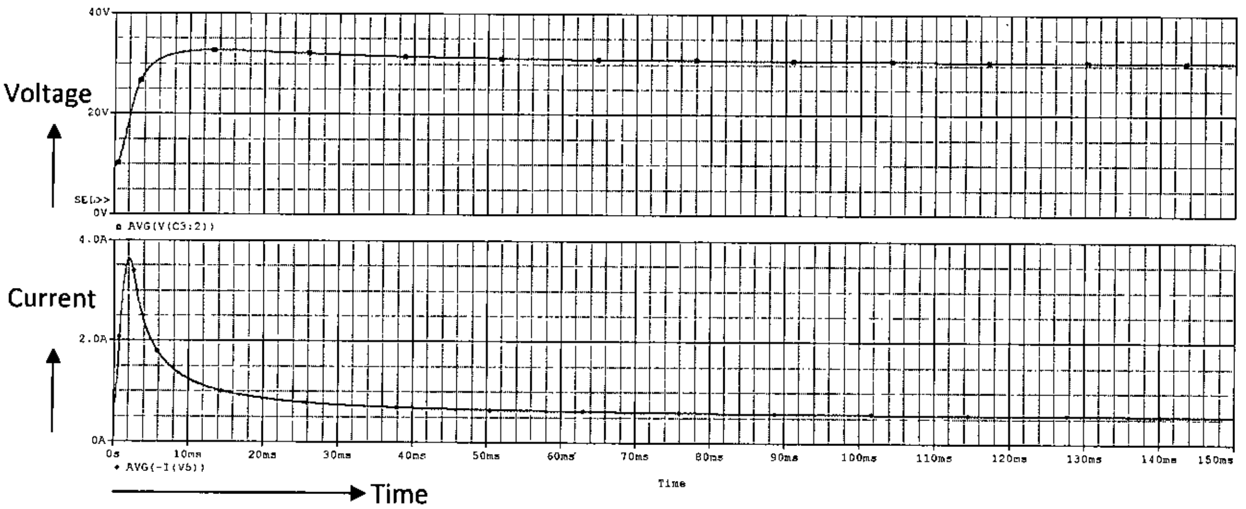


Figure- 2.12: Typical Waveforms of Boost DC-DC Converter of Figure-2.11

Table-2.1: Performance of Boost DC-DC Converter of Circuit of Figure-2.11

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage gain**	**Efficiency in percentage**
0.125	10	0.0841	12.46	0.062	0.84	0.77	1.24	91.66
0.25	10	0.156	16.82	0.084	1.56	1.41	1.68	90.38
0.375	10	0.261	22.49	0.112	2.61	2.51	2.24	80.45
0.50	10	0.40	26.56	0.127	4.00	3.37	2.65	84.25
0.625	10	0.544	30.54	0.152	5.44	4.64	3.05	85.29
0.75	10	1.00	39.75	0.198	10.00	7.87	3.97	78.70
0.875	10	4.30	77.72	0..388	43.00	30.15	7.77	70.11

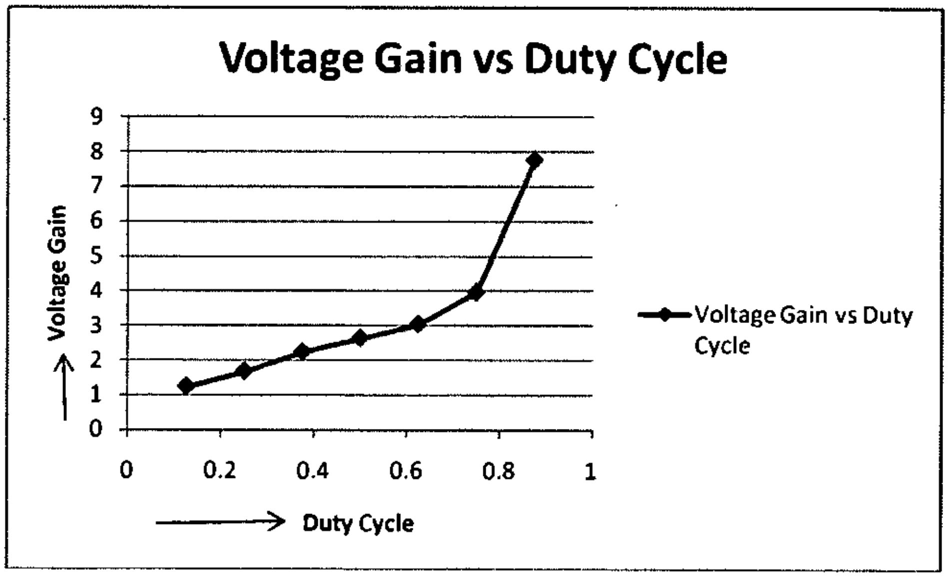


Figure-2.13: Voltage Gain vs Duty Cycle curve of Boost DC-DC Converter of Figure-2.11

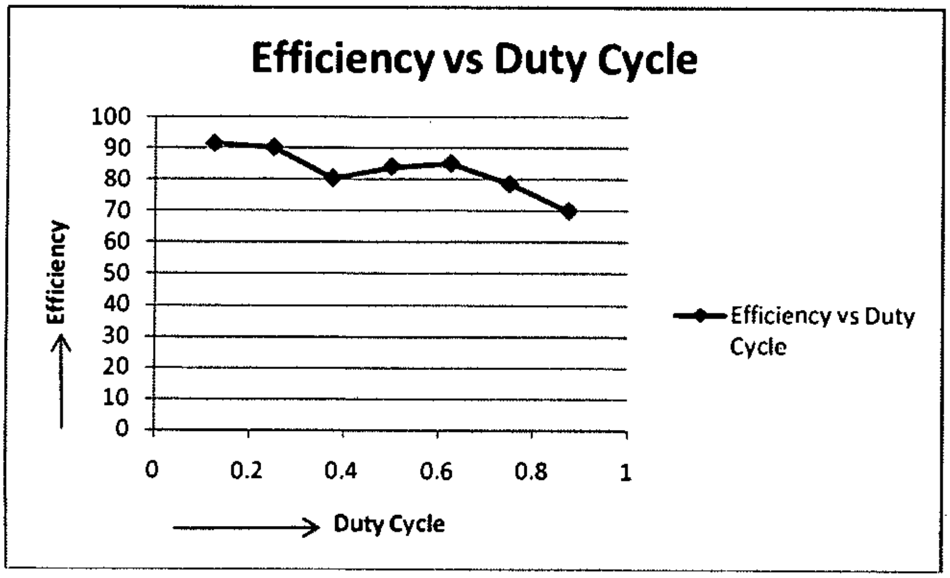


Figure-2.14: Efficiency vs Duty Cycle curve of Boost DC-DC Converter of Figure-2.11

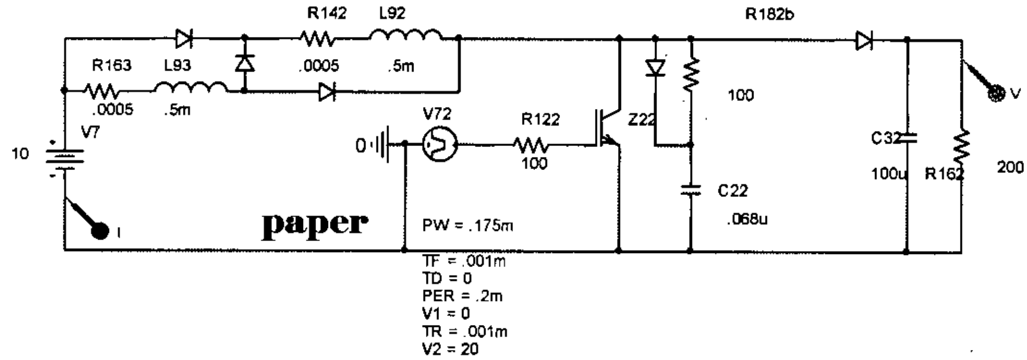


Figure-2.15 High Gain Hybrid Boost DC-DC Converter [1]

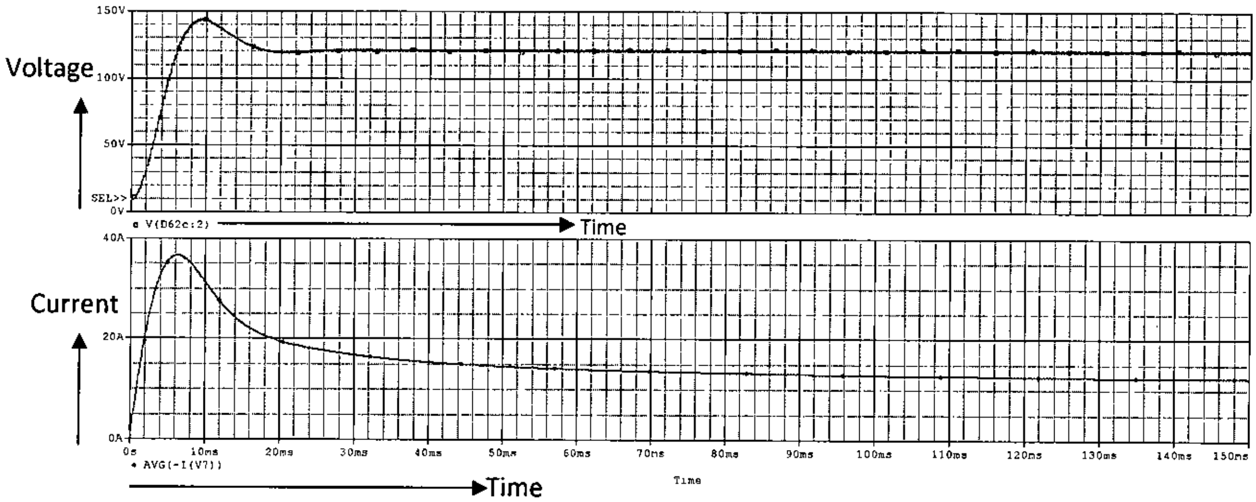


Figure-2.16: Typical Waveforms of High Gain Hybrid Boost DC-DC Converter of Figure-2.15

Table-2.2: Performance of High Gain Hybrid Boost DC-DC Converter of Figure-2.15 []

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage Gain**	**Efficiency in percentage**
0.125	10	0.152	16.18	0.0809	1.52	1.308962	1.618	86.11592105
0.25	10	0.377	24.7	0.1235	3.77	3.05045	2.47	80.9137931
0.375	10	0.704	34.95	0.17475	7.04	6.107513	3.495	86.75443892
0.5	10	1.164	42.09	0.21045	11.64	8.857841	4.209	76.09828608
0.625	10	1.763	51.485	0.257425	17.63	13.25353	5.1485	75.17598483
0.75	10	2.818	61.692	0.30846	28.18	19.02951	6.1692	67.52843974
0.875	10	12.52	118.248	0.59124	125.2	69.91295	11.8248	55.8410124

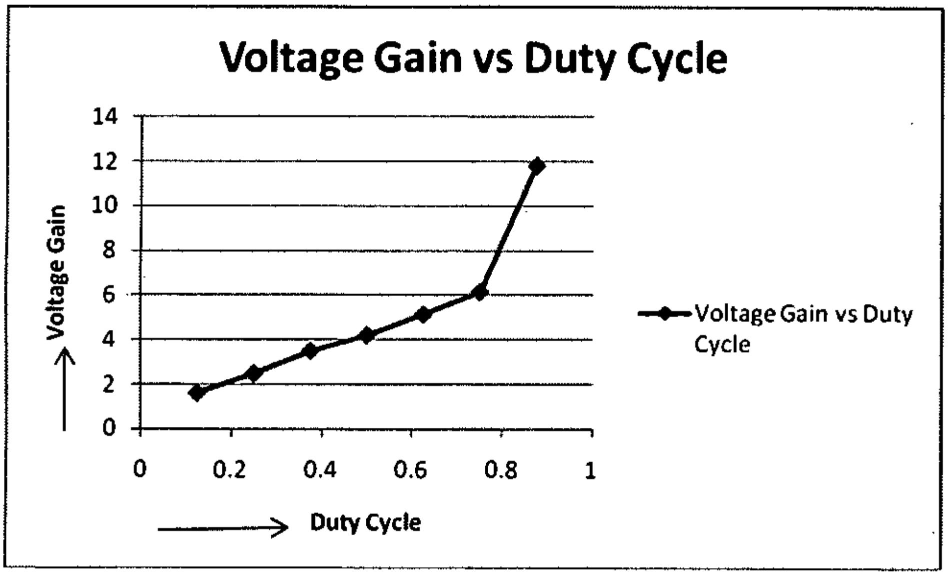


Figure-2.17: Voltage Gain vs Duty Cycle curve of High Gain Hybrid Boost DC-DC Converter of Figure-2.15

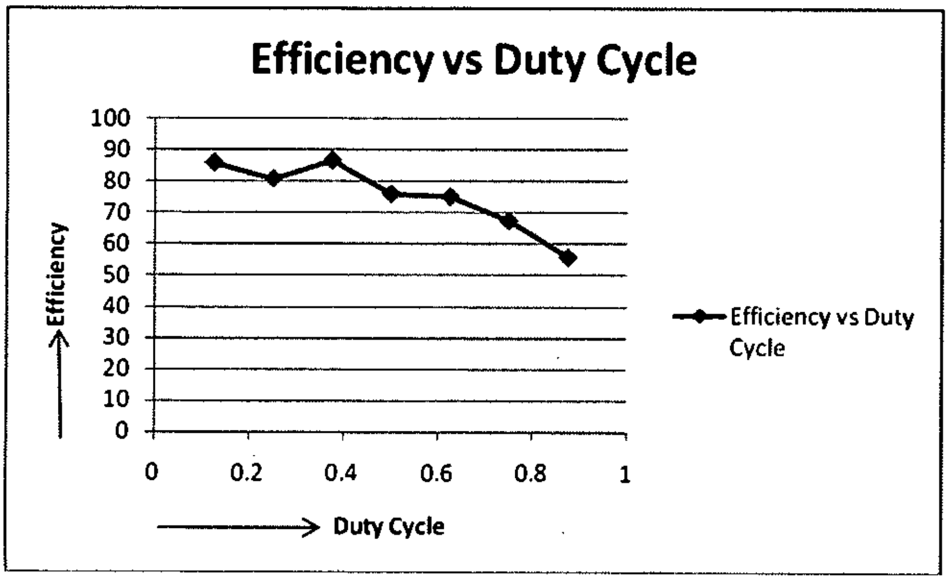


Figure-2.18: Efficiency vs Duty Cycle curve of High Gain Hybrid Boost DC-DC Converter of Figure-2.15

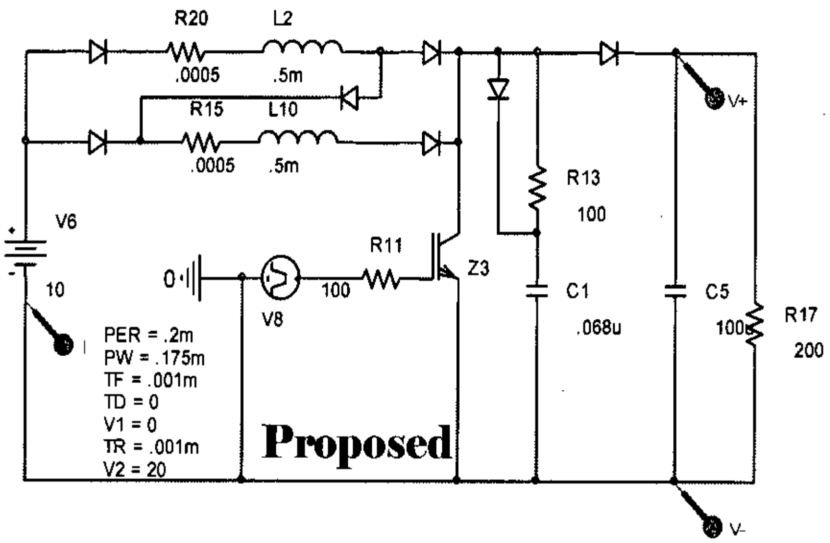


Figure -2.19: High Gain Hybrid Boost DC-DC Converter (proposed)

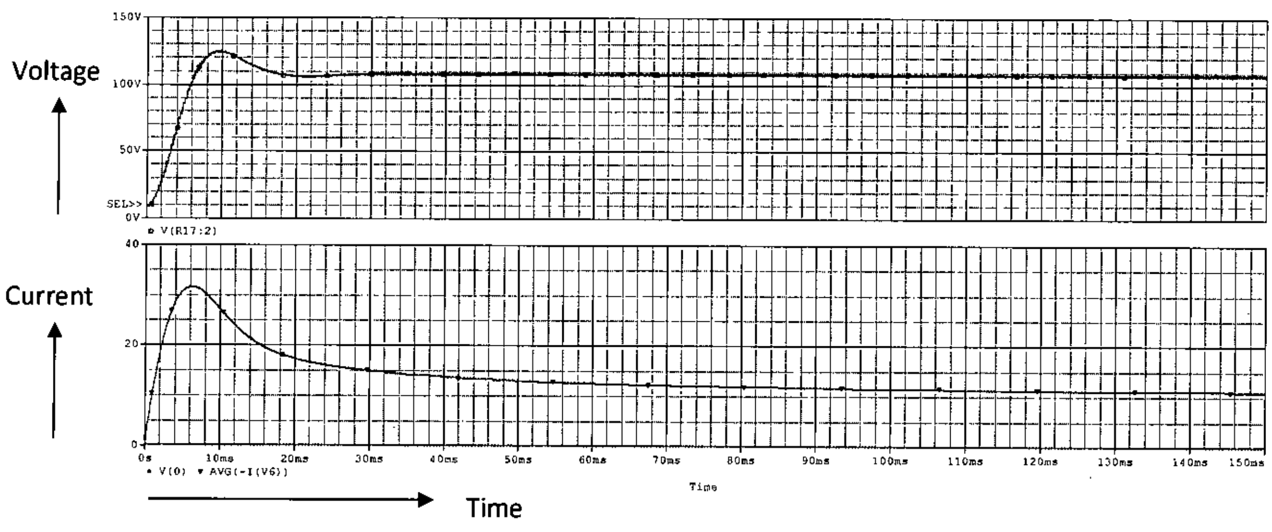


Figure-2.20: Typical Waveforms of High Gain Hybrid Boost DC-DC Converter of Figure-2.17(proposed)

Table-2.3: Performance of High Gain Hybrid Boost DC-DC Converter of Figure-2.19

Duty Cycle	Vin (V)	Iin (A)	Vout (V)	Iout (A)	Pin (W)	Pout (W)	Voltage Gain	Efficiency in percentage
0.125	10	0.139	14.25	0.07125	1.39	1.015313	1.425	73.04406475
0.25	10	0.347	22.92	0.1146	3.47	2.626632	2.292	75.69544669
0.375	10	0.644	31.25	0.15625	6.44	4.882813	3.125	75.82006988
0.5	10	1.057	39.12	0.1956	10.57	7.651872	3.912	72.39235572
0.625	10	1.6	46.49	0.23245	16	10.8066	4.649	67.54125313
0.75	10	2.54	55.65	0.27825	25.4	15.48461	5.565	60.96304134
0.875	10	11.22	105.55	0.52775	112.2	55.70401	10.555	49.64706996

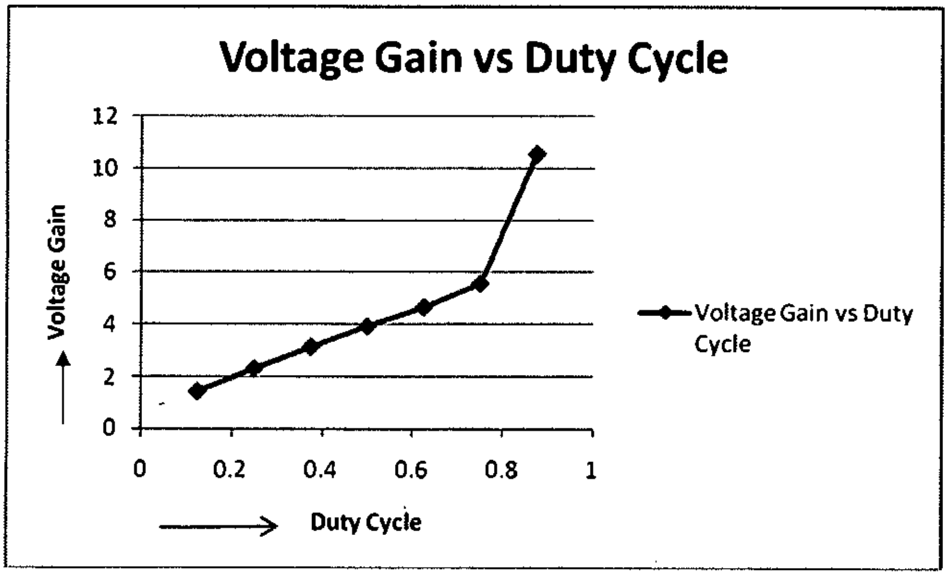


Figure-2.21: Voltage Gain vs Duty Cycle curve of High Gain Hybrid Boost DC-DC Converter of Figure-2.19

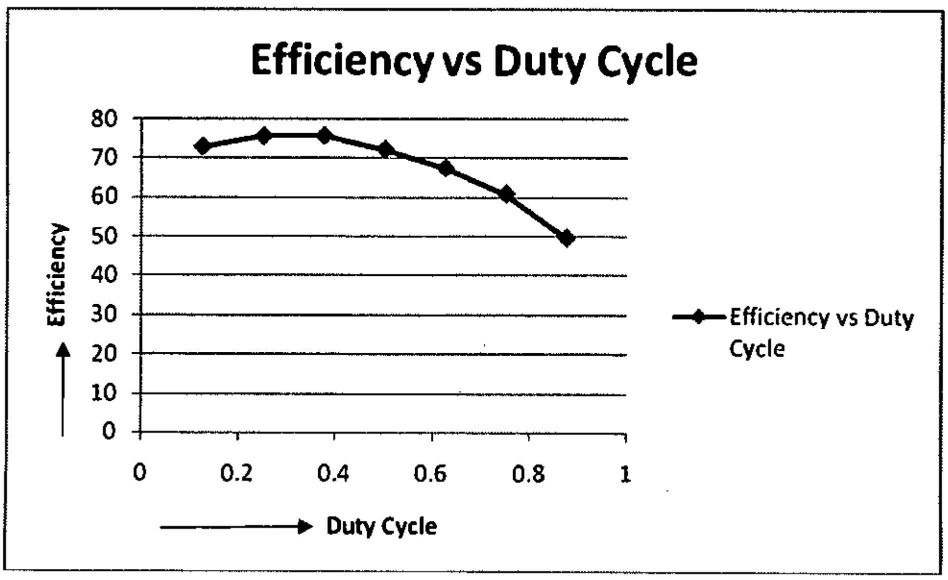


Figure-2.22: Efficiency vs Duty Cycle curve of High Gain Hybrid Boost DC-DC Converter of Figure-2.19

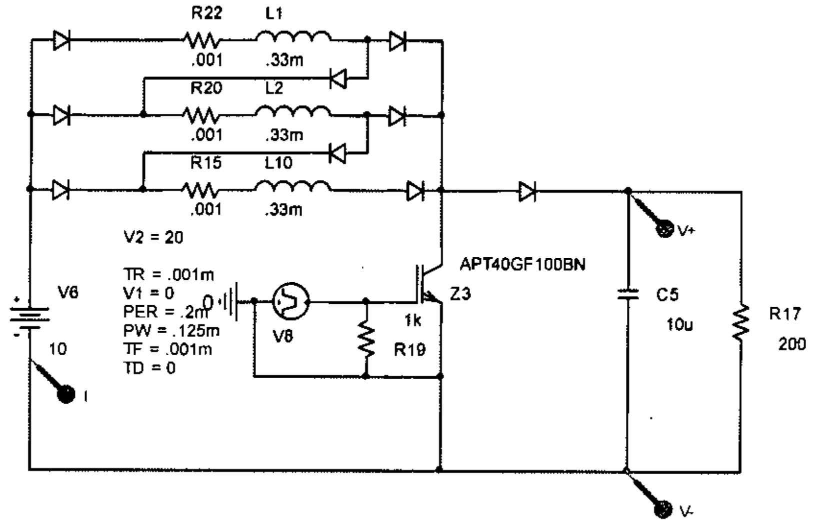


Figure-2.23: High Gain Hybrid Boost DC-DC Converter (proposed)

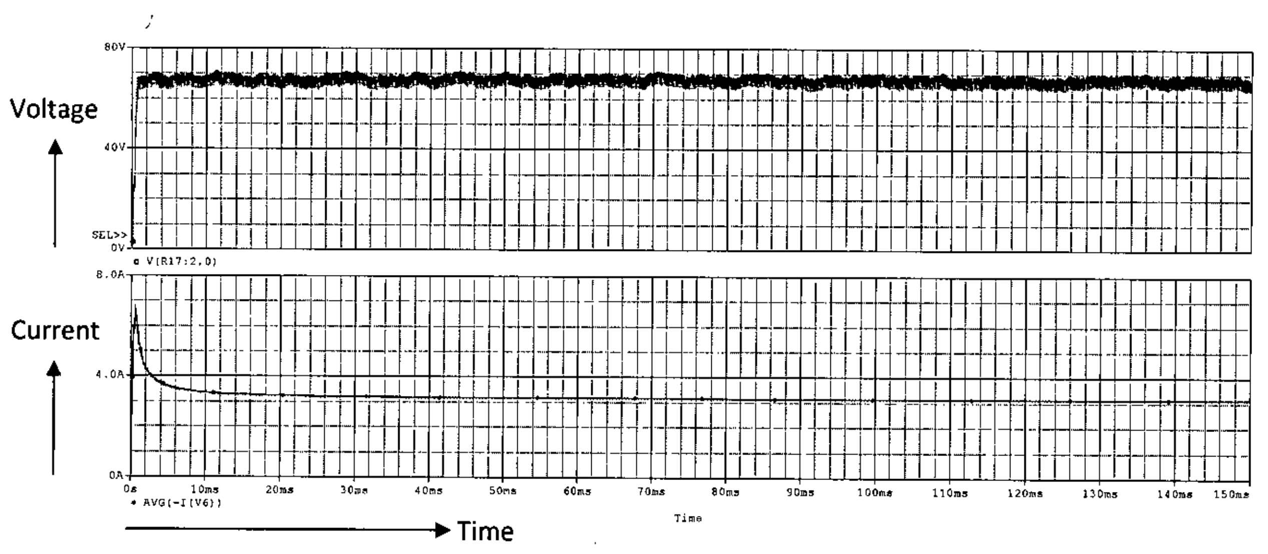


Figure-2.24: Typical Waveforms of High Gain Hybrid Boost DC-DC Converter of Figure-2.23 (proposed)

Table-2.4: Performance of High Gain Hybrid Boost DC-DC Converter of Figure-2.23

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage Gain**	**Efficiency in percentage**
0.125	10	0.22	19.47	0.097	2.21	1.89	1.947	85.84
0.25	10	0.63	32.44	0.16	6.30	5.19	3.244	82.38
0.375	10	1.25	45.17	0.22	12.5	9.93	4.517	79.49
0.5	10	2.10	56.72	0.28	21	15.88	5.672	75.62
0.625	10	3.12	67.07	0.33	31.2	22.13	6.707	70.93
0.75	10	4.58	77.38	0.38	45.8	29.40	7.738	64.20
0.875	10	16.97	133.58	0.66	169.7	89.21	13.358	52.56

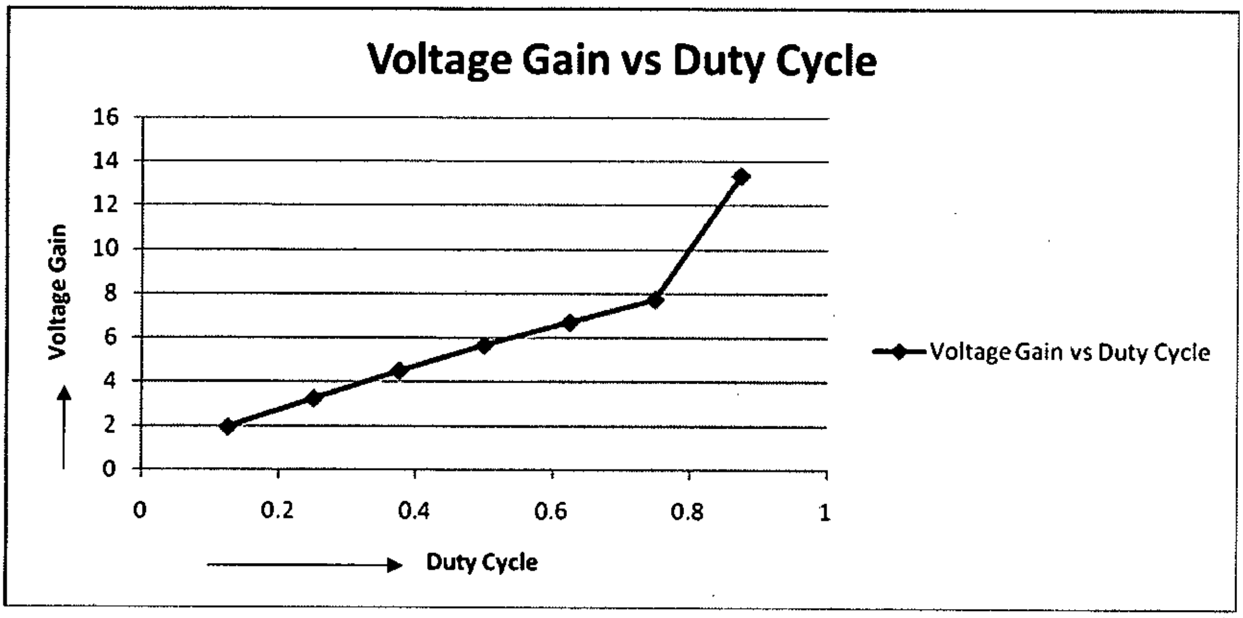


Figure-2.25: Voltage Gain vs Duty Cycle curve of High Gain Hybrid Boost DC-DC Converter of Figure-2.23

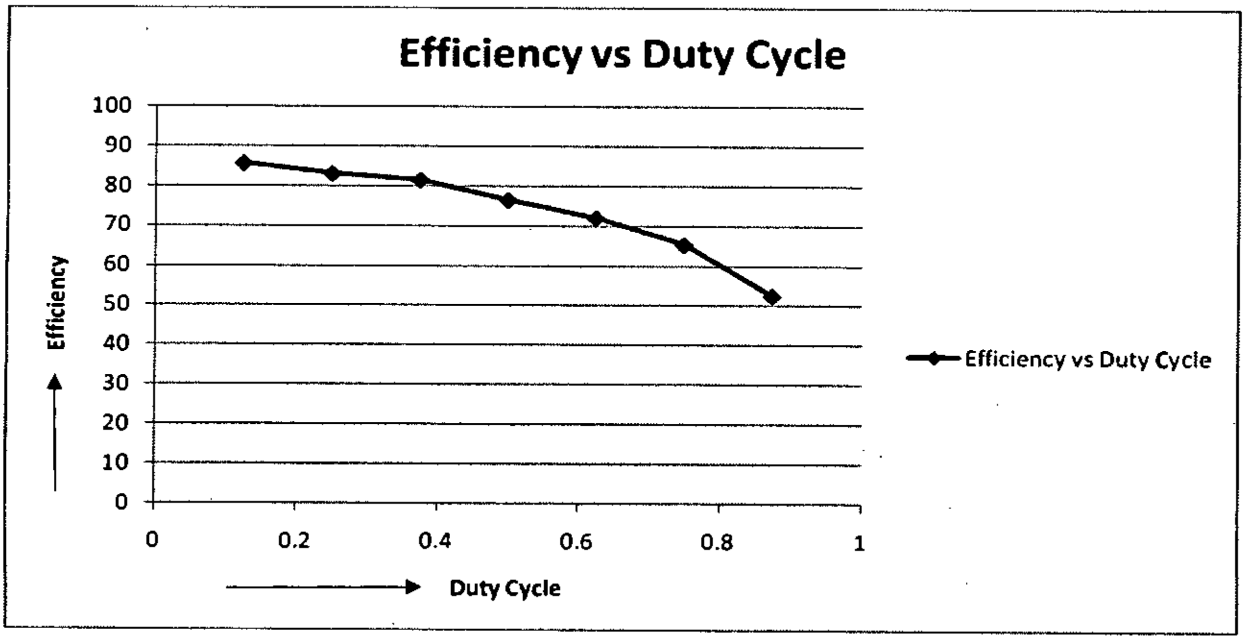


Figure-2.26: Efficiency vs Duty Cycle curve of High Gain Hybrid Boost DC-DC Converter of Figure-2.23

2.4 ĈUK HYBRID CONVERTER WITH MULTIPLE INDUCTOR MULTIPLIER CELL

The high gain ĈUK, the hybrid ĈUK dc-dc converter with two inductors[1], the ĈUK hybrid boost proposed converter with two inductors and the proposed ĈUK hybrid boost dc-dc converter with three inductors are studied by simulation at variable duty cycles. The total inductors in all the circuits are kept at 1 mH for the purpose of comparison on the same component value. The conventional ĈUK Boost circuit is shown in figure 2.27 and its typical waveforms are shown in figure 2.28. The ĈUK hybrid Boost circuit of reference [1] is shown in figure 2.31 and its typical waveforms is shown in Figure 2.32. The proposed ĈUK hybrid Boost circuit with two and three inductor cells are shown in Figures 2.35 and 2.39 respectively. Typical waveforms of Figures 2.35 and 2.39 are shown in Figures 2.35 and 2.40 respectively. The input voltage, output voltage, voltage gain, input power, output power and efficiency are tabulated in tables 2.5 -2.8 and depicted in graphs of Figure 2.29-2.30, Figure 2.33-2.34, Figure 2.37-2.38 and Figure 2.41-2.42 for circuits of Figure 2.27, Figure 2.31, Figure 2.35, Figure 2.39 respectively. Table 2.B compares the results of four configurations for voltage gain of 3.91 in the first row, which indicate that for 1mH total inductor the voltage gain 3.91 takes place at 0.62, 0.375, 0.375 and 0.4 duty cycle for normal, ĈUK hybrid of [1], proposed ĈUK hybrid of 2 inductors and proposed ĈUK hybrid of 3 inductor circuit. The efficiency of the ĈUK hybrid circuit with two inductors [1] is higher than normal, proposed hybrid circuit for two inductors and proposed hybrid circuit for three inductors.

Also in the second row of the table 2.C it is evident that voltage gain of the multiple inductors can be made higher than any other topology. The increase of inductor number keeping the total inductor value same is not possible in the hybrid circuit of Paper [1].

Table 2.B Comparison of Normal ĈUK, Hybrid ĈUK Topology of [1], Proposed Hybrid ĈUK Topology with Two Inductor, Proposed Hybrid ĈUK Topology with Three Inductor

Normal ĈUK			Hybrid ĈUK of [1] two Inductor		
Duty cycle	Voltage Gain	Efficiency %	Duty cycle	Voltage Gain	Efficiency %
0.62	3.91	84	0.375	3.91	91.99
0.875	6.4	77.30	0.875	10.29	64.87

Table 2.B (Continued)

Hybrid ĈUK of Proposed Topology with 2 Inductor			Hybrid ĈUK of Proposed Topology with 3 Inductor		
Duty cycle	Voltage Gain	Efficiency %	Duty cycle	Voltage Gain	Efficiency %
0.375	3.91	88.20	0.4	3.91	88
0.875	9.18	57.46	0.875	12.08	51.47

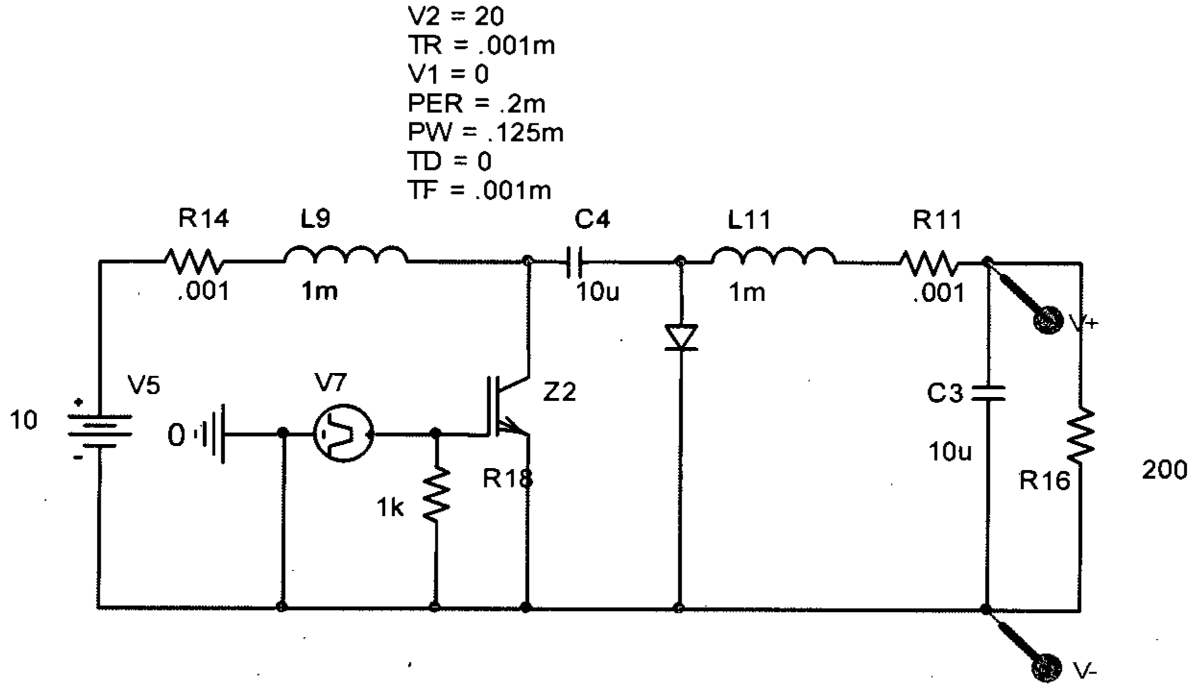


Figure-2.27: High gain ĈUK Boost DC-DC Converter

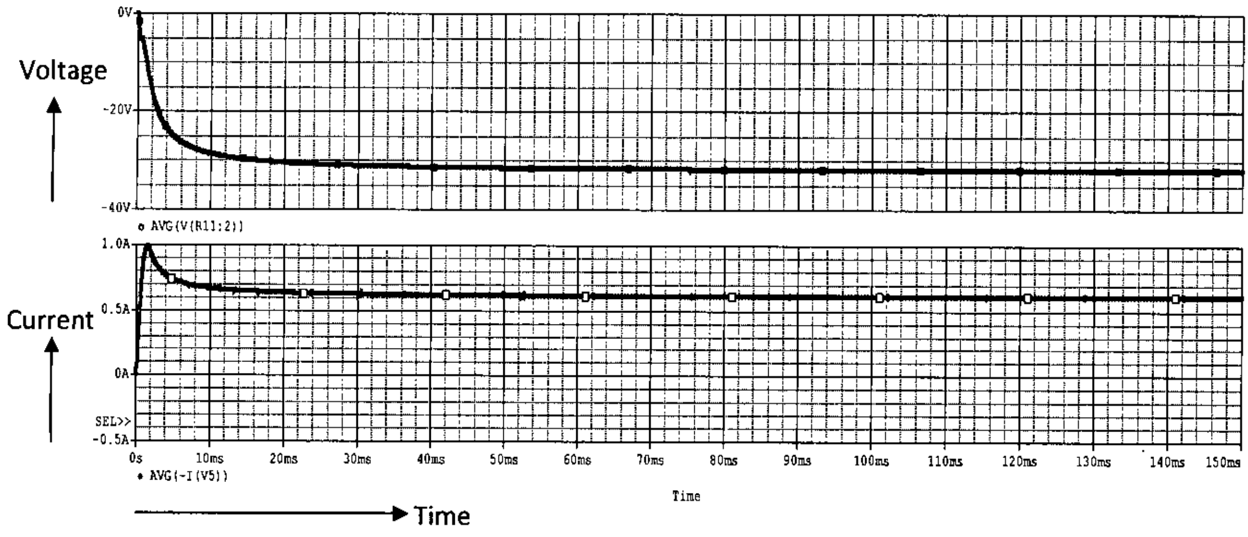


Figure-2.28: Typical Waveforms of High gain ĈUK Boost DC-DC Converter of Figure-2.27

Table-2.5 : Performance of High gain ĈUK Boost DC-DC Converter of Figure-2.27

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage Gain**	**Efficiency in percentage**
0.125	10	0.0252	6.4536	0.032268	0.252	0.208244765	0.64	82.63681143
0.25	10	0.0946	12.675	0.063375	0.946	0.803278125	1.26	84.91312104
0.375	10	0.213	19.021	0.095105	2.13	1.808992205	1.90	84.9292115
0.5	10	0.382	25.351	0.126755	3.82	3.213366005	2.52	84.11952893
0.625	10	0.604	32.004	0.16002	6.04	5.12128008	3.20	84.7894053
0.75	10	0.869	37.986	0.18993	8.69	7.21468098	3.79	83.02279609
0.875	10	2.665	64.192	0.32096	26.65	20.60306432	6.41	77.30980983

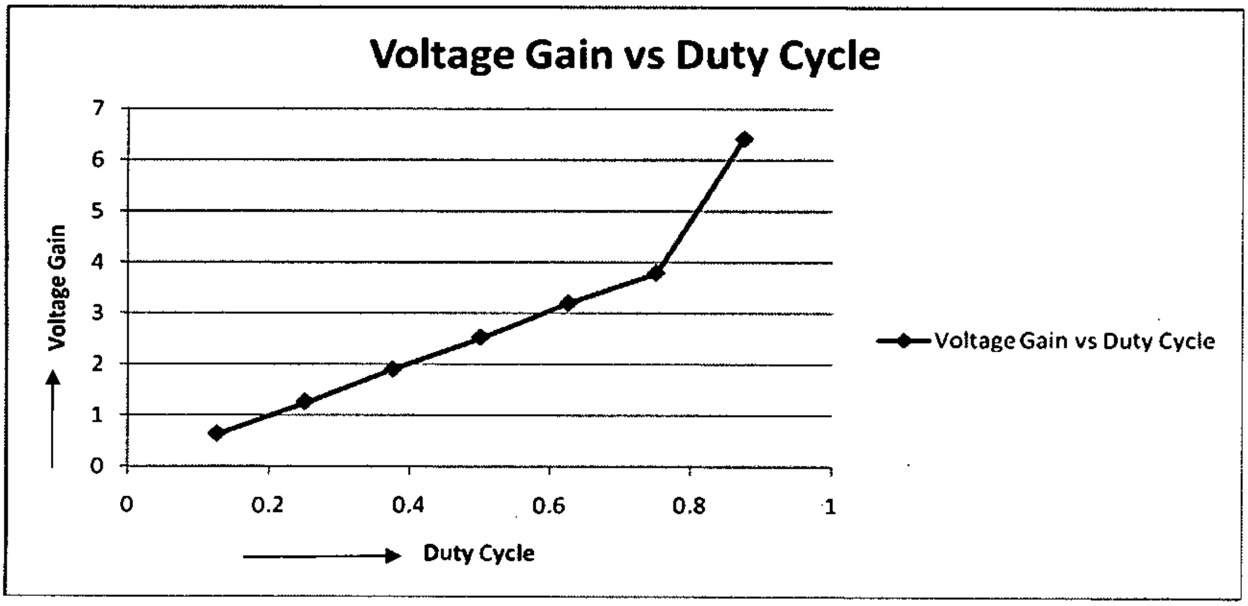


Figure-2.29: Voltage Gain vs Duty Cycle curve of High gain ĈUK Boost DC-DC Converter of Figure-2.27

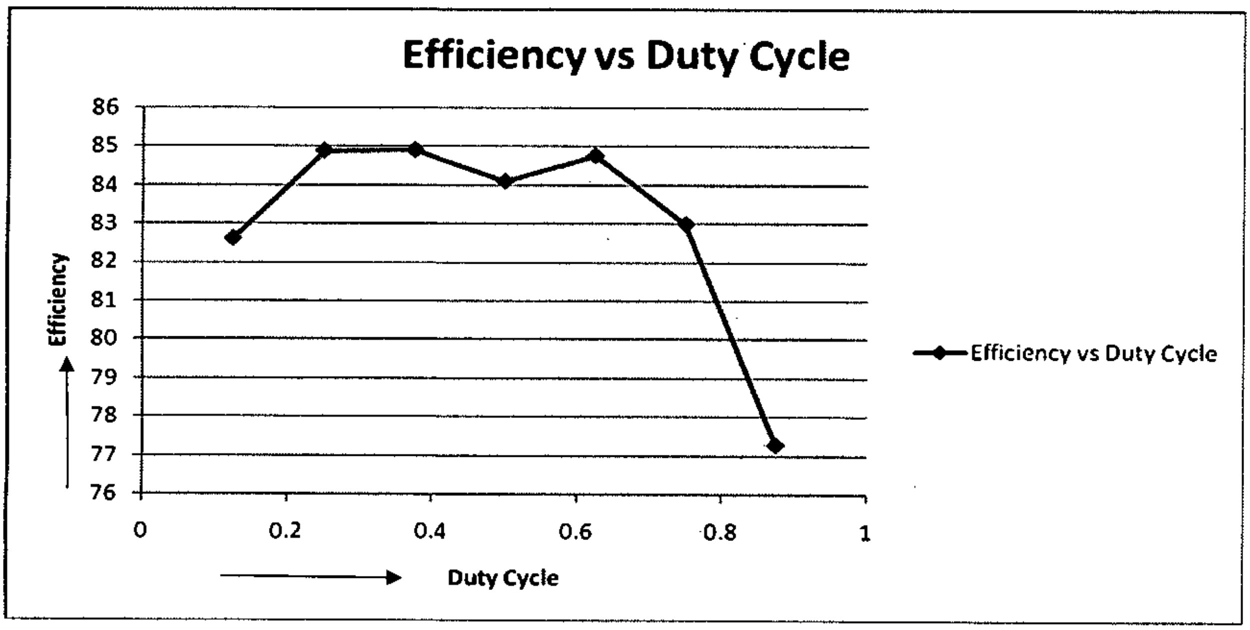


Figure-2.30: Efficiency vs Duty Cycle curve of High gain ĈUK Boost DC-DC Converter Figure-2.27

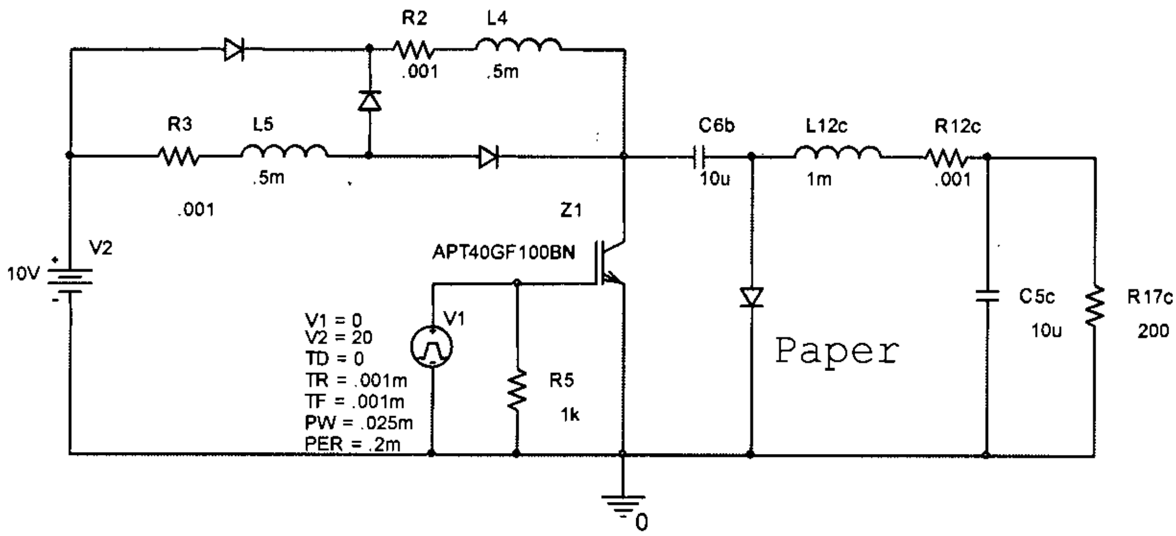


Figure-2.31: High Gain ĈUK Hybrid Boost DC-DC Converter [1]

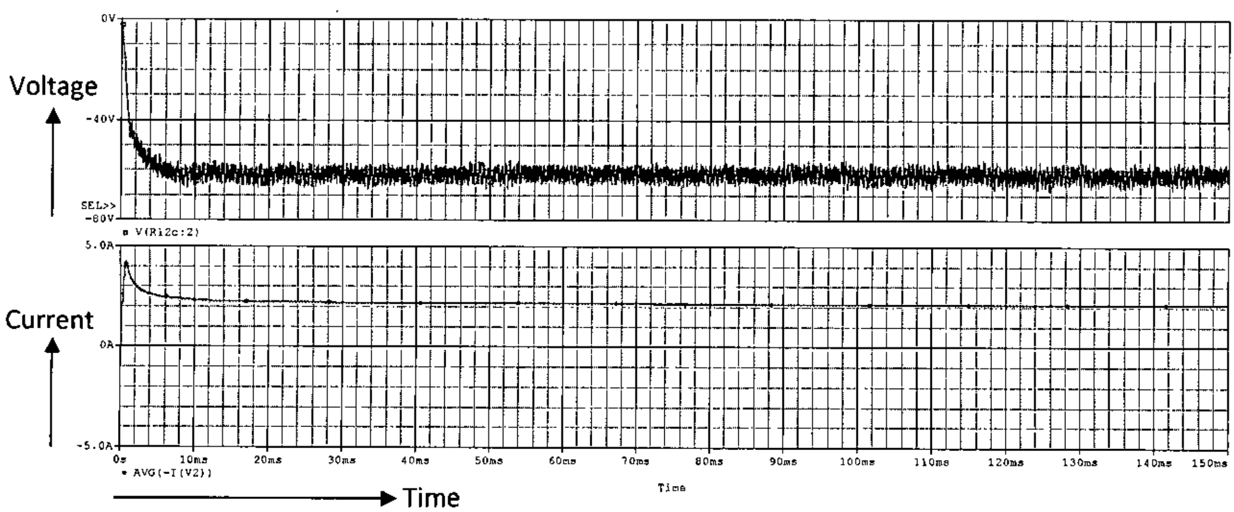


Figure-2.32: Typical Waveforms of High gain ĈUK Boost DC-DC Converter [1] of Figure-2.31

Table-2.6: Performance of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.31 [1]

Duty Cycle	Vin (V)	Iin (A)	Vout (V)	Iout (A)	Pin (W)	Pout (W)	Voltage gain	Efficiency in percentage
0.125	10	0.124	14.79	0.07395	1.24	1.093721	1.479	88.2032661
0.25	10	0.407	26.37	0.13185	4.07	3.476885	2.637	85.4271376
0.375	10	0.833	39.148	0.19574	8.33	7.66283	3.9148	91.9907505
0.5	10	1.43	50.36	0.2518	14.3	12.68065	5.036	88.6758601
0.625	10	2.37	61.02	0.3051	23.7	18.6172	6.102	78.5535949
0.75	10	3.65	78.11	0.39055	36.5	30.50586	7.811	83.5777
0.875	10	8.17	102.96	0.5148	81.7	53.00381	10.296	64.876142

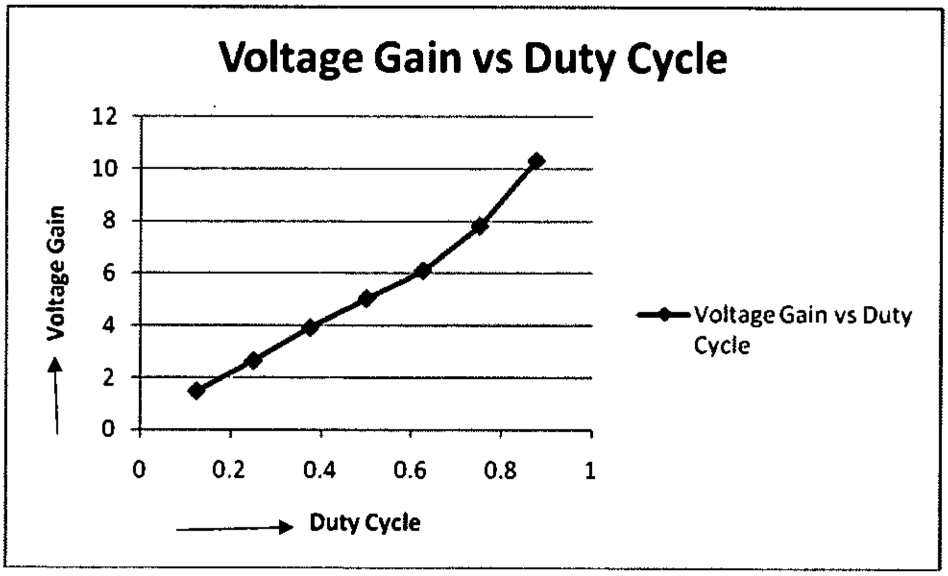


Figure-2.33: Voltage Gain vs Duty Cycle curve of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.31

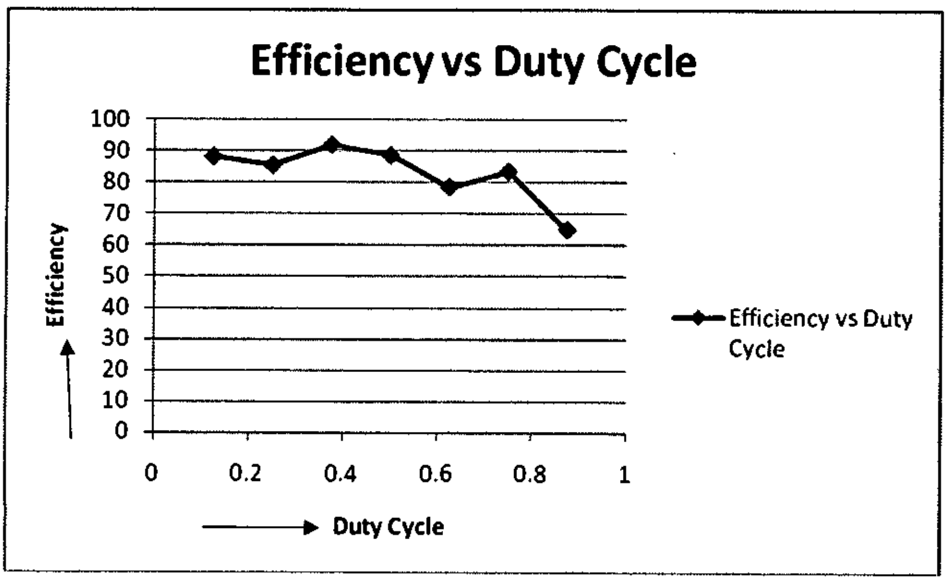


Figure-2.34: Efficiency vs Duty Cycle curve of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.31

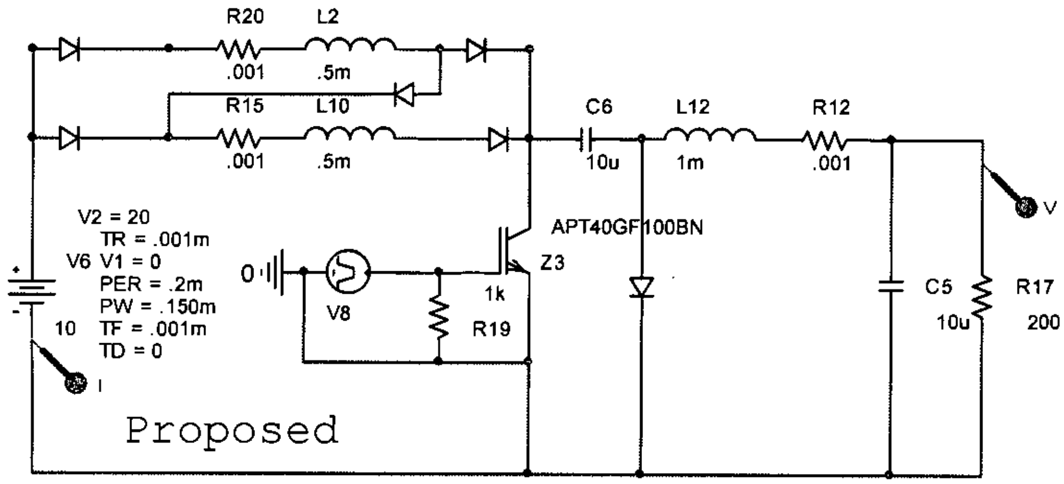


Figure- 2.35: High Gain ĈUK Hybrid Boost DC-DC Converter (proposed)

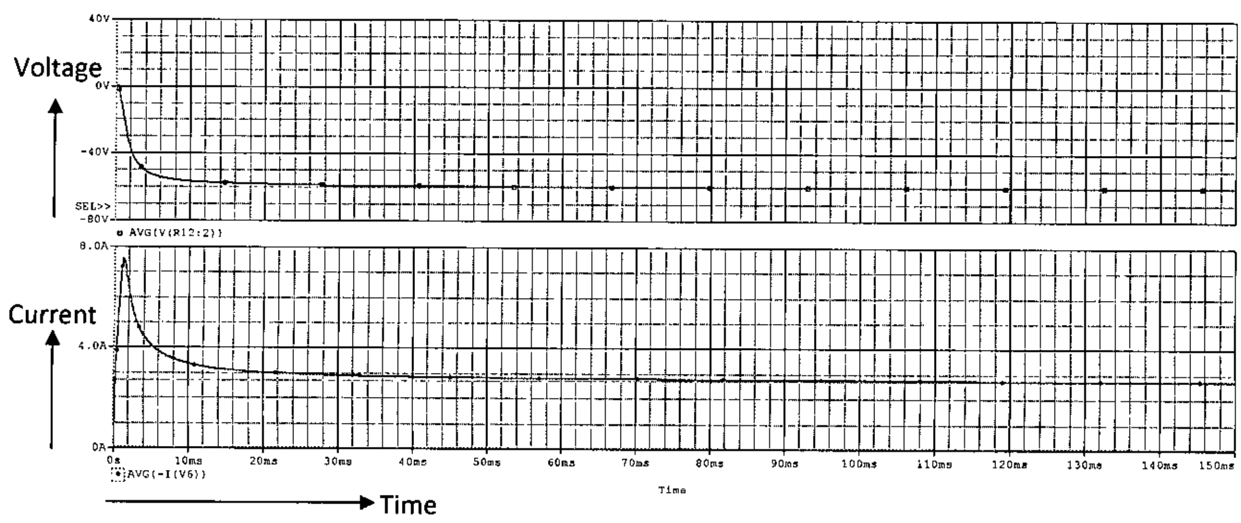


Figure- 2.36: Typical Waveforms of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.35

Table-2.7: Performance of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.35

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage gain**	**Efficiency in percentage**
0.125	10	0.134	15.34	0.0767	1.26	1.176578	1.534	87.9850
0.25	10	0.329	24.03	0.12015	3.29	2.887205	2.403	87.7569757
0.375	10	0.704	35.24	0.1762	7.04	6.209288	3.524	88.2001136
0.5	10	1.21	46.1	0.2305	12.1	10.62605	4.61	87.818595
0.625	10	1.92	56.26	0.2813	19.2	15.82594	5.626	82.4267604
0.75	10	2.77	63.96	0.3198	27.7	20.45441	6.396	73.8426282
0.875	10	7.34	91.85	0.45925	73.4	42.18211	9.185	57.4688181

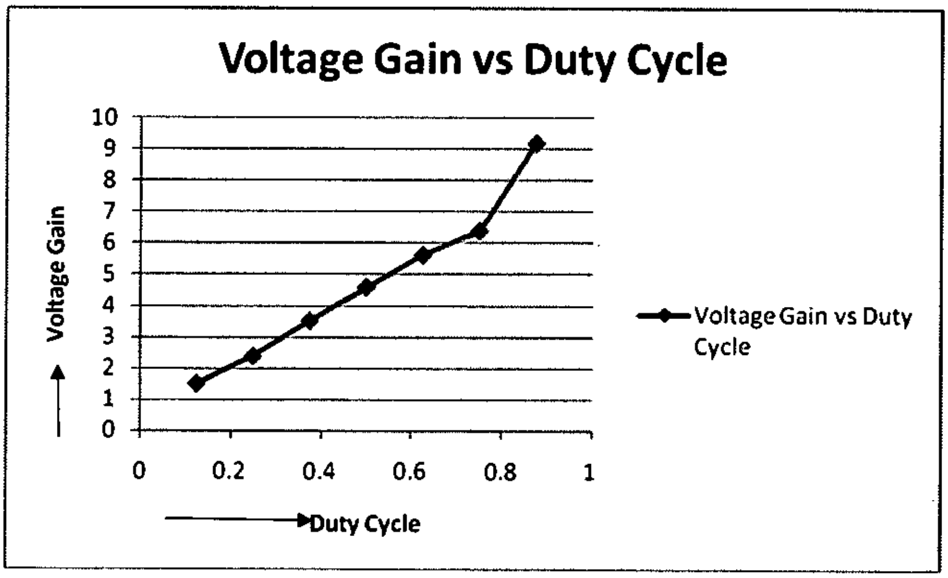


Figure-2.37: Voltage Gain vs Duty Cycle curve of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.35

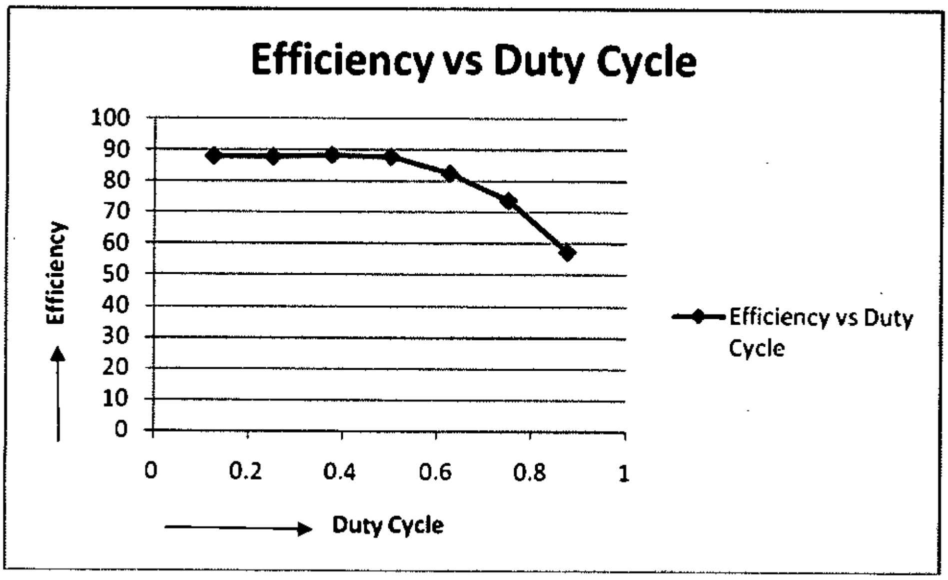


Figure- 2.38: Efficiency vs Duty Cycle curve of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.35

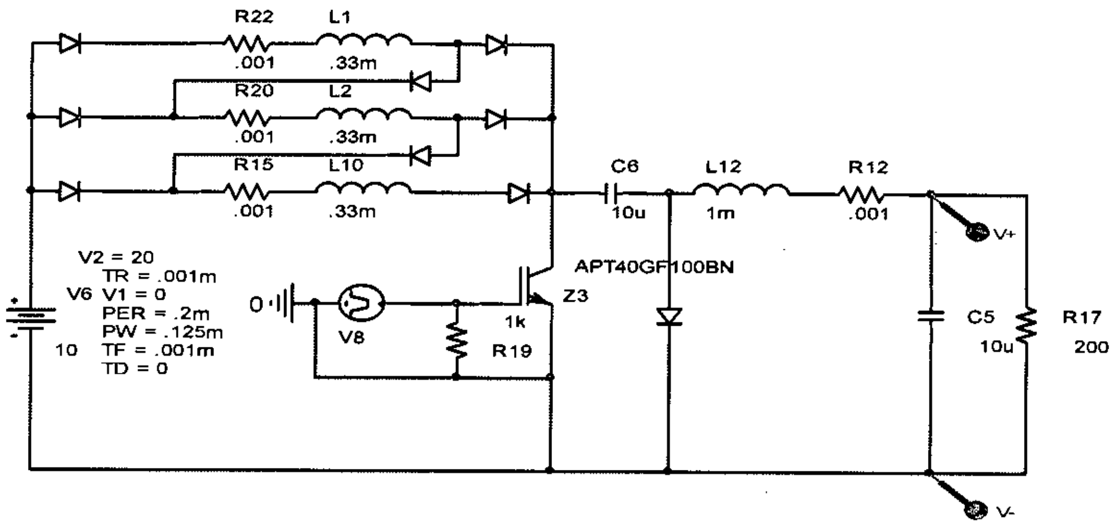


Figure- 2.39: High Gain ĈUK Hybrid Boost DC-DC Converter

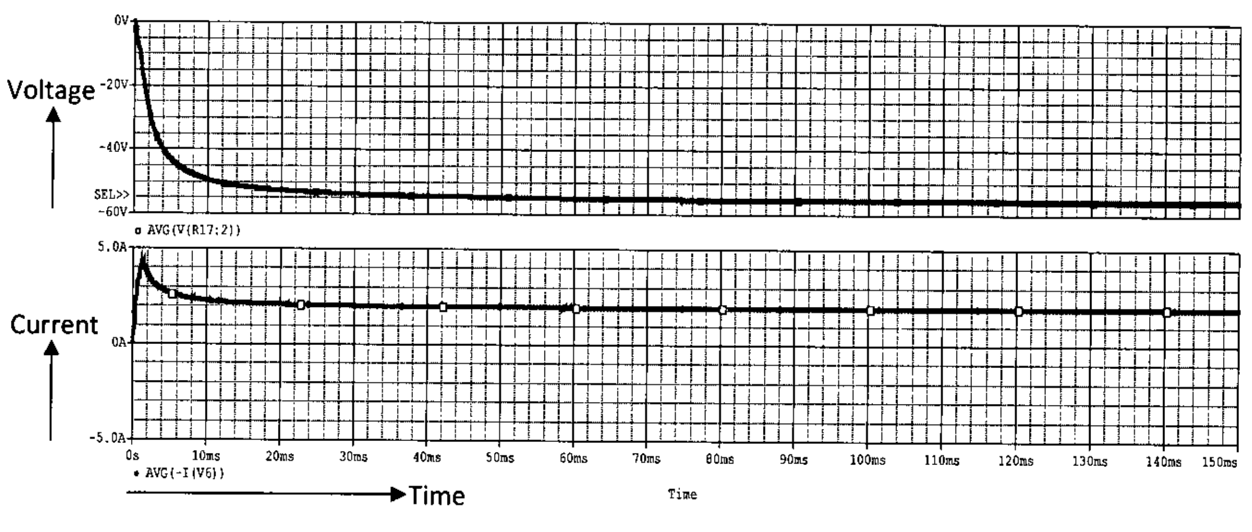


Figure- 2.40: Typical Waveforms of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.39

Table-2.8: Performance of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.39

Duty Cycle	Vin (V)	Iin (A)	Vout (V)	Iout (A)	Pin (W)	Pout (W)	Voltage Gain	Efficiency in percentage
0.125	10	0.0852	11.92	0.0596	0.852	0.710	1.19	83.3333
0.25	10	0.287	22.775	0.113875	2.87	2.5935031	2.27	90.36596254
0.375	10	0.633	33.96	0.1698	6.33	5.766408	3.39	91.09649289
0.5	10	1.1401	44.617	0.223085	11.401	9.9533834	4.46	87.30272296
0.625	10	1.8816	55.79	0.27895	18.816	15.562621	5.57	82.70950521
0.75	10	3.7297	70.679	0.353395	37.297	24.977605	7.06	66.96947531
0.875	10	14.195	120.885	0.604425	141.95	73.065916	12.08	51.4729948

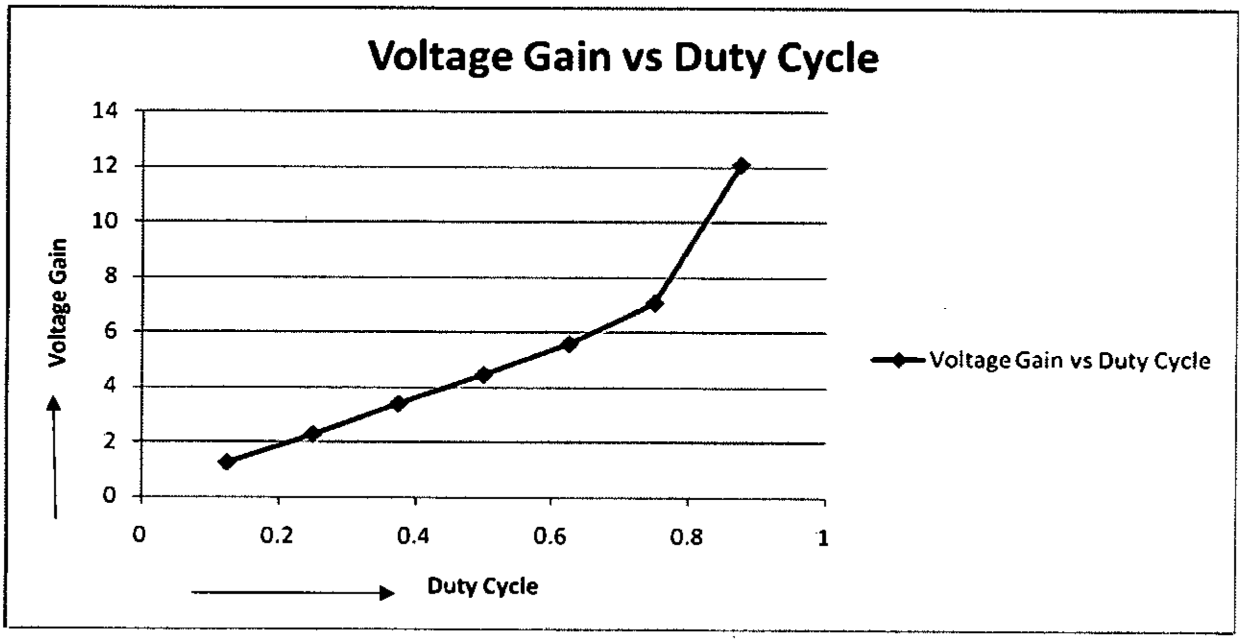


Figure- 2.41: Voltage Gain vs Duty Cycle curve of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.39

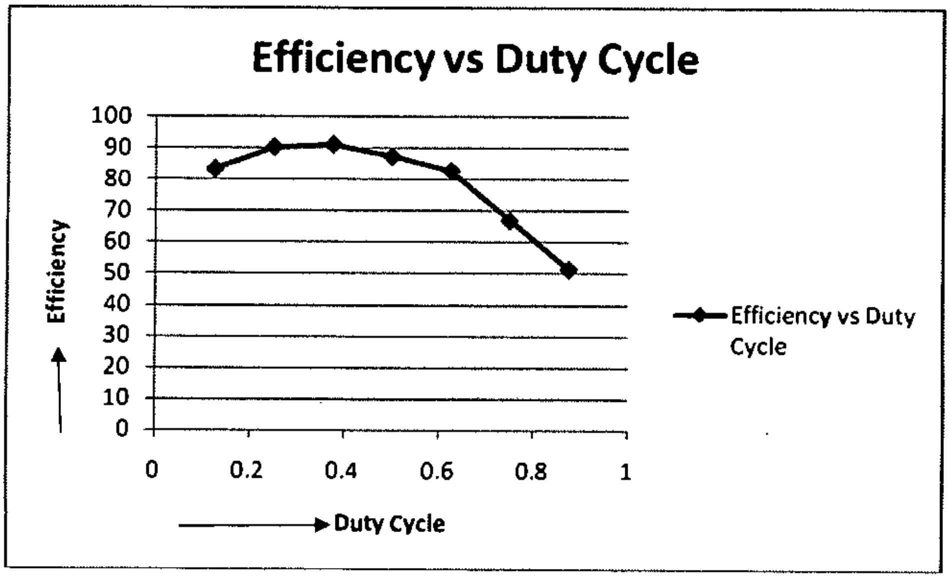


Figure-2.42: Efficiency vs Duty Cycle curve of High Gain ĈUK Hybrid Boost DC-DC Converter of Figure-2.39

2.5 SEPIC HYBRID CONVERTER WITH MULTIPLE INDUCTOR MULTIPLIER CELL

The SEPIC dc-dc convertor, the hybrid sepic [1] dc-dc converter with two inductors, the hybrid proposed sepic converter with two inductors and the proposed hybrid sepic dc-dc converter with three inductors are studied by simulation at variable duty cycles. The total inductors in all the circuits are kept at 1 mH for the purpose of comparison on the same component value. The conventional SEPIC circuit is shown in figure 2.43 and its typical waveforms are shown in figure 2.44. The SEPIC hybrid boost circuit of reference [I] is shown in figure 2.47 and its typical waveforms is shown in Figure 2.48. The proposed SEPIC hybrid circuit with two and three inductor cells are shown in Figures 2.51 and 2.55 respectively. Typical waveforms of Figures 2.51 and 2.55 are shown in Figures 2.52 and 2.56 respectively. The input voltage, output voltage, voltage gain, input power, output power and efficiency are tabulated in tables 2.9-2.12 and depicted in graphs of Figure 2.45 -2.46, Figure 2.49 -2.50, Figure 2.53 -2.54 and Figure 2.57 - 2.58 for circuits of Figure 2.43, Figure 2.47, Figure 2.51, Figure 2.55 respectively. Table 2.C compares the results of four configurations for voltage gain of 5.1 in the first row, which indicate that for 1mH total inductor the voltage gain 5.1 takes place at 0.8, 0.5, 0.6 and .4 duty cycle for normal SEPIC, hybrid SEPIC [1], proposed hybrid SEPIC of 2 inductors and proposed hybrid of 3 inductor circuit. The efficiency of the [1] SEPIC hybrid circuit is higher than normal, proposed hybrid circuit for two inductors and also for 3 inductor circuit.

Also in the second row of the table 2.B it is evident that voltage gain of the multiple inductors can be made higher than any other topology. The increase of inductor number keeping the total inductor value same is not possible in the hybrid circuit of the paper [1].

Table 2.C Comparison of Normal SEPIC, SEPIC Hybrid Topology of[1], Proposed SEPIC Hybrid Topology with Two Inductor, Proposed Topology with Three Inductor

Normal SEPIC			SEPIC Hybrid of [1] with 2 Inductor		
Duty cycle	Voltage Gain	Efficiency %	Duty cycle	Voltage Gain	Efficiency %
0.8	5.1	90	0.5	5.145	96.11
.875	6.4	79.78	.875	10.32	67.01

Table 2.C (Continued)

Sepic Hybrid of Proposed Topology with 2 Inductor			SEPIC Hybrid of Proposed Topology with 3 Inductor		
Duty cycle	Voltage Gain	Efficiency %	Duty cycle	Voltage Gain	Efficiency %
0.6	5.1	85	0.4	5.1	85
0.875	9.24	60.39	0.875	12.12	34.47

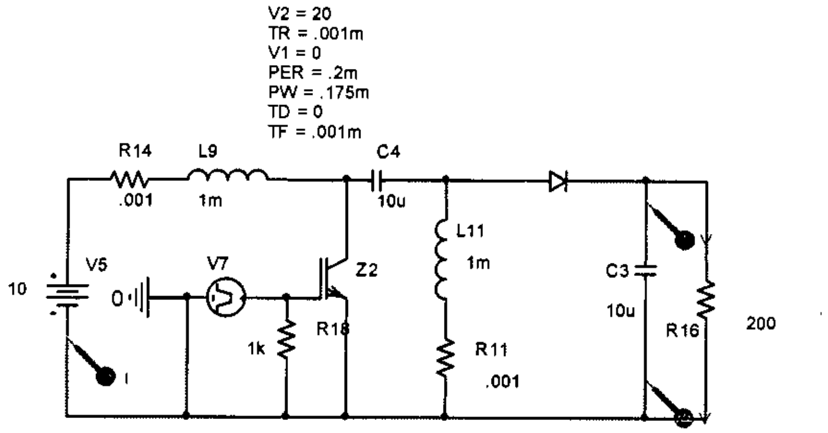


Figure-2.43 SEPIC DC-DC Converter

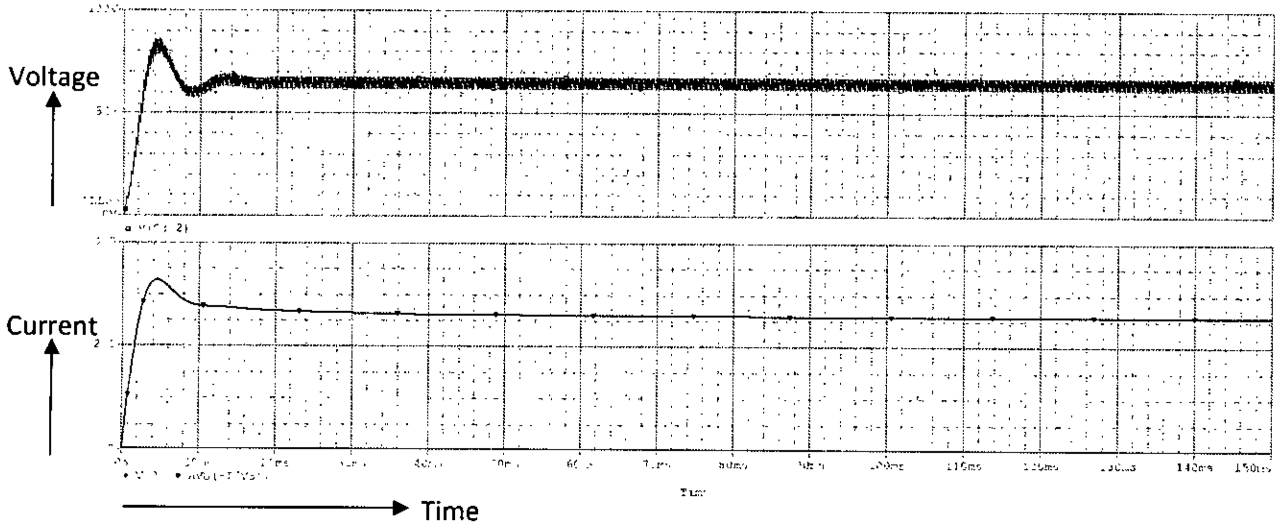


Figure-2.44: Typical Waveform Sepic DC-DC Converter of Figure-2.43

Table-2.9: Performance of Sepic DC-DC Converter Circuit of Figure-2.43

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage gain**	**Efficiency in percentage**
0.125	10	0.041	8.99	0.044	0.41	0.39	.899	95.12
0.25	10	0.155	17.17	0.087	1.55	1.52	1.71	98.06
0.375	10	0.294	23.50	0.117	2.94	2.74	2.35	93.19
0.50	10	0.522	31.17	0.155	5.22	4.83	3.11	92.52
0.625	10	0.821	39.53	0.197	8.21	7.51	3.95	91.47
0.75	10	1.21	46.78	0.233	12.10	10.89	4.678	90.00
0.875	10	2.577	64.25	0.321	25.77	20.56	6.425	79.78

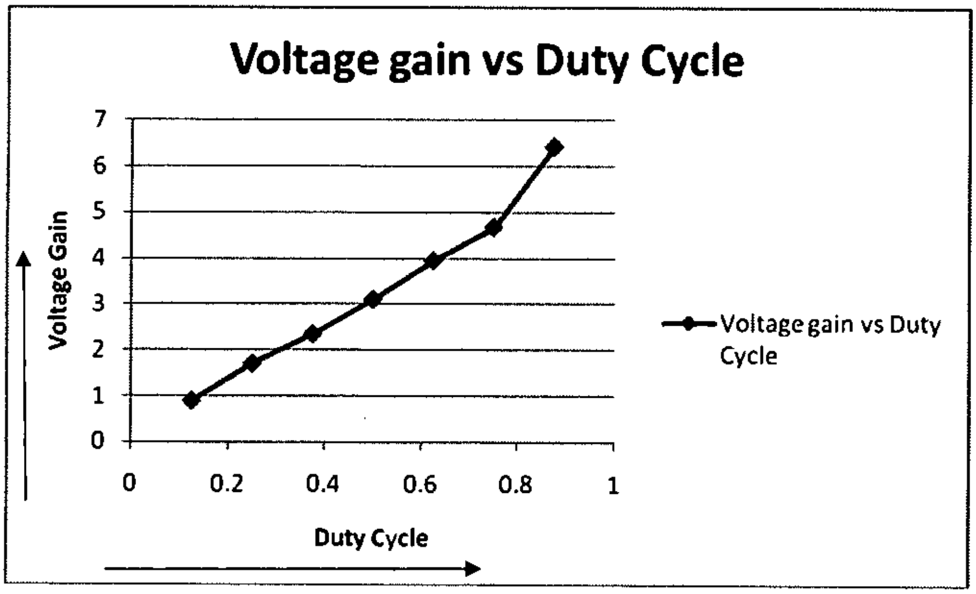


Figure-2.45: Voltage Gain vs Duty Cycle curve of Sepic DC-DC Converter of Figure-2.43

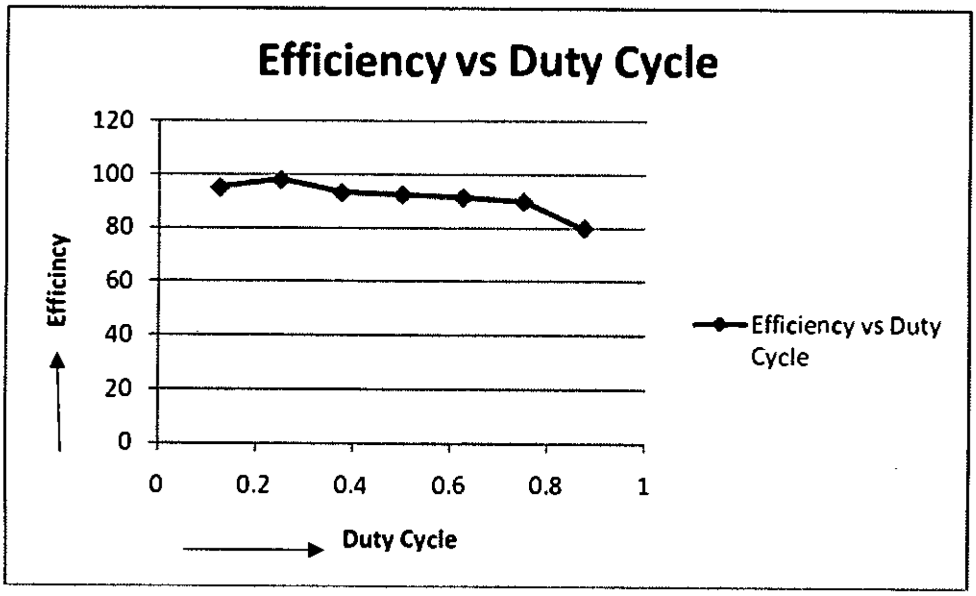


Figure-2.46: Efficiency vs Duty Cycle curve of Sepic DC-DC Converter of Figure-2.43

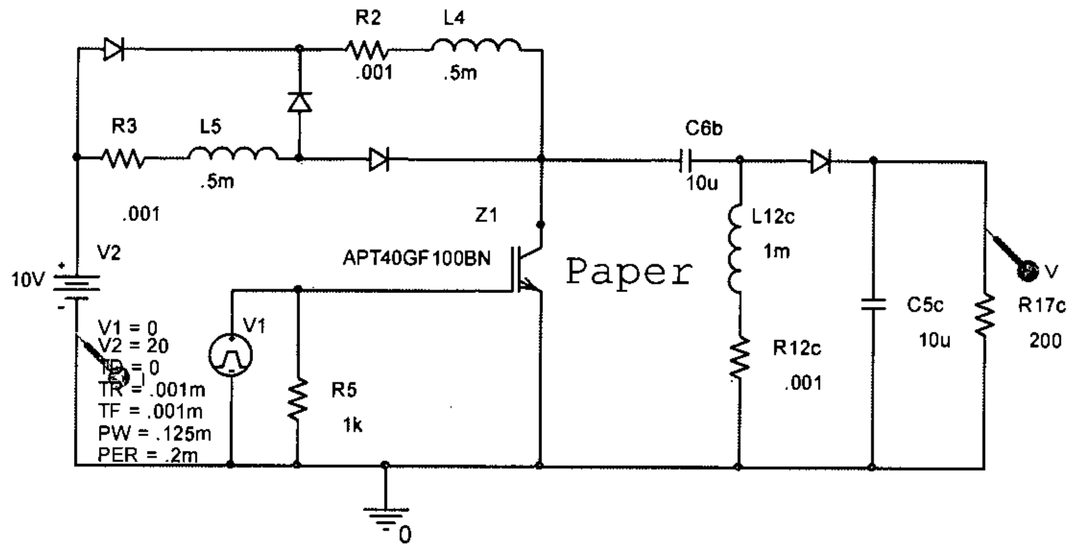


Figure-2.47 SEPIC Hybrid DC-DC Converter [1]

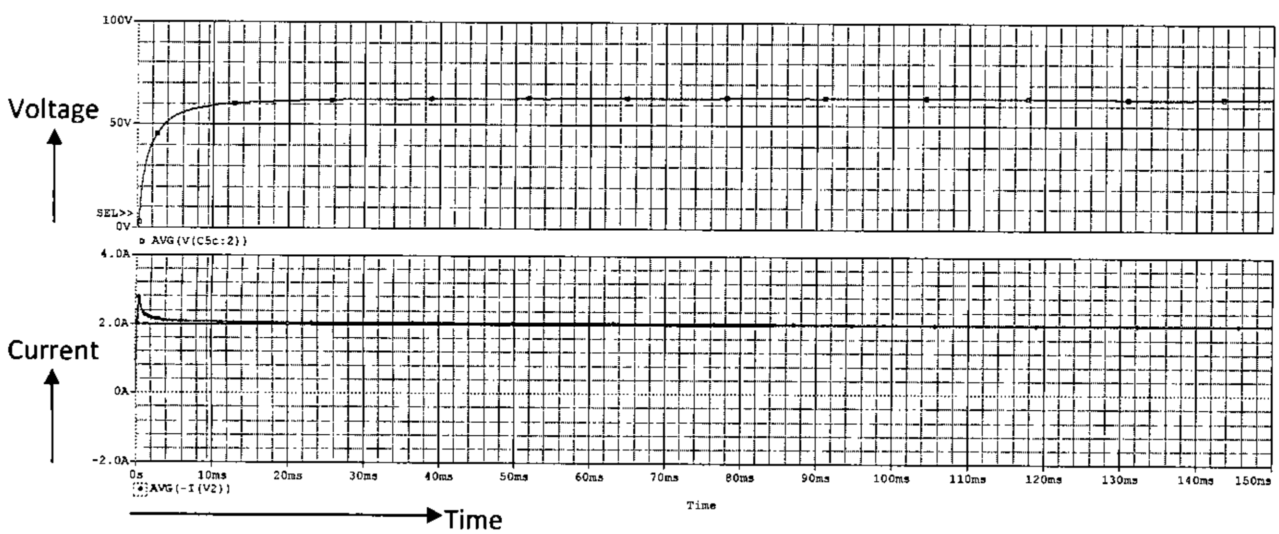


Figure-2.48: Typical Waveform Sepic Hybrid DC-DC Converter of Figure-2.47 [1]

Table-2.10: Performance of Sepic Hybrid DC-DC Converter of Figure-2.47 [1]

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage gain**	**Efficiency in percentage**
0.125	10	0.14	16.08	0.0804	1.4	1.292832	1.608	92.3451429
0.25	10	0.383	27.09	0.13545	3.83	3.669341	2.709	95.805235
0.375	10	0.791	39.6	0.198	7.91	7.8408	3.96	99.125158
0.5	10	1.377	51.45	0.25725	13.77	13.23551	5.145	96.1184641
0.625	10	2.06	62.8	0.314	20.6	19.7192	6.28	95.7242718
0.75	10	2.98	72.33	0.36165	29.8	26.15814	7.233	87.7790084
0.875	10	7.95	103.227	0.516135	79.5	53.27907	10.3227	67.0176952

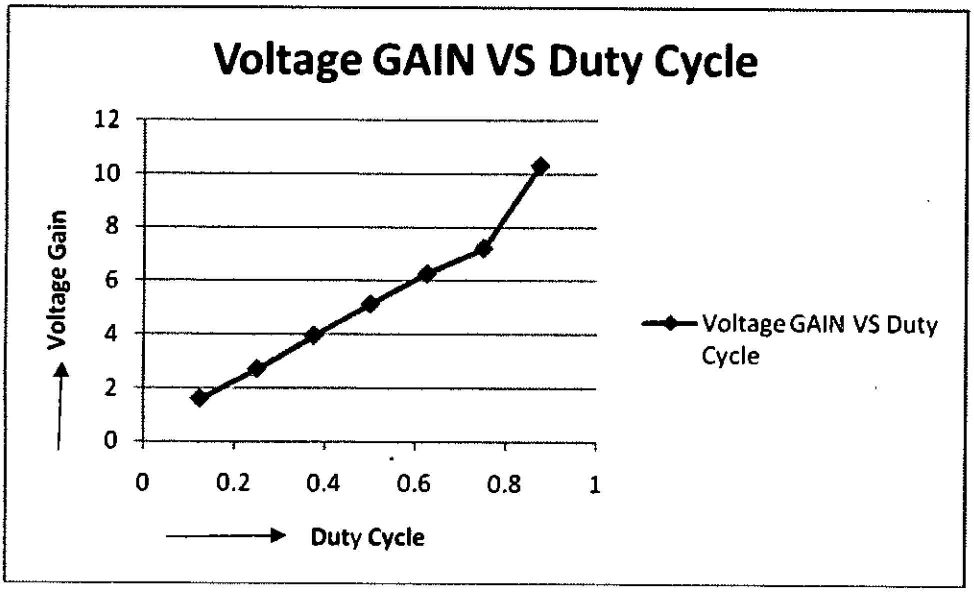


Figure-2.49: Voltage Gain vs Duty Cycle curve of Hybrid Sepic DC-DC Converter of Figure-2.47 [ ]

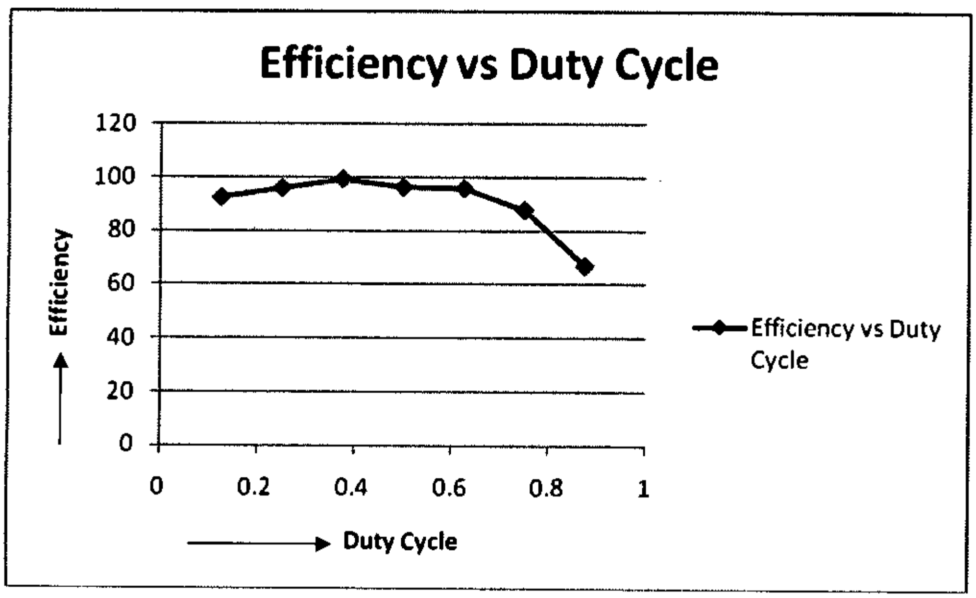


Figure-2.50: Efficiency vs Duty Cycle curve of Hybrid Sepic DC-DC Converter of Figure-2.47

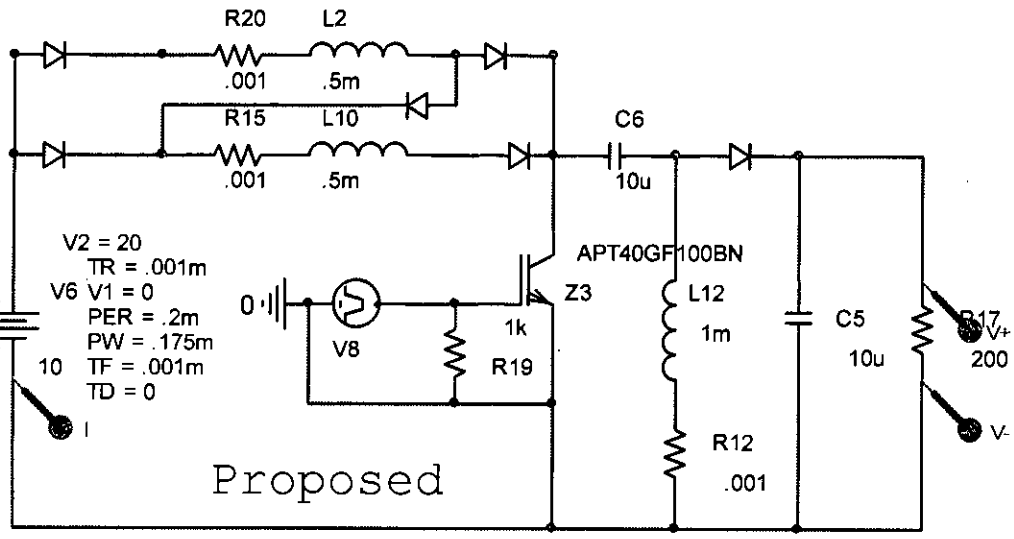


Figure-2.51: SEPIC Hybrid DC-DC Converter (proposed)

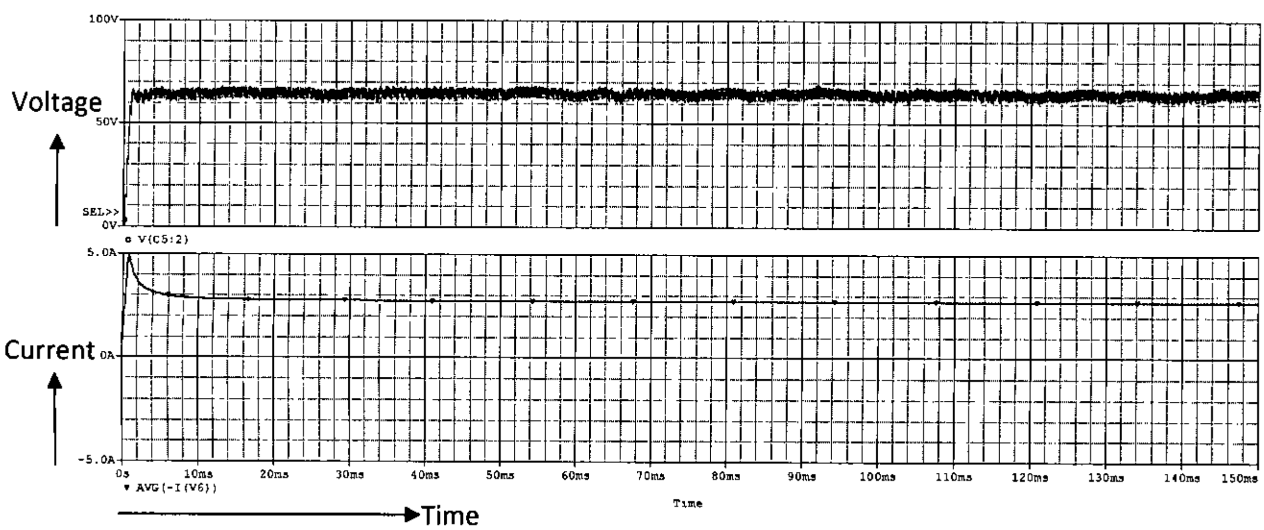


Figure-2.52: Typical Waveform SEPIC Hybrid DC-DC Converter of Figure-2.51

Table-2.11: Performance of Sepic Hybrid DC-DC Converter of Figure-2.51

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage gain**	**Efficiency in percentage**
0.125	10	0.109	14.04	0.0702	1.02	0.985608	1.404	90.4282353
0.25	10	0.317	22.96	0.1148	3.17	2.635808	2.296	83.1485174
0.375	10	0.699	35.29	0.17645	6.99	6.226921	3.529	89.083269
0.5	10	1.18	45.15	0.22575	11.8	10.19261	4.515	86.378072
0.625	10	1.86	56.13	0.28065	18.6	15.75288	5.613	84.6929274
0.75	10	2.84	64.14	0.3207	28.4	20.5697	6.414	72.4285141
0.875	10	7.08	92.48	0.4624	70.8	42.76275	9.248	60.3993672

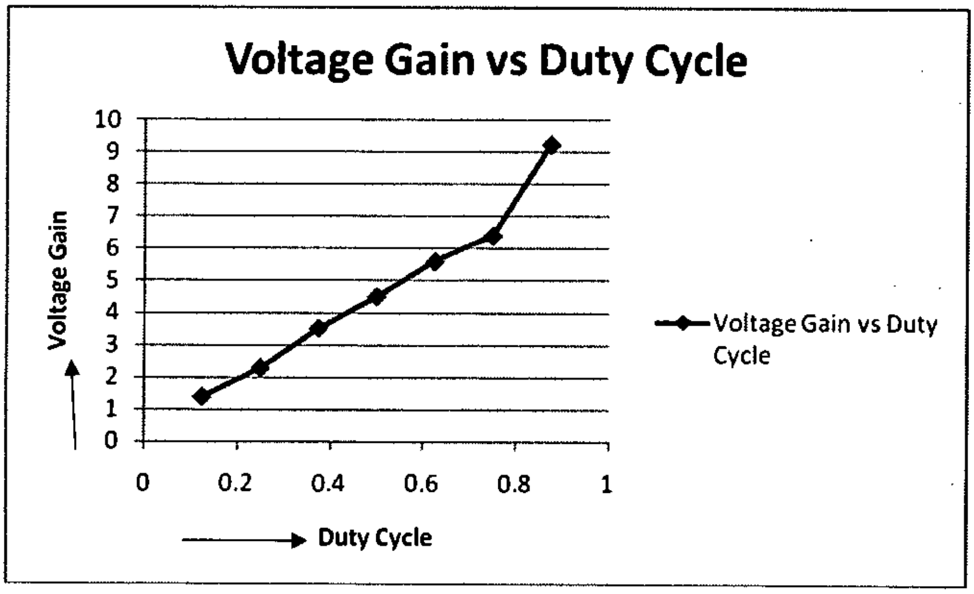


Figure-2.53: Voltage Gain vs Duty Cycle curve of Hybrid Sepic DC-DC Converter of Figure-2.51

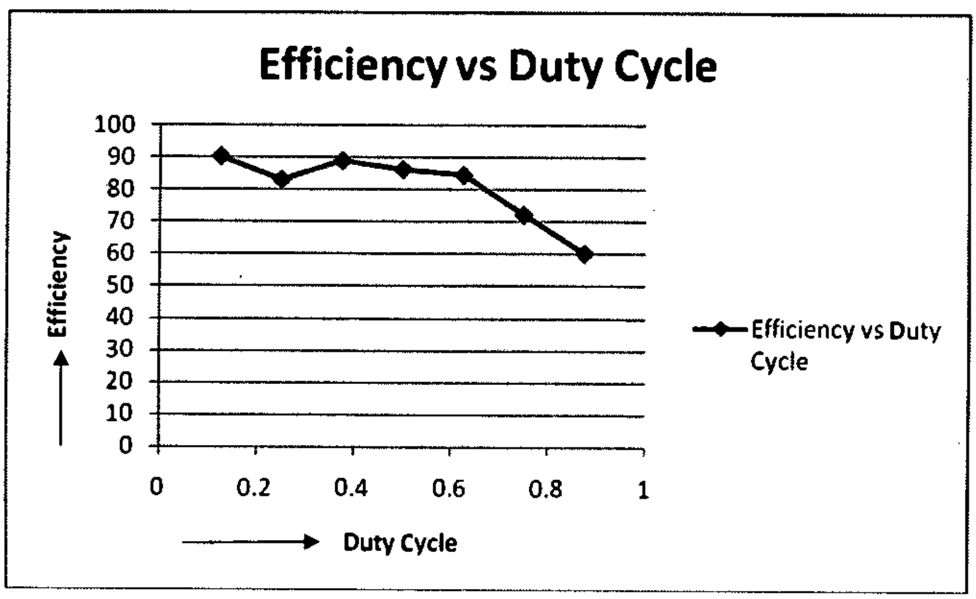


Figure-2.54: Efficiency vs Duty Cycle curve of Hybrid Sepic DC-DC Converter of Figure-2.51

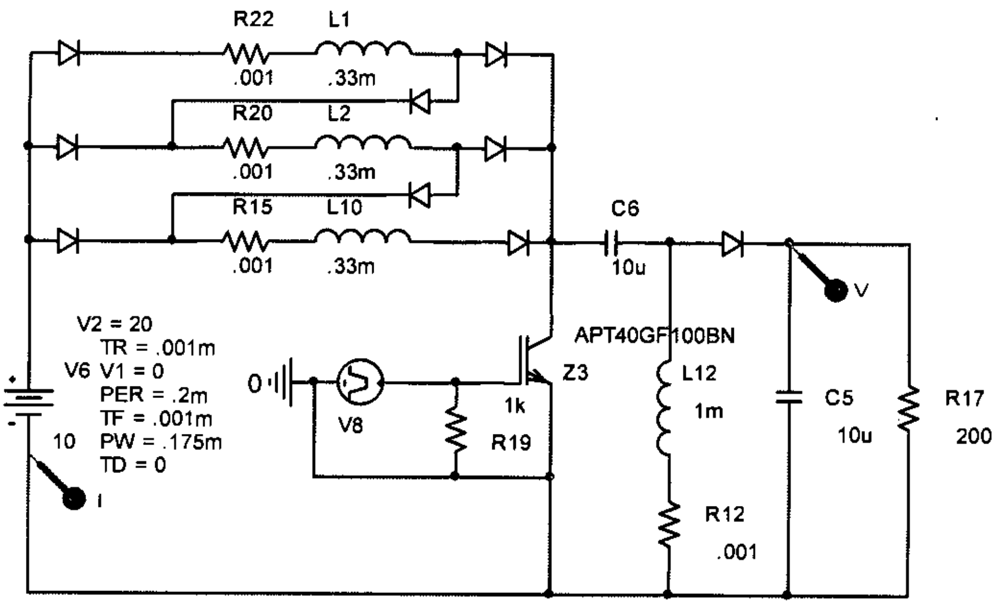


Figure-2.55: SEPIC Hybrid DC-DC Converter

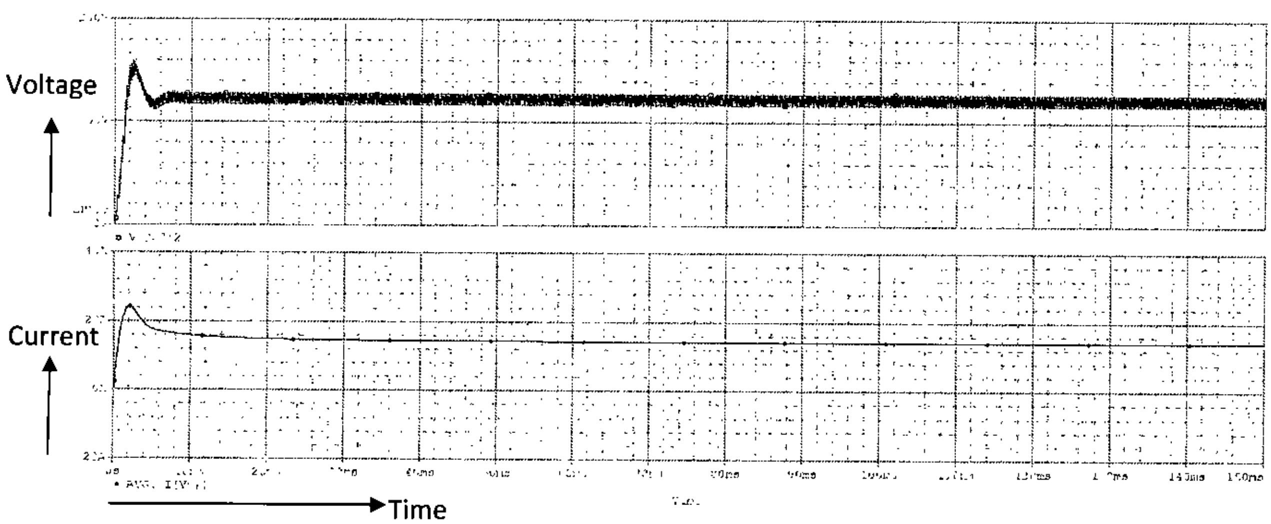


Figure-2.56: Typical Wave from Sepic Hybrid DC-DC Converter of Figure-2.55

Table-2.12: Performance of Sepic Hybrid DC-DC Converter of Figure-2.55

Duty Cycle	Vin (V)	Iin (A)	Vout (V)	Iout (A)	Pin (W)	Pout (W)	Voltage gain	Efficiency in percentage
0.125	10	0.244	19.30	0.096	2.44	1.85	1.930	75.81
0.25	10	0.680	31.50	0.157	6.80	4.94	3.150	80.45
0.375	10	1.33	48.44	0.242	13.30	11.72	4.844	88.12
0.50	10	2.344	61.06	0.305	23.44	18.62	6.106	79.43
0.625	10	3.733	74.27	0.371	7.33	27.55	7.427	73.80
0.75	10	6.955	85.84	0.429	69.55	36.82	8.584	52.94
0.875	10	20.707	121.22	0.606	207.07	73.45	12.122	34.47

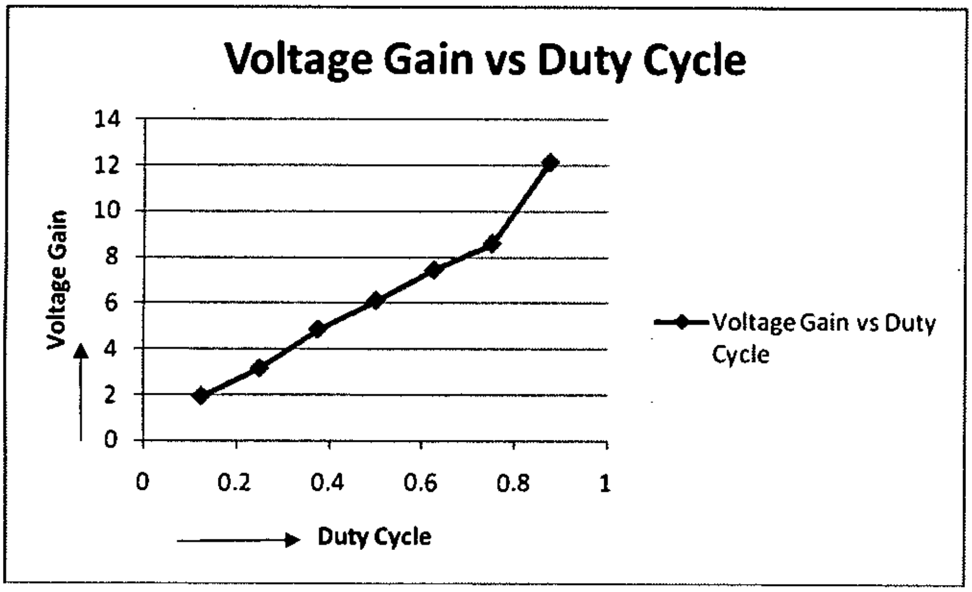


Figure-2.57: Voltage Gain vs Duty Cycle curve of Hybrid SEPIC DC-DC Converter of Figure-2.55

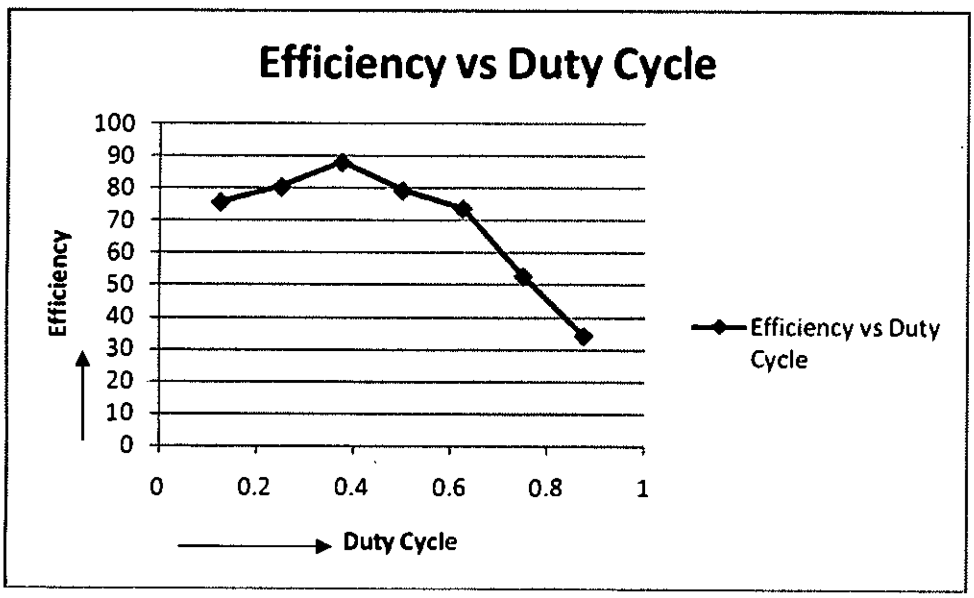


Figure-2.58: Efficiency vs Duty Cycle curve of Hybrid Sepic DC-DC Converter of Figure-2.55

2.6 BUCK BOOST HYBRID CONVERTERWITH MULTIPLE INDUCTOR MULTIPLIER CELL

The buck boost, the hybrid buck boost dc-dc converter with two inductors [1], the hybrid proposed buck boost converter with two inductors and the proposed hybrid buck boost dc-dc converter with three inductors are studied by simulation at variable duty cycles. The total inductors in all the circuits are kept at 1 mH for the purpose of comparison on the same component value. The conventional Buck Boost circuit is shown in figure 2.59 and its typical waveforms are shown in figure 2.60. The hybrid Buck boost circuit of reference [1] is shown in figure 2.63 and its typical waveforms is shown in Figure 2.64. The proposed Buck Boost hybrid circuit with two and three inductor cells is shown in Figures 2.67 and 2.71 respectively. Typical waveforms of Figures 2.67 and 2.71 are shown in Figures 2.68 and 2.72 respectively. The input voltage, output voltage, voltage gain, input power, output power and efficiency are tabulated in tables 2.13-2.16 and depicted in graphs of Figure 2.61 -2.62, Figure 2.65-2.66, Figure 2.69-2.70 and Figure 2.73-2.74 for circuits of Figure 2.59, Figure 2.63, Figure 2.67, Figure 2.71 respectively. Table 2.D compares the results of four configurations for voltage gain of 4.9 in the first row, which indicate that for 1mH total inductor the voltage gain 4.9 takes place at 0.8, 0.75, 0.76 and 0.5 duty cycle for normal, hybrid buck boost of paper, proposed hybrid buck boost of 2 inductors and proposed hybrid of 3 inductor circuit. The efficiency of all three are worse than the normal buck boost circuit.

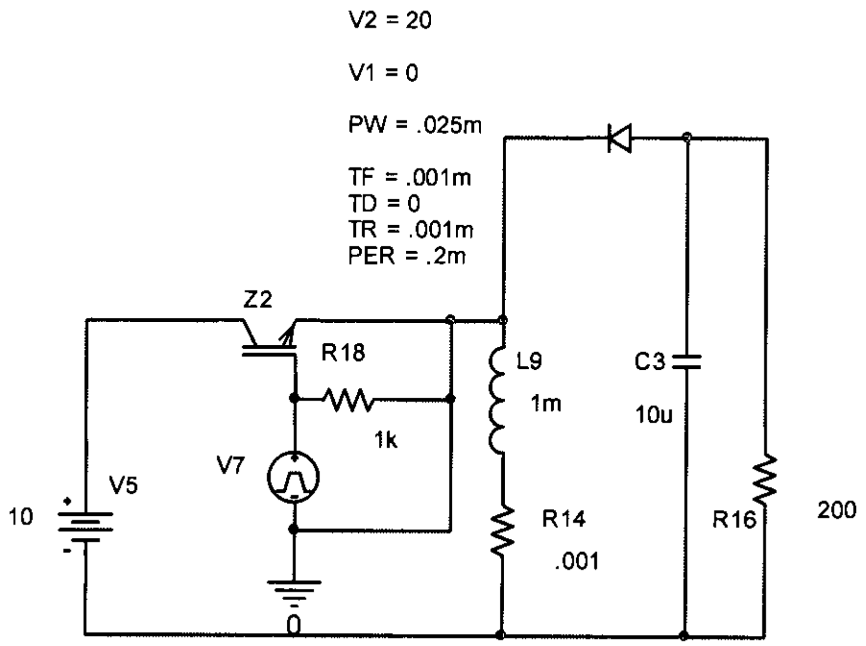
The second row of the table 2.D it is evident that voltage gain of the multiple inductors can be made higher than any other topology. The increase of inductor number keeping the total inductor value same is not possible in the hybrid circuit of the paper [1].

Table 2.D Comparison of Normal Buck Boost, Buck Boost Hybrid Topology of [1], Proposed Buck Boost Topology with Two inductor, Proposed Topology with Three Inductor

Normal Buck Boost			Hybrid Buck Boost of [1] with two Inductor		
Duty cycle	Voltage Gain	Efficiency %	Duty cycle	Voltage Gain	Efficiency %
0.8	4.9	84	0.75	4.9	60
0.875	6.2	77	0.875	10.01	59

Table 2.D (Continued)

Hybrid Buck Boost of Proposed Topology with 2 Inductor			Hybrid Buck Boost of Proposed Topology with 3 Inductor		
Duty cycle	Voltage Gain	Efficiency %	Duty cycle	Voltage Gain	Efficiency %
0.76	4.9	53	0.5	4.9	31
0.875	8.9	53	0.875	11.73	44



Normal

Figure- 2.59: High Gain Buck Boost DC-DC Converter

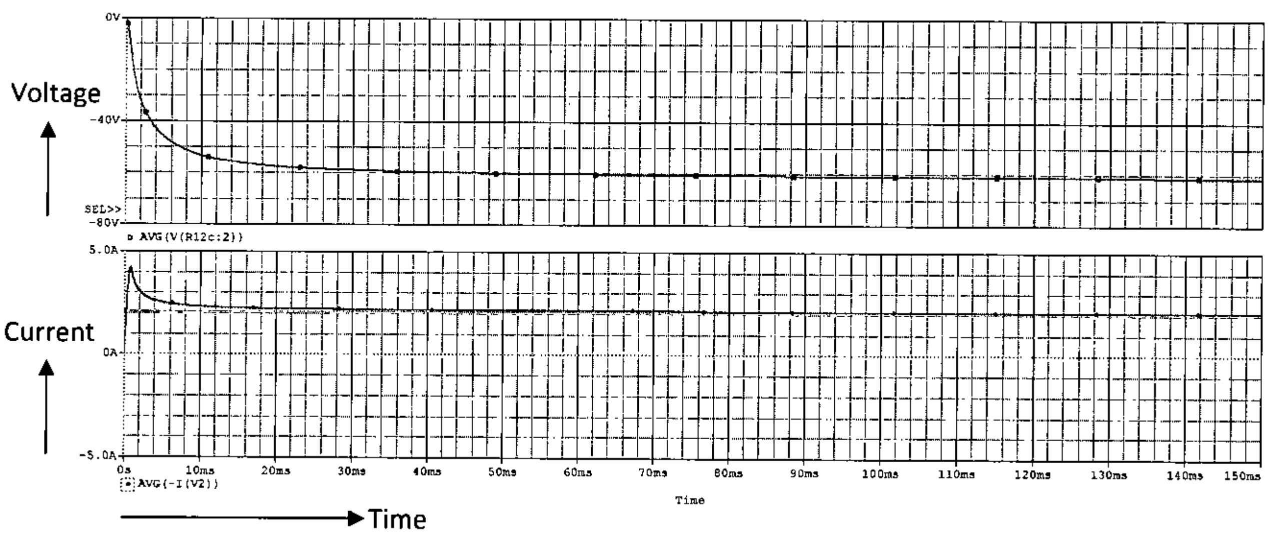


Figure-2.60: Typical Waveform of High Gain Buck Boost DC-DC Converter of Figure-2.59

Table-2.13: Performance of High Gain Buck Boost DC-DC Converter of Figure-2.59

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage Gain**	**Efficiency in percentage**
0.125	10	0.0187	5.84	0.0292	0.187	0.170528	0.0584	91.191
0.25	10	0.0734	12.01	0.0600	0.734	0.7206	1.201	98.174
0.375	10	0.152	17.22	0.0861	1.52	1.4826	1.722	97.54
0.5	10	0.286	22.13	0.11065	2.86	2.448	2.21	85.559
0.625	10	0..412	26.57	0.13285	4.12	3.529	2.65	85.56
0.75	10	0.578	31.193	0.1559	5.78	4.86	3.11	84.169
0.875	10	2.5193	62.611	0.3130	25.193	19.60	6.26	77.802

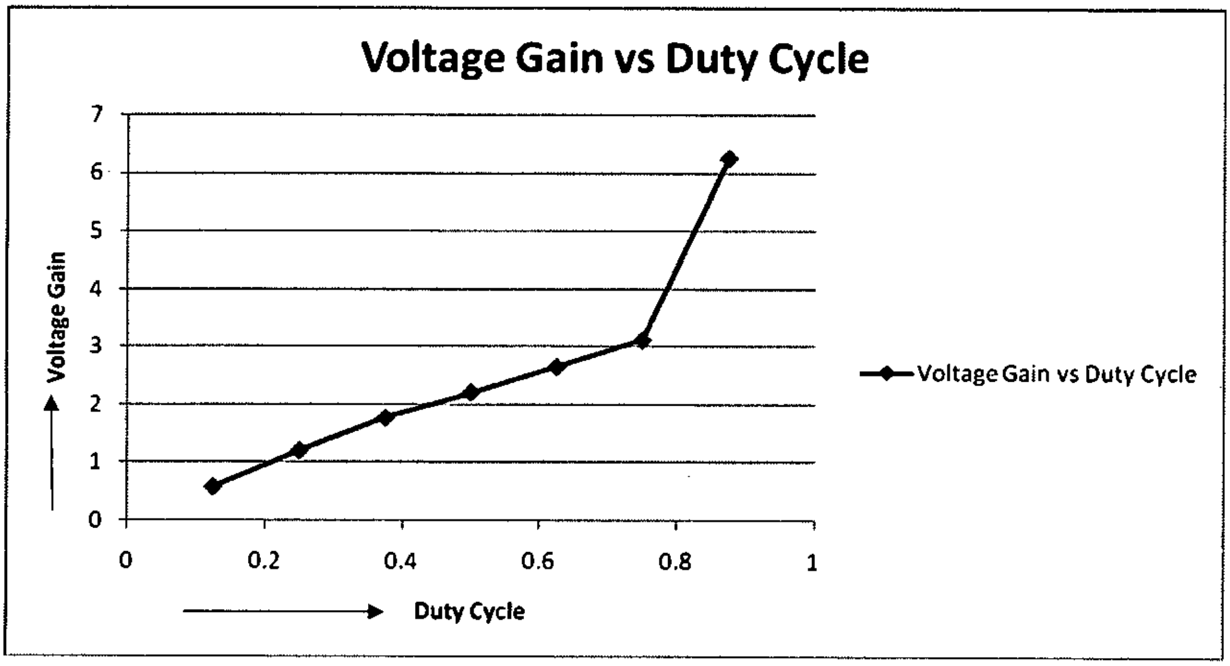


Figure- 2.61: Voltage Gain vs Duty Cycle curve of Buck Boost DC-DC Converter of Figure-2.59

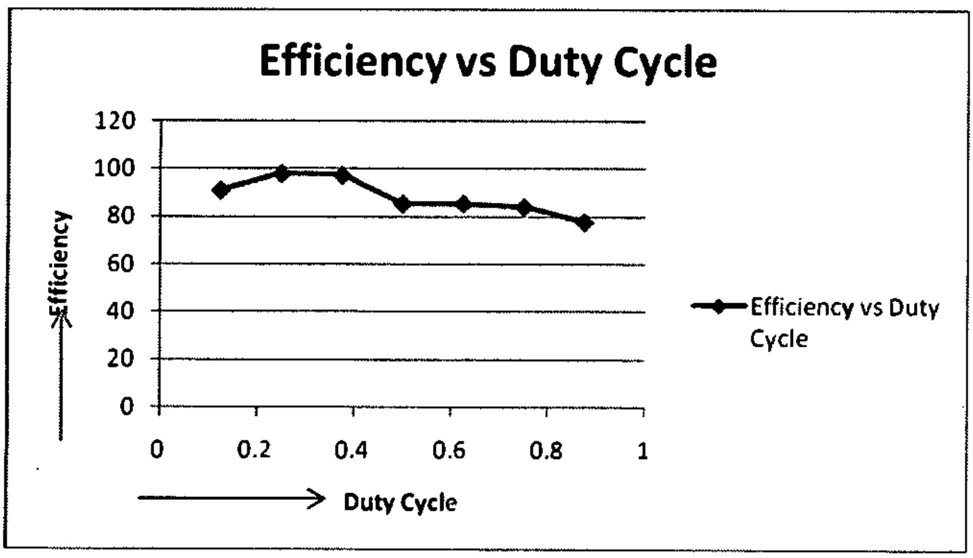


Figure- 2.62: Efficiency vs Duty Cycle curve of High Gain Buck Boost DC-DC Converter of Figure-2.59

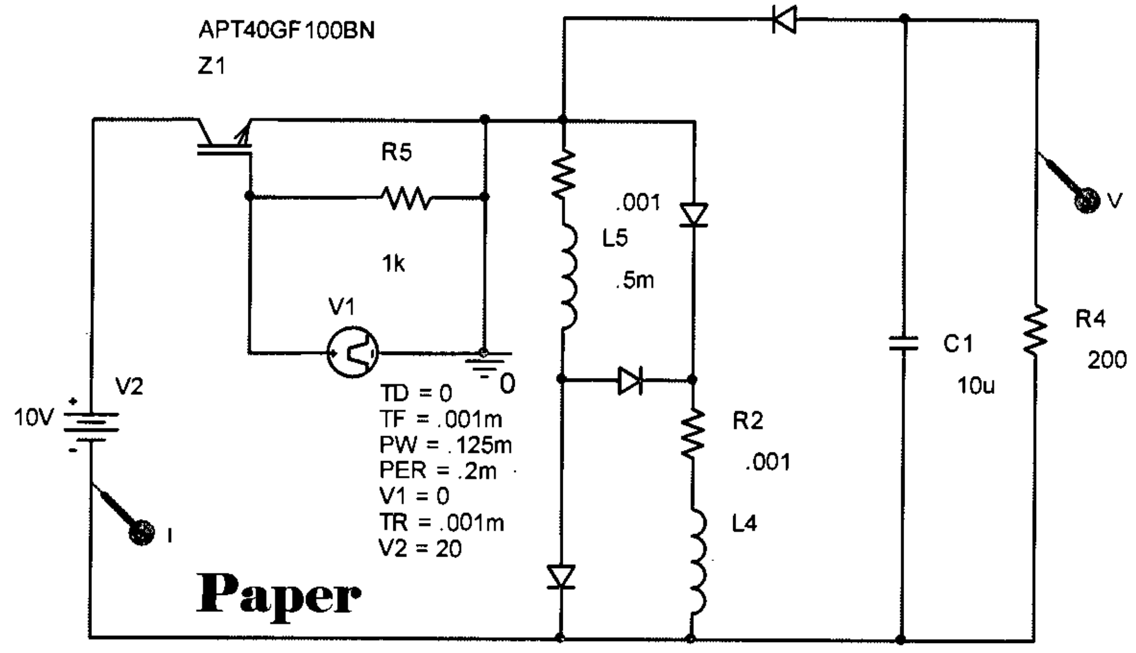


Figure- 2.63: Buck Boost Hybrid DC-DC Converter [1]

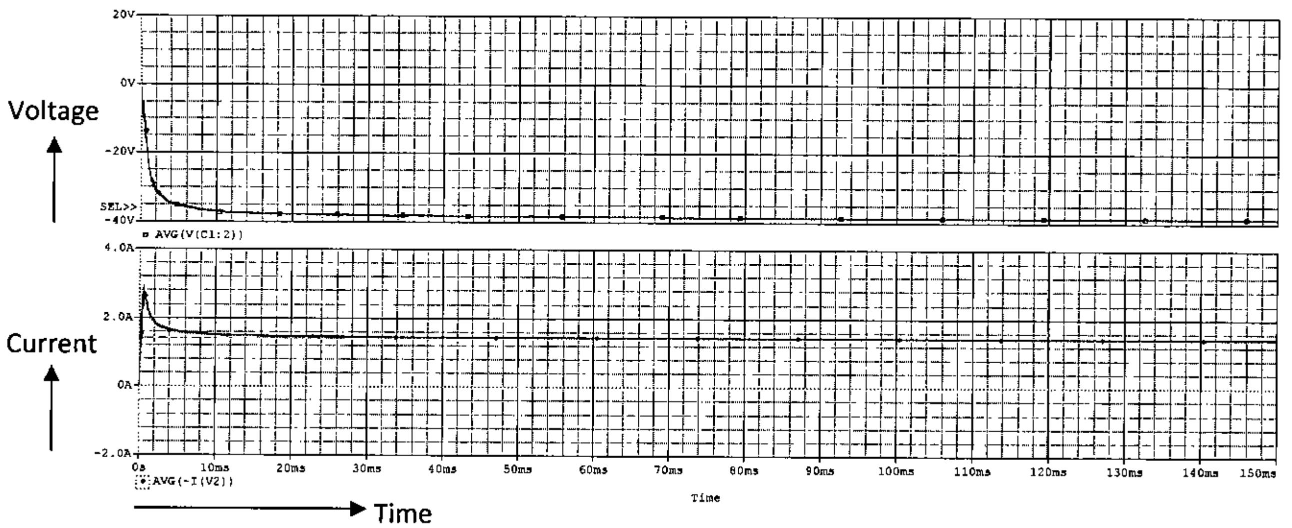


Figure-2.64: Typical Waveforms of High Gain Buck Boost DC-DC Converter of Figure- 2.63 [1]

Table-2.14: Performance of High Gain Hybrid Buck Boost DC-DC Converter of Figure-2.63 [1]

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage gain**	**Efficiency in percentage**
0.125	10	0.063	3.09	0.01545	0.63	0.047741	0.309	7.57785714
0.25	10	0.253	11.09	0.05545	2.53	0.614941	1.109	24.3059486
0.375	10	0.525	19.89	0.09945	5.25	1.978061	1.989	37.6773429
0.5	10	0.912	29.71	0.14855	9.12	4.413421	2.971	48.3927686
0.625	10	1.39	38.59	0.19295	13.9	7.445941	3.859	53.5679173
0.75	10	2.01	49.39	0.24695	20.1	12.19686	4.939	60.680898
0.875	10	8.45	100.16	0.5008	84.5	50.16013	10.016	59.3610982

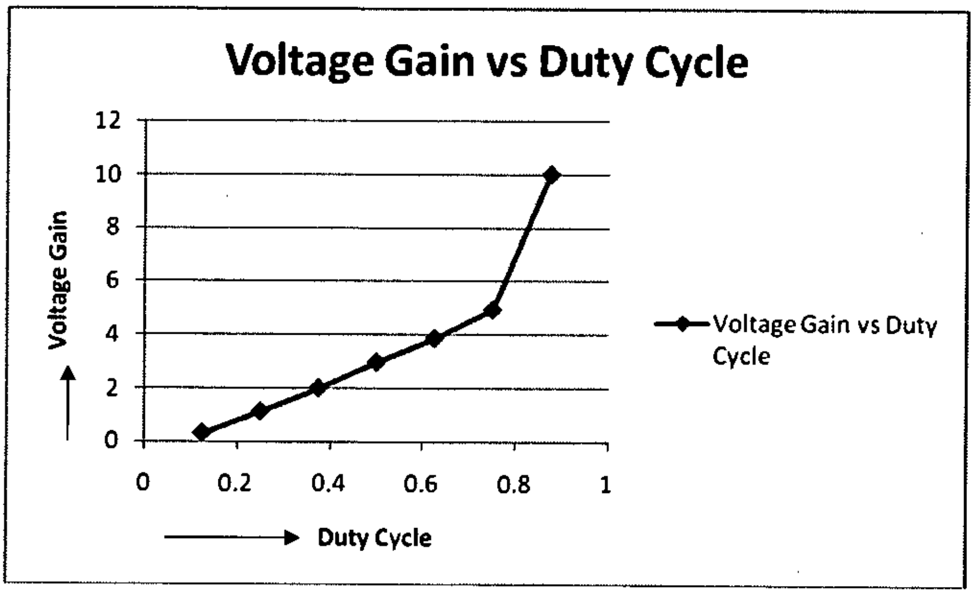


Figure-2.65: Voltage Gain vs Duty Cycle curve of Buck Boost DC-DC Converter of Figure-2.63 [1]

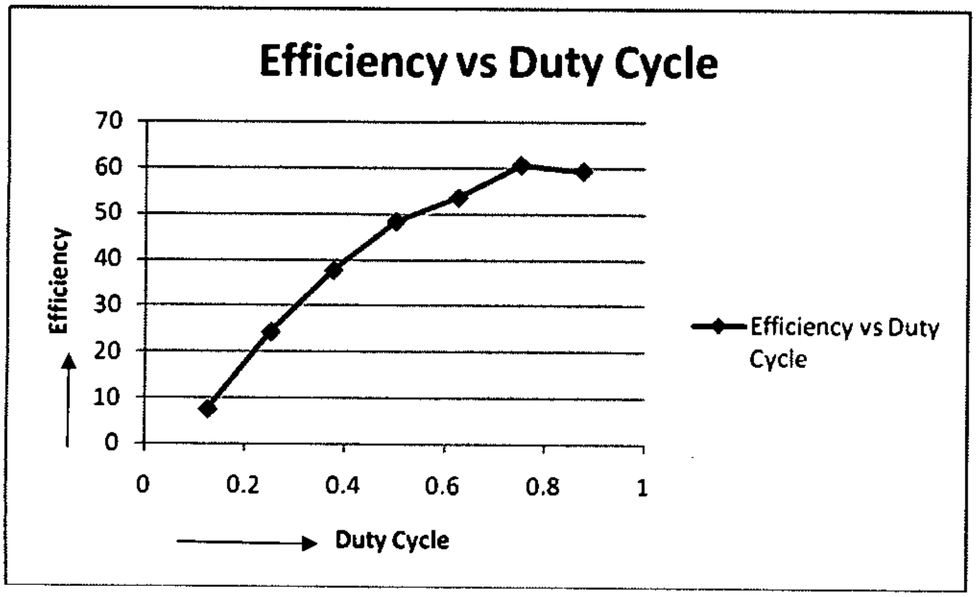


Figure-2.66: Efficiency vs Duty Cycle curve of Hybrid Buck-Boost DC-DC Converter of Figure-2.63 [1]

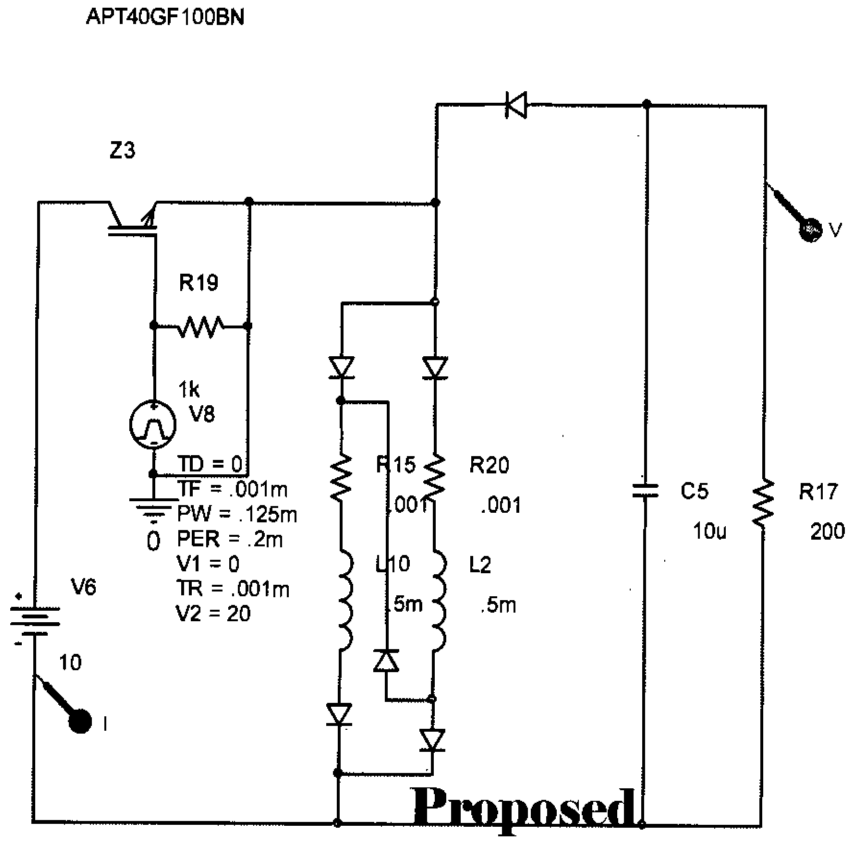


Figure- 2.67: Buck Boost Hybrid DC-DC Converter (proposed)

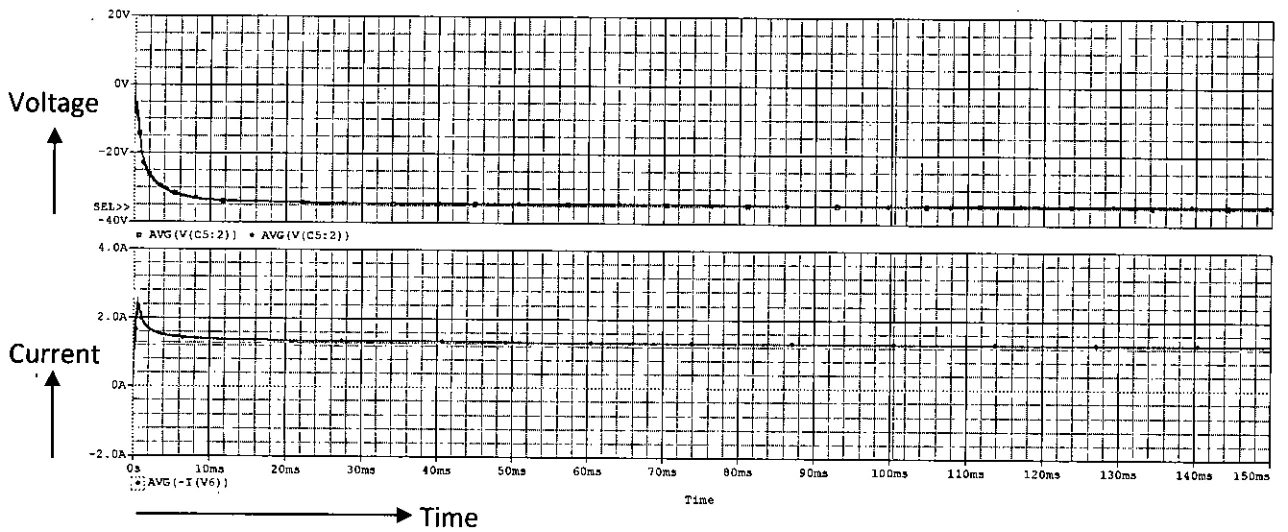


Figure- 2.68: Typical Waveforms of High Gain Hybrid Buck Boost DC-DC Converter of Figure- 2.67

Table-2.15: Performance of High Gain Hybrid Buck Boost DC-DC Converter of Figure-2.67

Duty Cycle	Vin (V)	Iin (A)	Vout (V)	Iout (A)	Pin (W)	Pout (W)	Voltage gain	Efficiency in percentage
0.125	10	0.062	3.57	0.01785	0.62	0.063725	0.357	10.2781452
0.25	10	0.235	7.74	0.0387	2.35	0.299538	0.774	12.7462979
0.375	10	0.49	16.07	0.08035	4.9	1.291225	1.607	26.3515204
0.5	10	0.862	25.34	0.1267	8.62	3.210578	2.534	37.2456845
0.625	10	1.3	34.83	0.17415	13	6.065645	3.483	46.6588038
0.75	10	1.93	45.26	0.2263	19.3	10.24234	4.526	53.0691088
0.875	10	7.5	89.47	0.44735	75	40.0244	8.947	53.3658727

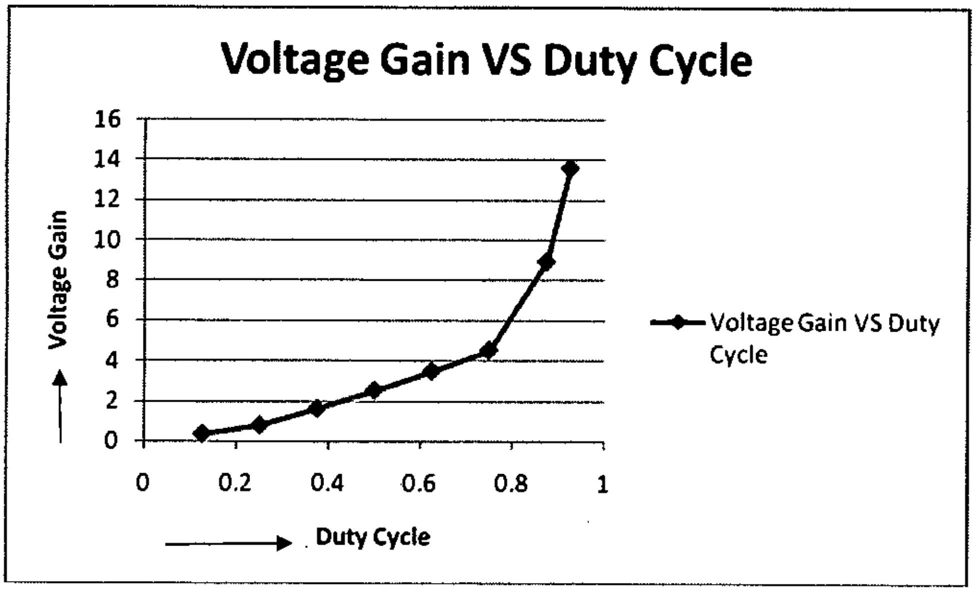


Figure- 2.69: Voltage Gain vs Duty Cycle curve of Buck Boost DC-DC Converter of Figure-2.67

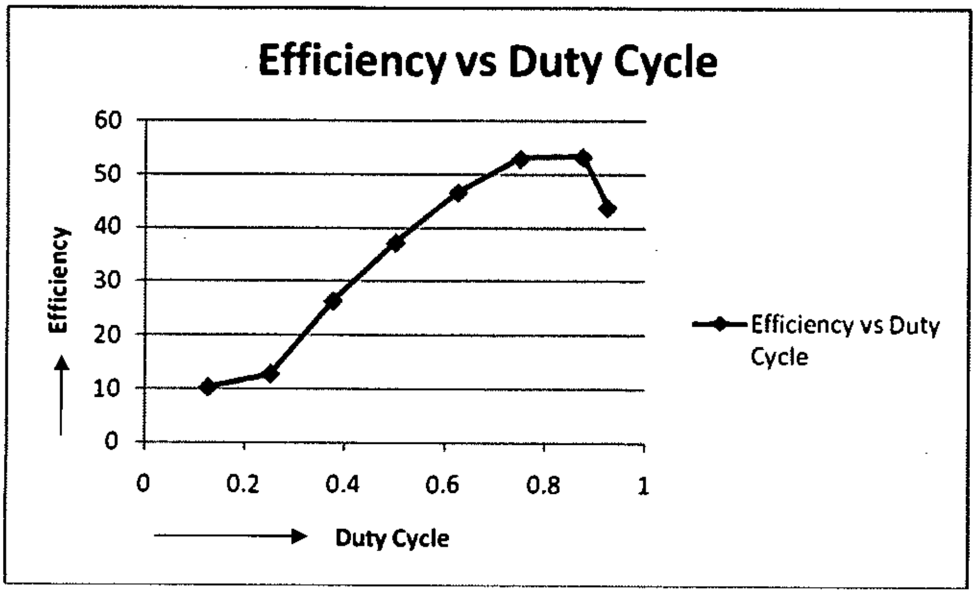


Figure- 2.70: Efficiency vs Duty Cycle curve of High Gain Buck Boost DC-DC Converter of Figure-2.67

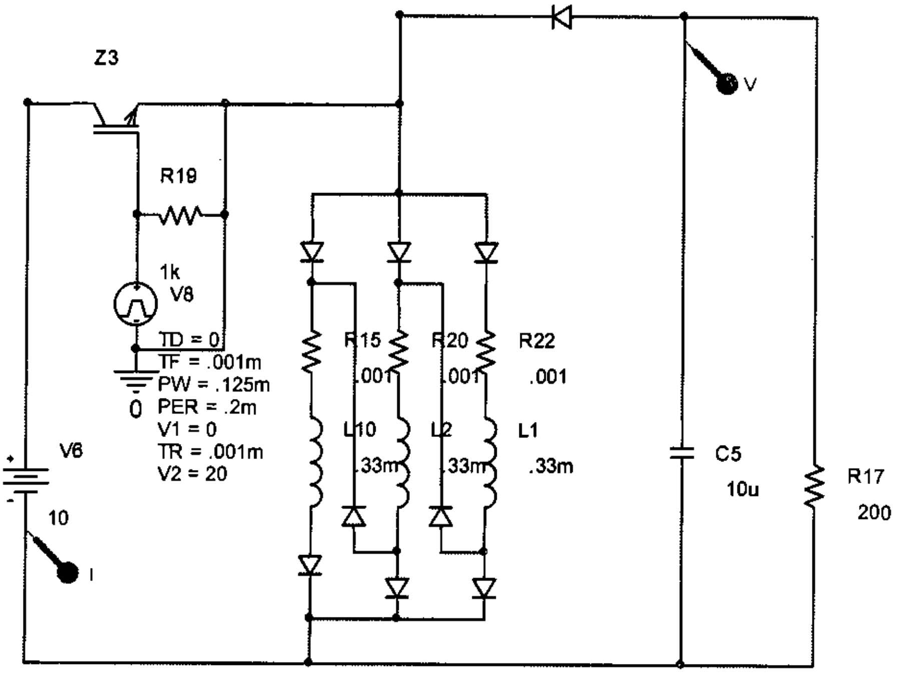


Figure- 2.71: Buck Boost Hybrid DC-DC Converter

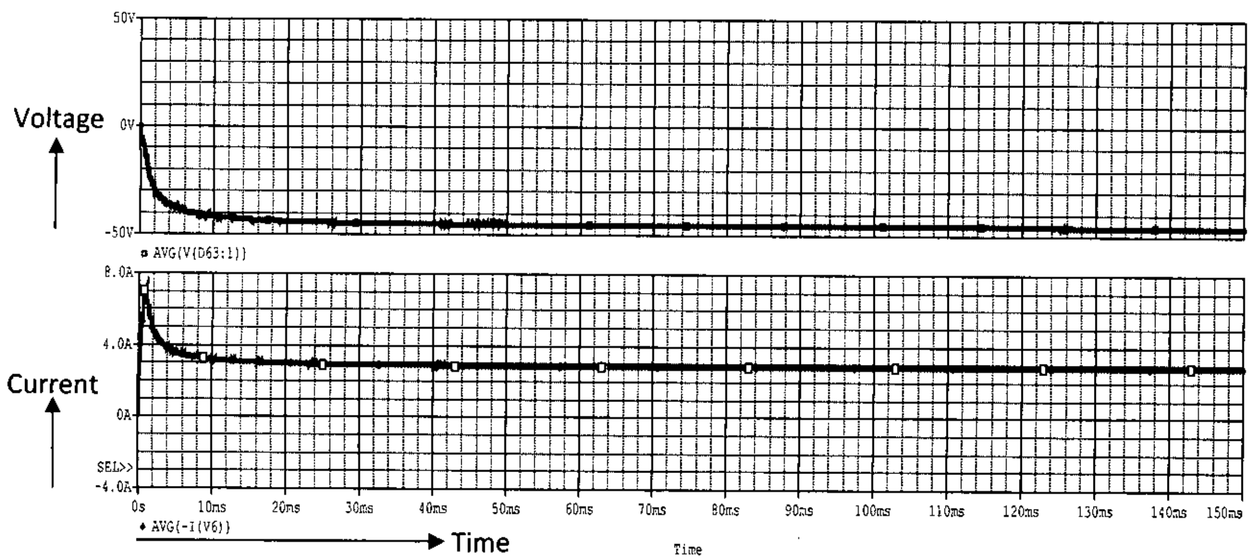


Figure- 2.72: Typical Waveforms of High Gain Hybrid Buck Boost DC-DC Converter of Figure-2.71

Table-2.16: Performance of High Gain Hybrid Buck Boost DC-DC Converter of Figure-2.71

Duty Cycle	**Vin (V)**	**Iin (A)**	**Vout (V)**	**Iout (A)**	**Pin (W)**	**Pout (W)**	**Voltage gain**	**Efficiency in percentage**
0.125	10	0.129	5.1662	0.025831	1.29	0.13344811	0.516	10.3448149
0.25	10	0.475	12.786	0.06393	4.75	0.81740898	1.27	17.20861011
0.375	10	1.0321	22.576	0.11288	10.321	2.54837888	2.25	24.69120124
0.5	10	1.818	33.855	0.169275	18.18	5.73080513	3.38	31.52258045
.625	10	2.7761	45.99	0.22995	27.761	10.5754005	4.59	38.09445085
0.75	10	4.1239	61.542	0.30771	41.239	18.9370888	6.15	45.92033953
0.875	10	15.428	117.371	0.586855	154.28	68.8797582	11.73	44.64594128

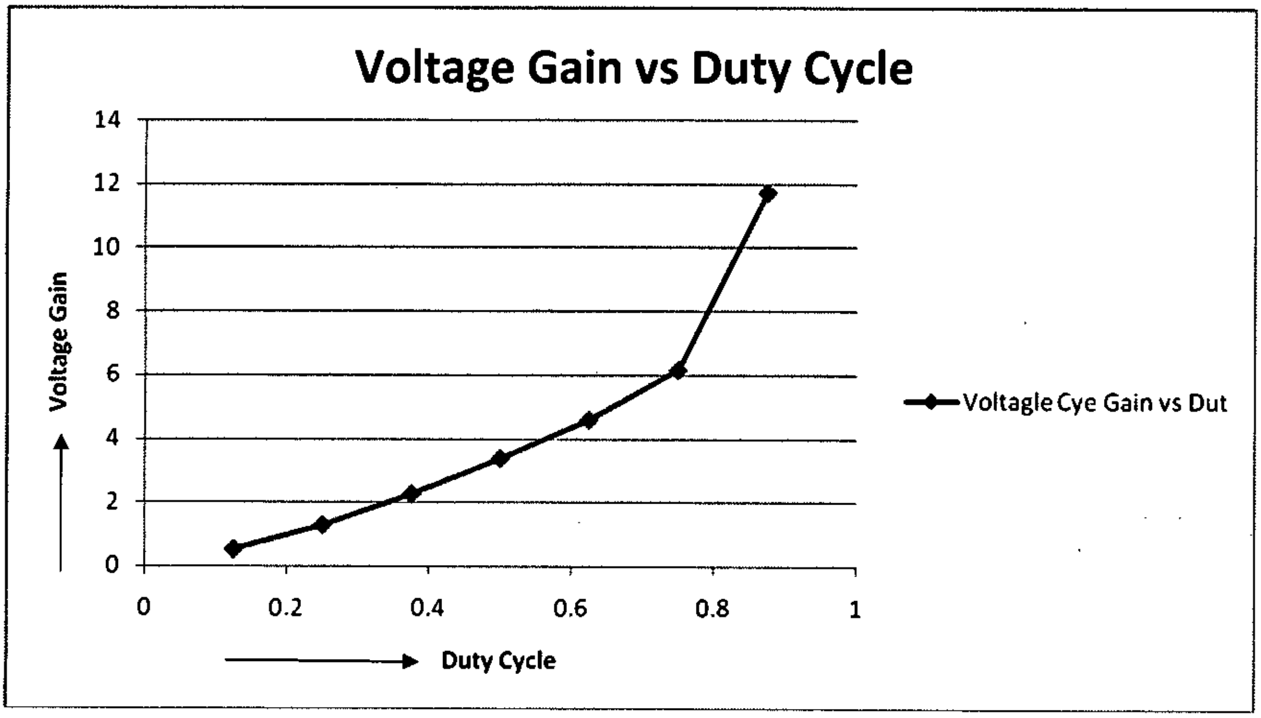


Figure- 2.73: Voltage Gain vs Duty Cycle curve of Buck Boost DC-DC Converter of Figure-2.71

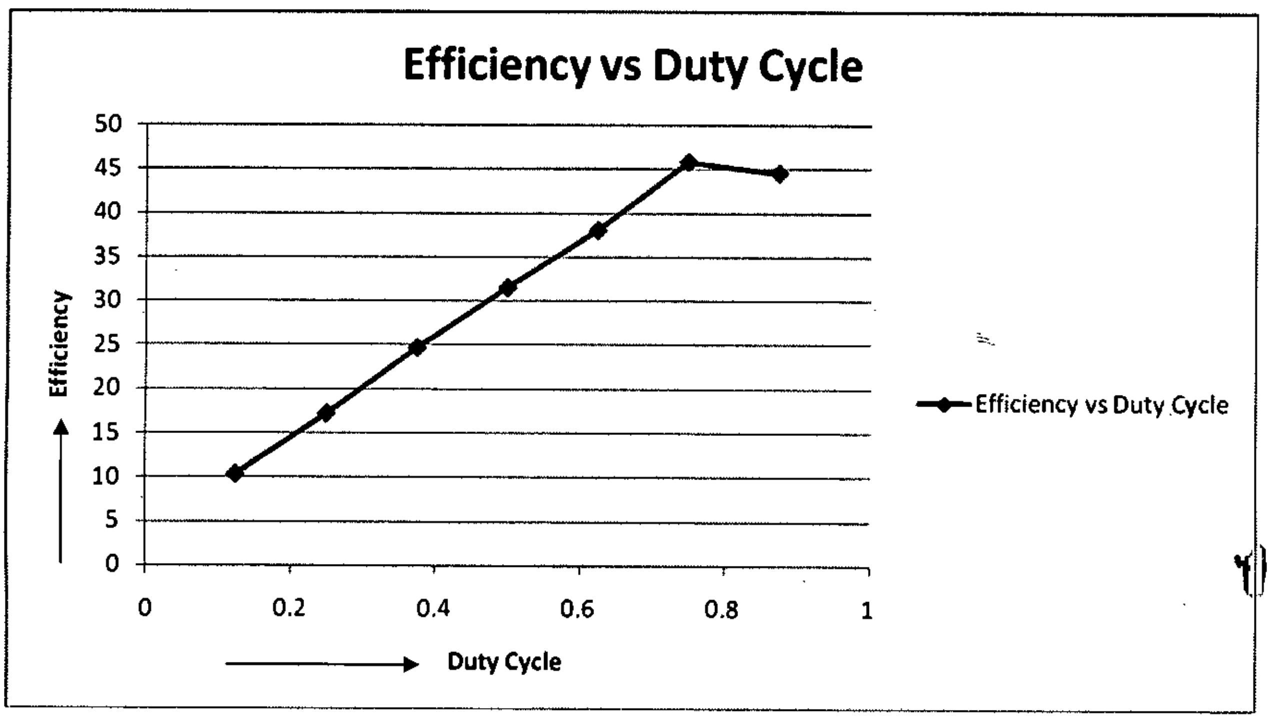


Figure-2.74: Efficiencyvs Duty Cycle curve of Hybrid Buck-Boost DC-DC Converter of Figure-2.71

Chapter-3

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

3.1 CONCLUSIONS

A new multi-inductor voltage multiplier cell is proposed in the thesis to be incorporation with commonly used switch-mode dc-dc converters for their high voltage gain operation with acceptable efficiency of energy conversion. The proposed multiplier cell can use more than two parallel inductors with appropriate diode connections for voltage build up in them during ON time of the switch of the dc-dc converter. The charged inductors with voltage across them are connected in series during OFF time of the switch and charge the capacitor across the load to boost up the voltage of the load.

The proposed cell is investigated with conventional Boost, Ĉuk, SEPIC and Buck-Boost dc-dc converters topologies with expected result of attaining same voltage gain than conventional dc-dc converter counterpart with higher efficiencies at lower duty cycle. The dc-dc converters were found to behave similarly for voltage gain and efficiency at higher duty cycles. It was also observed that the voltage gain of these converters in hybrid mode operations can be varied widely to higher gain levels than conventional converters.

Voltage multiplier cell made of parallel inductors and diodes at the input of conventional dc-dc converters have been found to operate satisfactorily for Boost, Ĉuk and SEPIC converters. However, the hybrid Buck-Boost converter was found to exhibit the desired tread with very low efficiency. Hence the voltage multiplier cell made of inductors and diodes in its present form as repotted in literature, and that proposed in this thesis is not suitable for hybrid operation of Buck-Boost dc-dc converters.

3.2 RECOMMENDATIONS FOR FUTURE WORK

The proposed voltage multiplier cell has been investigated by simulation for hybrid operation of Boost, Ĉuk, SEPIC and Buck-Boost dc-dc converters. In future, investigation may include practical implementation of the proposed hybrid dc-dc converters. The operational limits of two, three and four inductor multiplier cell may be investigated in future works. Ideal voltage and practical voltage gain relationships of the investigated hybrid dc-dc converters may be subject of future investigation. Research may continue to find an inductor multiplier cell based efficient hybrid Buck-Boost dc-dc converter in future.

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