CHAPTER 1

INTRODUCTION

The entire world essestially is dependant upon fossil fuels as energy sources namely coal, oil and natural gas. The major drawback, however, is that it would require millions of years to replenish the sources of fossil fuel consumed within the last few decades. Renewable energy is the answer to the global concern for the non-renewable fossil fuel as it requires a short time to naturally restore itself. Renewable energy comes from many commonly known sources such as solar power, wind, running water and geothermal energy. Renewable energy sources are wonderful options because they are limitless. Also another great benefit from using renewable energy is that many of them do not pollute our air and water, the way burning fossil fuels does.

One of the most commonly used renewable energy is solar photovoltaic. Electronic devices named solar panel utilizes the photovoltaic effect to convert solar energy to electricity. Two of the classifications of PV applications are Utility-Interactive and Stand-alone applications. Utility-interactive helps maintain an alternate system which is able to guarantees production of electricity under various weather conditions roung the year. On the contrary, stand-alone system runs on the electricity produced on-site without any connection to utility. PV-charged battery is used to provide for the energy requirement during cloud and gloomy weather conditions. Since battery storage using PV system is capable of powering both DC and AC equipements, they are widely used to power lights, telephones, switches, appliances, sensors and even power tools. The availability of low DC power requirement for remote lighting and mobile application renders PV as an ideal source. But the main disadvantage of solar PV is the output voltage from solar PV is variable and a suitable controller is required to make it usable. Boost converter is widely used converter with solar PV. With the growing demand of solar PV the demand of boost converter is also growing. It necessitates the improvement of conventional dc-dc converters and development of new type of dc-dc converters that could convert a variable dc voltage level into a desired and stable level in the most efficient way. Without the solar photovoltaic potential applications of dc-dc step up converters also include other renewable energy system applications, such as fuel cell and wind turbine, dc micro-grid, telecommunication industries, high intensity discharge (HID) lamp ballast used in automotive headlamps, hybrid vehicles and switching mode regulators such as uninterruptable power supplies (UPS) and high efficiency LED power sources.

1.1 Introduction

DC-DC converters known as dc transformer have been used for so many years. Prior to the development of technologies concerning power semiconductor devices, one of the methods of converting a DC voltage to a higher value for use in low-power application, was to use a vibrator to convert it to AC; thereby using a step-up transformer and rectifier. An electric motor operated the generator producing the required voltage for higher power (a combination of a generator and motor called "dynamotor" unit with two winding producing the voltage output and driving the motor respectively). These were comparatively costly and ineffective methods used in absence of any other substitute such as operating a radio in a car. Advancement of Power Semiconductors and Integrated circuits meant the coversion of DC to AC at high frequency by using low cost and low weight high frequency transformers to vary the voltage and thereafter rectifying it back to DC. Few novices persisted to use vibrator supplies and dynamotors for mobile transceivers with high power even though transistorized car radio receivers with lower voltages were available by1976. The drawback, however, from deriving a lower voltage from a linear electronic circuit or even a resistor is the excess dissipation of heat. Solid-state switching mode circuits help overcome this problem by achieving an efficient enery conversion.

1.2 Literature review

In today's world, energy is a global issue and energy demand is increasing day by day. To satisfy the increasing demand renewable and non-renewable energy resources are used. However, renewable energy sources are fast gaining importance over non-renewable ones due to the depletion of the non-renewable. Among different source of renewable such as solar, wind, hydro, tidal, bio-mass, solar power generation system tops the list as they provide a clean, cheap and environment friendly solution [1]-[4].

Photovoltaic (PV) modules are used to generate electricity from the solar energy. Basically, photovoltaic system is a source of DC voltage generator. When sunlight falls on the PV modules, it converts sun light into DC electricity. Apart from the advantages of renewable energy sources, the PV based systems has few more added advantages. The PV based systems are employed in stand-alone applications such as water pumping, street lighting and can be installed in remote area like remote IoT sensor node. Like others PV systems have also some shortcoming. PV system is less efficient and the power available from photovoltaic source is variable in nature. The voltage, current and consequently the power continuously vary depending on the load and the climate condition such as solar irradiance, cloud, and temperature [5]. To minimize the effect DC-DC boost converter is used between the source and the load. The input voltage can be step-up as required using the boost converter. Theoretically, a boost converter can achieve a high step-up voltage gain with an extremely high duty ratio near to 100% [6]-[9]. However, in practice, the step-up voltage gain is limited due to the effect of power switches, rectifier diodes, the equivalent series resistance (ESR) of inductors and capacitors, and the saturation effects of the inductors and capacitors [30].

Traditional energy resources are on the verge of exhaustion, while inducing terrible effects on environment. On the other contrary, constant search for clean and abundant source of energy continues in remote areas where power grids are unavailable. Considering the aforementioned criteria, solar energy is the most suitable and sustainable solution for the growing demands. Wind and geothermal energy is also becoming quite popular. However, voltage levels obtained from such renewable energy sources produce low and unregulated voltage output. But in some applications such as telecom power supplies, motor drives, battery chargers, electroplating, and desktop/laptop computer power supplies, maximum power point tracking systems and defense equipment require constant voltage level, lower ripple, and superior dynamic performances, i.e., efficient and reliable power converters [10]-[11]. Therefore, suitable power converter especially boost converter may be used to increase and regulate the output voltage levels to make it usable with the above devices. In some cases, boost converter may also be used as pre-regulator. It is evident that in order to increase the efficiency of PV system, DC-DC converters must have desirable and efficient operation.

The dc-dc boost converter (BC) is one of the basic power electronics converters, which is serving the purpose to step up the voltage from lower level to higher level [12]-[13]. In a solar PV system a very high gain conversion ratio may require in case of big reduction of PV output voltage due to partial shading [14]. However, the conventional BC fails to achieve these goals due to poor dynamic performances and presence of higher ripple in source current and in output voltage. To eliminate some of these problems, BCs are frequently connected in parallel [15], [16]. When connected in parallel dc converter often called Interleaved Boost Converter (IBC).

In high power applications, it is advantageous to use interleaved connection (parallel connection of multiple switching converters) of two or more boost converters to increase the output power and to reduce the input and output ripple [17]. Interleaved converters also provide higher efficiency at lower complexity rather than multiple cascaded converters [18]-[19]. In interleaved boost converters, effective switching frequency can be doubled which helps to increase the reliability and reduce switching losses [20]-[27]. However, interleaved topology improves converter performance at the cost of additional power switching device and inductors. The leakage inductance of the IBC can increase the diode current stress causing extra EMI (Electro-magnetic interference) problem [28]-[29].

An IBC has two phases and each phase current of IBCs can be controlled in two manners: continuous conduction mode (CCM) or discontinuous conduction mode

(DCM) [31]. When an IBC is operated in DCM, a switch can be operated by zero current switching (ZCS), so that turn-on switching loss and reverse recovery loss of a diode are eliminated [32], and small-size inductance can also be used [33]. However, the pattern of the input current ripple of an IBC in DCM is very complicated and does not vary linearly. Moreover, the phase of an IBC can be expanded as the power rate of the system is increased. This makes the pattern of the input current ripple more complex. Because of this, hardware design that includes an EMI filter and inductors becomes very difficult [32].

Analyses of the input current of the IBC in CCM have been discussed [34]-[37], and analyses of DCM have been introduced [38]-[41]. However, there have been limitations in these analyses because only 2-phase IBCs or the inductor current is mainly considered. In terms of the design for the IBC, many studies have been focused on improving efficiency and power density of the system without consideration of the input current ripple [34],[42]-[44]. As such, accurate analysis and proper design methodology of IBCs in DCM while considering the input current ripple are strongly needed.

D. H Kim and G.Y. Choe done an excellent work on DCM. They analyzed the complicated input current ripple of 3-phase IBC in DCM and derived mathematical equation for the magnitude of the input current ripple. From their analysis it is clear that input current ripple of a boost converter is related to input voltage variation, inductance and the duty ratio of the switching pulse. They also proposed an effective design guideline to find the optimize inductor for minimum input current ripple [45]. The effect of variation of duty ratio on the different performance parameters of boost converter was discussed by B. J. Saharia and B. K. Talukdar [46].

1.3 Research Motivation

With growing population, economic and industrial development, the need to examine alternative sources for generation of electricity has become very important. Solar Photovoltaic (SPV) system is gaining importance as a renewable source due to zero fuel cost, negligible maintenance, low noise and wear due to the absence of moving parts, but limited by the high installation cost and low energy conversion efficiency. Solar energy production is clean, as it is emission free with continuous supply during day while being portable and scalable. Recent decreases in the cost of solar technologies have spurred wider deployment of PV electricity generation systems.

With a view towards bolstering power generation free of carbon-emission, the Government of Bangladesh is eager to establish grid-connected solar parks. Engreen Sharishabari Solar Plant Ltd., Jamalpur went into commission in August 2017 as the first grid connected plant with a capacity of 2MW. An addition six solar parks with a combined rating of 230 MW is underway with a goal of 2000 MW by the end of 2021.

Two solar power hubs - one over 4000 acres of land with capacity 1000 MW in Chandpur economic zone and one over 2000 acres of land with capacity 600 MW in Mirsarai, Chittagong – will be delveloped by the Bangladesh Economic Zone Authority. For meeting these goals efficient solar system installation at reduced cost will require and for that advance, high performance power converters will be required for maximizing energy conversion.

Solar photovoltaic system is not very efficient system. Hence, while the theoretical maximum efficiency may be higher, the real efficiency of silicon solar cells is usually around 15 to 17 percent. But solar cell or module alone is not enough for a practical solar photovoltaic system. So, power converter or conditioner circuit is required which further reduced the overall efficiency. So, there is a big opportunity and requirement to work for efficiency improvement of solar photovoltaic system.

1.4 Problem Definition

There are many parameters which have impact on efficiency of solar system; Efficiency of a PV system depends on the solar panel, power conditioning circuit, and battery management circuit. Performance variation in any part can affect the efficiency of a solar PV system. A great deal of research has been done to improve operation of solar system. First stage DC-DC converter which directly connected to PV arrays is aimed to gain maximum power point (MPP) under variation of solar irradiation and temperature. It is obvious in order to increase efficiency of system; DC-DC converter must have desirable operation. In other words, one important step toward increasing efficiency of PV systems is to improve the efficiency of DC-DC converters. Boost converters became most widely used converters in PV power generation systems as most of the cases a higher voltage is required than the voltage produce by solar panel.

Several problems are noted in the conventional boost converter circuit as:

(a) High reverse recovery current across the rectifier diode
(b) Turn ON and turn OFF losses
(c) Leakage inductance energy (induces high voltage spikes across the active switch), and
(d) Current stress in switching device
(e) Low efficiency, high input current and output voltage ripple.

A solution is to replace the traditional boost converter with interleaved boost converter. The interleaved boost converter has the following advantages

(a) High gain, conversion ratio
(b) Small voltage stress on the switches and low switching loss
(c) Soft-switching operation of active and passive switches, and solving the recovery problem of the diode

(d) Lower EMI, lower ripple and higher reliability.

Close loop interleaved boost converter has better performance than open loop interleaved boost converter. Implementing appropriate controller and choosing appropriate component value the performance, reliability and stability can be improved further.

Traditional boost converter is not suitable for high power application due to high ripple current. Rather interleaved boost converter is suitable for high power application due to lower ripple current. An interleaved boost converter consists of several identical boost converters connected in parallel and controlled by the interleaved method which has the same switching frequency and phase shift. Interleaved boost converter has lower ripple in input-output current and voltage waveforms. It can operate on higher switching frequency and thus reduces losses and overall size of the converter.

1.5 Thesis Objective

The main thesis objective is to study the high gain dc-dc step up converters for PV system and to find a way to improve the efficiency of the overall system. However, more particularly, the objectives include:

i. To study the different type of interleaved boost converter.
ii. To investigate the effect of variation of input parameters of IBC.
iii. To investigate the effect of different control parameter (i.e. duty ratio) and the design parameter (i.e. inductance, capacitance) on the overall performance of IBC
iv. To propose and develop an improved model of IBC suitable for photovoltaic application.
v. To obtain a simulation model of the proposed controller and compare the result with current controllers.

1.6 Scope of the Thesis

Solar photovoltaic system is one of the most inefficient electronic systems. Moreover the output of the solar photovoltaic is very unstable. So, an efficient controller is required to make the output stable and ripple free. In this thesis effect of variation of one of the control parameter duty cycle and one of the design parameter inductance on the performance (input current ripple, output voltage ripple) of IBC is investigated. A new IBC model is proposed considering the findings of the analysis. In this book the proposed circuit and a SIMULINK model for Interleaved Boost Converter is presented. The proposed circuit requires a suitable digital controller for maintaining optimum switching and an algorithm for the proposed controller is also represented. The model is simulated using MATLAB/SIMULINK and the simulation result is presented and analyzed. The output is also compared with traditional converter. After software simulation and analyzing the result its one of the low power application e.g. IoT sensor node is discussed.

1.7 Research Approach

The process of achieving the research goal is mainly divided into three main parts; investigating the relation of input voltage, duty ratio and inductance with the input current ripple and output voltage ripple. Then choosing appropriate inductance and duty ratio for a specific input voltage and finally, developing a new topology using optimized inductor and simulating the circuit. After completing the simulation analysis and comparison will be done. All the steps are discussed below.

Stage 1: Review and study several kind of theory and literature. Study works covered:

a) Study about renewable energy and photovoltaic system.
b) Study and investigate different types of converter used in photovoltaic system.
c) Study about different type of boost converter and different close loop controller used in boost converter.
d) Study about most suitable dc-dc converter for photovoltaic system, advantages and disadvantages.

Stage 2: In this period several of work will be done. Like

a) Choosing an appropriate converter for solar photovoltaic.
b) Find a way to improve the current model in term of ripple and efficiency.
c) Developing the SIMULINK model for the proposed converter.
d) Develop a digital controller for controlling the switching.
e) Develop an algorithm for the controller.

Stage 3: In this period simulation was made. The steps involved was

a) Simulate the photovoltaic with traditional IBC.
b) Simulate the photovoltaic with proposed Interleaved Boost Converter.
c) Simulate the proposed converter by changing different parameters.

Stage 4: In this stage the main activity was

a) Analysis and compare the simulation result.

b) Find the feasibility of photovoltaic system with interleaved boost converter for low power IoT application.

Stage 5: Write and rearrange the research report and make a presentation to present the research.

1.8 Outline of the Report

In chapter 1, introduction describes the background and motivation of the research, goal and scope of research, and objective of the research. This chapter also includes literature review and the stages of work to fulfill the research.

In chapter 2, the background part describes the operation of photovoltaic cell, DC-DC converter, different type of DC-DC converter, boost converter, interleaved boost converter, necessity of using DC-DC converter with PV system etc.

In chapter 3, model building introduces a new topology of the interleaved boost converter. The schematic, the control algorithm, and simulink model is also presented in this chapter.

In chapter 4, simulation and analysis covers the details result of interleaved boost converter, analysis of the simulation result, comparison of the result with traditional controller, and advantages of the proposed controller.

In chapter 5, presents the conclusion of the work and future scope.

CHAPTER 2

BACKGROUND

The growing demand of dc-dc step up converters for various household and industrial applications necessitates further improvement of conventional dc-dc converters and development of new type of dc-dc converters that could convert a fixed dc voltage level into a desired level in the most efficient way. The potential applications of dc-dc step up converters include renewable energy system applications, such as photovoltaic, fuel cell and wind turbine, dc micro-grid, telecommunication industries, high intensity discharge (HID) lamp ballast used in automotive headlamps, hybrid vehicles and switching mode regulators such as uninterruptable power supplies (UPS), high efficiency LED power sources and remote IoT sensor node.

2.1 Photovoltaic Cells

All energy on earth are directly or indirectly come from the sun. The most effective way to harvest solar energy is by converting it into electricity directly. Solar energy can directly be converted to electricity by using solar photovoltaic cell. It is also the most known and widely used way of using solar energy. Light has a mass less particle called photon which moves at light speed. This photon is responsible for producing electricity form solar cell. Photovoltaic is a noise less electricity generation technique because no mechanical generators are involved in the process.

In recent year electricity generation from photovoltaic (PV) cell has gaining considerable attention as one of most prominent energy alternative. This is for environment friendly and noise less conversion of sunlight to electricity by PV. In a meter electron can exist as free or as valence. This free electron can move freely and valance electrons keep associated with the atom. A valence electron can become free by getting enough energy which is equal or more than the binding energy. Photoelectric effect occers when electron acquairs enough energy from collision with photon for getting free from the influence of the atom. The whole energy acquired from the collision of photon is not required to become free and the remaining energy is converted to kinetic energy. This kinetic energy can create more free electron. This new free electrons attained by the photoelectric effect are called as photoelectrons. On the other side the energy involved to release a valence electron from the bang of an atom is called a *work out* and it depends on the type of material in which the photoelectric effect has occurred.

The photoelectric effect can be detected in nature from variety of materials, but semiconductor material shows the best performance in sunlight. When photon form the sun are absorbed by the semiconductor matrials free electrons are created. Generally, the electric field is created from a solar cell by created a junction of two different materials which have singular electrical properties. The effect of photovoltaic can be easily described for P-N junction in an semiconductor. P-N junction is nothing but a simple boundary between two differently doped semiconductor layers. In a P-N junction P type layer has a deficiency of electrons and N type layer has a excess of electrons. In this junction after absorving photons the free electrons of N layer starts to flow to the P layer and the hole (deficiency of electron) of the P layer starts to flow to the N layer to compensate the difficiency of each layer. This diffusion creates an electric field and the filed continues to increase until it reaches equilibrium.

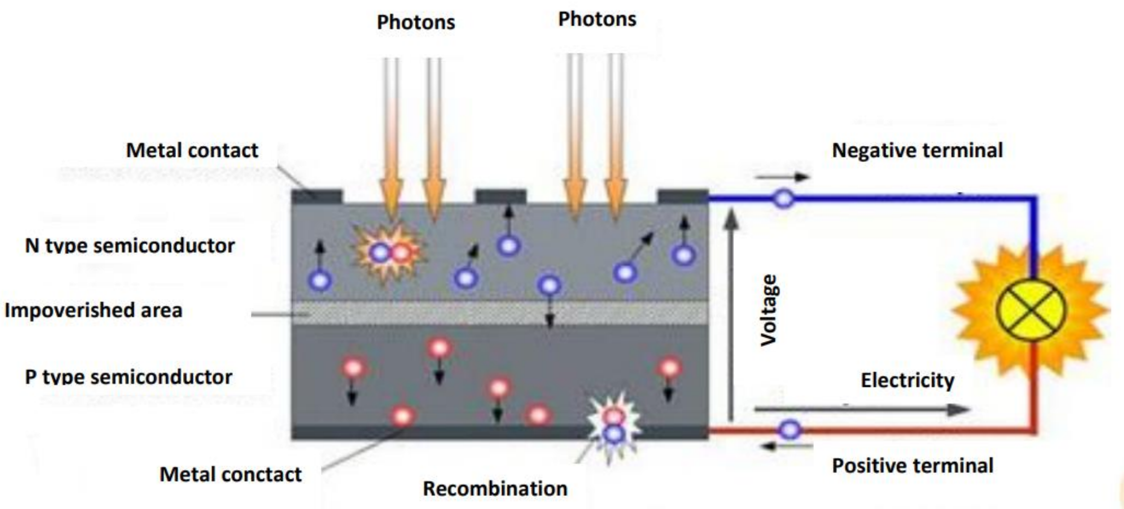


Figure 2.1 Construction of photovoltaic cell

In a photovoltaic cell the contact are made with two differently doped semiconductor materials and contacts are usually connected through external electrical conductor to carry the flow of electron from n type material to p type material. Thus the free electrons enter into holes through the external conductor and both are removed. The flow of electrons through the external conductor makes an electric current and maintains as long as more free holes and electrons are created by solar radiation. In this way solar energy is created into electrical energy and called as photovoltaic conversion. Each of the individual solar cell produce a voltage around 0.5 to 0.7 volts with a current density of about several tens of mA/cm^2 depending on the radiation spectrum as well as power of solar radiation known as solar irradiance. The current density is directly related to the cell area and the voltage produced by an individual cell is not enough for useful work. So, multiple cells are connected in series parallel combination to maintain a particular voltage, power and reliability and these connected cells are called solar panel.

In terrestrial applications atmospheric degradation of the solar panel may occure due to oxidation of the metal contact. To protect the panel from environment weather fight front transparent covering made by acrylics, glass or silicon epaxies are used.

2.1.1 Mathematical Model of Solar Cell

For batter understanding of the working of a solar panel researchers continuously updating the mathematical model of the PV module. Modeling of solar cell can be expressed by many ways and it differ depending on the software packages used to develop the model. Excel, Matlab, Simulink, and Pspice are some of the most common software type.

Performance of the solar panel depends on several physical parameters like series resistance, shunt resistance, diode's quality factor and saturation current. So, these parpameters must be condiderd during the development of mathematical model. The equivalent circuit of a practical solar cell is shown in figure 2.2. The current source I_L represent the photocurrent of the soalr cell. In the circuit R_{sh} represents shunt resistance and R_s represent the series resistance and I_d represent the diode current of a PV junction cell.

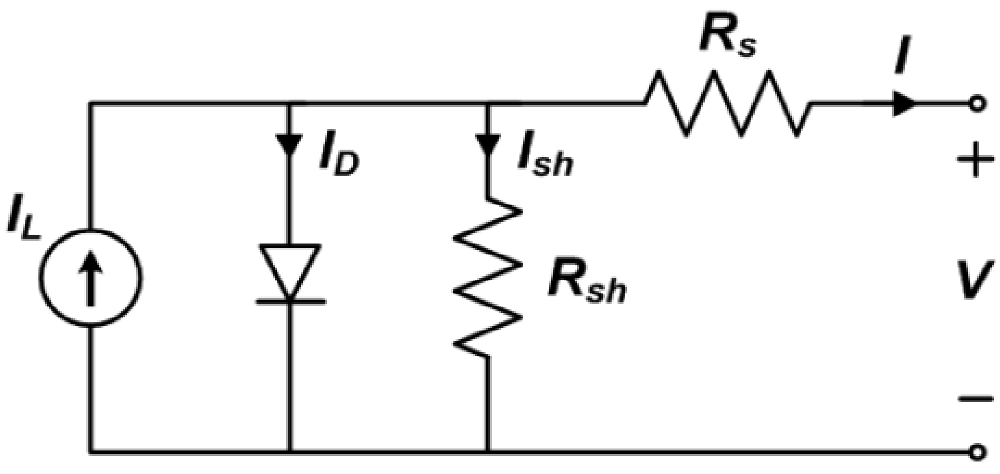


Figure 2.2 Equivalent Circuit of PV Cell

Compare to the shunt resistance the series resistance has immense impact on I-V characteristics of solar cell. I_d represent diode current and Ish is the leakage current of the cell. By applying KCL in the above equivalent circuit I can be estimated as follows:

$$I = I_{ph} - (I_d + I_{sh})$$

The equation can be simplified by replaceing the sum of saturation current and diode leakage current with I_0 and the simplified equation will be:

$$I = I_{ph} - I_o$$

Here, I_{ph} represent photon current and it generates by absorbing solar radiation by solar cell. Photocurrent is directly proportional to the change in temperature and solar irradiance. Photocurrent can be represented by the equation:

$$I_{ph} = (I_{scr} + k_i)\frac{G}{G_r}$$

In the above equation $\mathbf{I_{scr}}$ represents solar current at normal weather conditions (e.g. 25ºC and 1000w/m^2), $\mathbf{k_i}$ is short circuit temperature coefficient. **G** is solar irradiance in W/m^2 and $\mathbf{G_r}$ is nominal irradiance in normal weather conditions (25ºC and 1000w/m^2). Δ**T** is difference between the operating temperature and the nominal temperature (T – T_{ref}). On the other side, reverse saturation current of a solar cell can be calculated by:

$$I_o = I_{rs}\left(\frac{T}{T_{ref}}\right)\exp[(\frac{qE_{go}}{AK})(\frac{\Delta T}{T_{ref}T})]$$

Where $\mathbf{I_{rs}}$ is for reverse saturation current of the solar cell for normal room temperature and nominal irradiance. $\mathbf{E_{go}}$ represents the band-gap energy of the semiconductor material used to make the cell. The values of $\mathbf{I_o}$ and $\mathbf{I_{ph}}$ expands the value of **I** and it will be as follows:

$$I_{pv} = I_{ph} - I_o\left[\exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{AKT}\right) - 1\right] - \frac{(V_{pv} + I_{pv}R_s)}{AKT}$$

2.2 DC-DC Converter

DC –DC converters are power electronic circuits that convert a dc voltage to a different voltage level. There are different types of conversion method such as electronic, linear, switched mode, magnetic, capacitive. The circuits described in this report are classified as switched mode DC-DC converters. These are electronic devices that are used whenever change of DC electrical power from one voltage level to another is needed. DC-DC converters are used in variety of applications, such as power supplies for office equipment, personal computers, aircraft power systems unit, laptop and desktop computers, and different high power telecommunications equipment, as well as dc and ac motor drives. Low power applications of DC-DC converters includes the field where 5V or 3.3V DC is provided from AA or AAA cell. On a PC or laptop motherboard 3V and 1.8V or less for one of the latest CPU chips provided by stepping down of 5 volts from power supply; where 1.5V from a single cell must be stepped up to 5V or more, to operate electronic circuitry. In all of the above applications, we need to change the level of DC energy from one voltage level to another. While making this conversion wasting of energy should be kept as little as possible. In other way we can say, we want to perform the conversion process with the highest possible efficiency. DC-DC Converters are needed because unlike AC, DC can't simply be stepped down or up by using a transformer. In many ways, a DC-DC converter can be treated as a DC equivalent of a AC transformer. Essentially DC-DC converter just change the input energy into output energy of a different impedance level. So whatever the level of output voltage, the output power always comes from the input; there is no way to generate energy inside a converter.

It is very much essential to maintain high efficiency in DC-DC converter, because inefficient converter produce more heat and cooling is difficult and expensive. The ideal converter shows 100% efficiency; but in reality, efficiencies of 70% to 95% are generally obtained. This can be achieved by using switched-mode, or chopper circuits whose elements waste negligible power. Pulse-width modulation (PWM) permits regulation and control of the total output voltage. This method is also employed in applications of alternating current, which includes high-efficiency ac-ac power converters, dc-ac power converters (power amplifiers and inverters), and some ac to dc power converters (low-harmonic rectifiers).

2.3 Types of DC-DC Converter

There different kinds of DC-DC converters. A variety of the converter names are included here:

a) The BUCK converter
b) The BOOST converter
c) The BUCK-BOOST converter
d) The CUK converter
e) The Fly-back converter
f) The Forward Converter
g) The Push-pull Converter
h) The Full Bridge converter
i) The Half Bridge Converter
j) Current Fed converter
k) Multiple output converters

2.4 Study of DC-DC Converters

There are a variety of DC-Dc converters are possible. But from the list of the converters only the buck, boost, buck-boost and interleaved boost converter are to be described which are basically of non isolated input output terminals.

2.4.1 The Buck Converter

The buck converter is a commonly used in circuits that steps down the voltage level from the input voltage according to the requirement. It has the advantages of simplicity and low cost. Figure 2.3 shows a buck converter. The operation of the Buck converter starts with a switch that is open (so no current flow through any part of circuit). When the switch is closed, the current flow through the inductor is slow at first, but building up over time. When the switch is closed the inductor pulls current through the diode, and this means the voltage at the inductors "output" is lower than it first was. This is the very basic principle of operation of buck circuit.

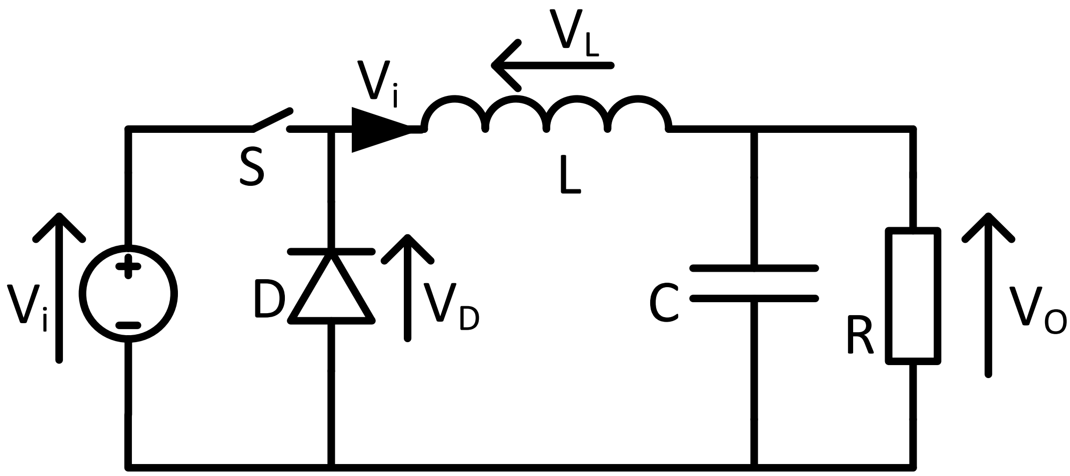


Figure 2.3 The buck converter

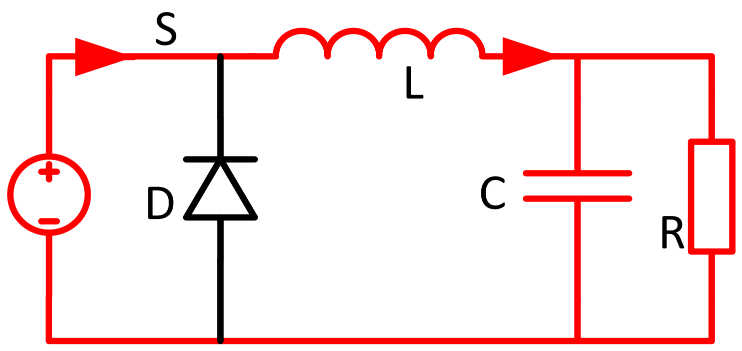
Analysis of the buck converter begins by making these assumptions:

1. The circuit is in the steady state operation.
2. Current of the inductor is always positive
3. The capacitor value is large enough to held constant output voltage Vo. This constraint will be tranquil later to display the effects of finite capacitance.
4. The switch is on for time DT and off for time (1-D)T wher T is the time period.
5. All the components like diode, transistors are ideal

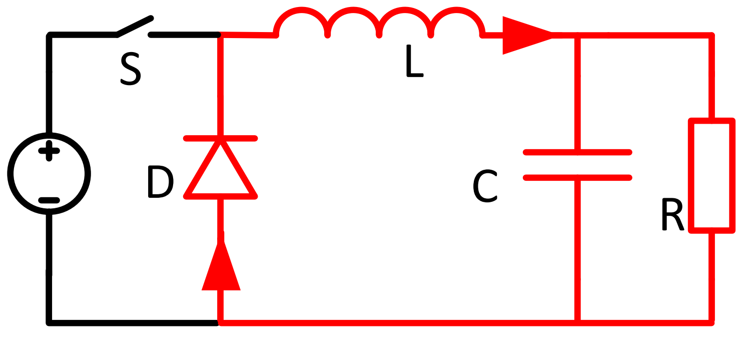
The way to make analysis for determining the output voltage $\mathbf{V_o}$ is to study the inductor current and the inductor voltage first for when switch is on and then for when switch is off. The total change in inductor current for one period must be zero for steady state operation. The average inductor voltage is zero. There are two types of operational mode for this circuit a) Continuous Conduction Mode and b) Discontinuous Conduction Mode. They are described below.

2.4.1.1 Continuous Conduction Mode

If the inductor curren never goes to zero for or a complete cycle then this buck converter is considered as operating in continuous conduction mode. The operating principle of continuous mode can be described by the chronogram in Figure 2.4.



(a) On-state



(b) Off-state

Figure 2.4 On and off state of buck converter

Figure 2.4 shows the two circuit configurations of a buck converter: (a) On-state, when the switch is closed, and (b) Off-state, when the switch is open

- If the switch shown above is on/closed (On-state, top of figure 2.4), the voltage across the inductor is $V_L = V_i - V_o$. The current passing through the inductor increases linearly. At this state the diode is reverse-biased by the input voltage source V_i, no current flows through the diode;
- When the switch is opened/off (off state, bottom of figure 2.4), the diode is forward biased. The voltage across the inductor is $V_L = - V_o$ (neglecting diode drop). Current IL decreases.

The energy stored in inductor L is

$$E = \frac{1}{2}L \times I_L^2$$

It can be observed that the total energy stored in inductor L increases in on-time and decreases during the off-time. The inductor L is used to transfer energy from input side to the output side of the converter. The rate of change of the inductor current can be determined from:

$$V_L = L\frac{dI_L}{dt}$$

With V_L equal to V_i - V_o during the On-state, and - V_o during the Off-state. So, the rises in current at the time of On-state is given by:

$$\Delta I_{L_{on}} = \int_0^{t_{on}} \frac{V_L}{L} dt = \frac{(V_i - V_o)}{L} t_{on} \qquad t\{on\} = DT$$

Identically, the fall of inductor current during the Off-state is specified by:

$$\Delta I_{L_{off}} = \int_{t_{on}}^{t_{off}} \frac{V_L}{L} dt = -\frac{V_o}{L} t_{off} \qquad t\{off\} = T$$

If we consider for steady state operation of the converter, the stored energy in each component at the finish of a commutation period T is equal to the beginning of the period. That means that the inductor current I_L is same at t=0 and at t=T (shown in figure 2.5). So we can write from the above formulas:

$$\frac{(V_i - V_o)}{L} t_{on} - \frac{V_o}{L} t_{off} = 0$$

The above integrations can also be done graphically: In figure 2.5, $\Delta \boldsymbol{I}_{\boldsymbol{L_{on}}}$ is proportional to the total area of the yellow surface, and $\Delta \boldsymbol{I}_{\boldsymbol{L_{off}}}$ **to** the area of the orange surface, as these surfaces are defined by the inductor voltage (red) curve. As these surfaces are simple rectangles, their areas can be found easily: $(V_i - V_o)t_{on}$ for the yellow rectangle and $-V_O t_{off}$ for the orange one. For steady state operation, these areas must be equal. As can be seen on figure 4, $t_{on} = DT$ and $t_{off} = (1 - D)T$. Here D represents the *duty cycle* with a value between 0 and 1. This yield:

$$(V_i - V_o)DT - V_o(1 - D)T = 0$$

$$V_o - DV_i = 0$$

$$D = \frac{V_o}{V_i}$$

From the above equation, it is seen that the output voltage of the considering converter differs linearly with the duty ratio for a given input voltage. As the duty ratio D is equal to the ratio between t_{on} and the period T, it cannot be more than 1. Therefore, $V_o \leq V_i$.

This is why this converter is referred to as *step-down converter*. So, for example, stepping 12 V down to 3V (output voltage equal to one fourth of the input voltage) would need a duty ratio of 25%, in the theoretical ideal circuit.

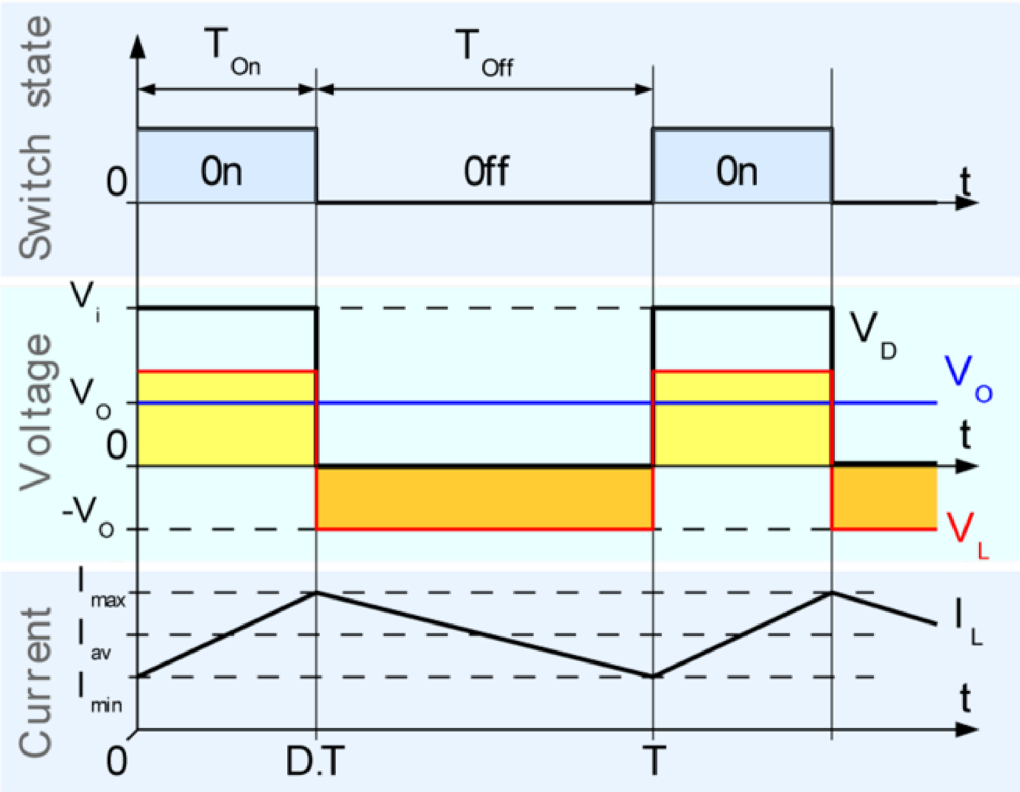


Figure 2.5 Evolution of the voltages and currents with time in an ideal buck converter operating in continuous mode

2.4.1.2 Discontinuous Conduction Mode

When, the amount of energy demanded by the load is small enough and be transferred in a time lower than the whole commutation cycle, the current passing through the inductor drops to zero during a part of the period. The difference in the principle defined above is that the inductor is totally discharged at the completion of the commutation period (figure 2.6). This has, however, some effect on the previous equations.

We still consider that the converter operates in steady state. Therefore, the energy in the inductor is the same at the beginning and at the end of the cycle (in the case of discontinuous mode, it is zero). This means that the average value of the inductor voltage (VL) is zero; i.e., that the area of the yellow and orange rectangles in figure 3.5 are the same. This yield:

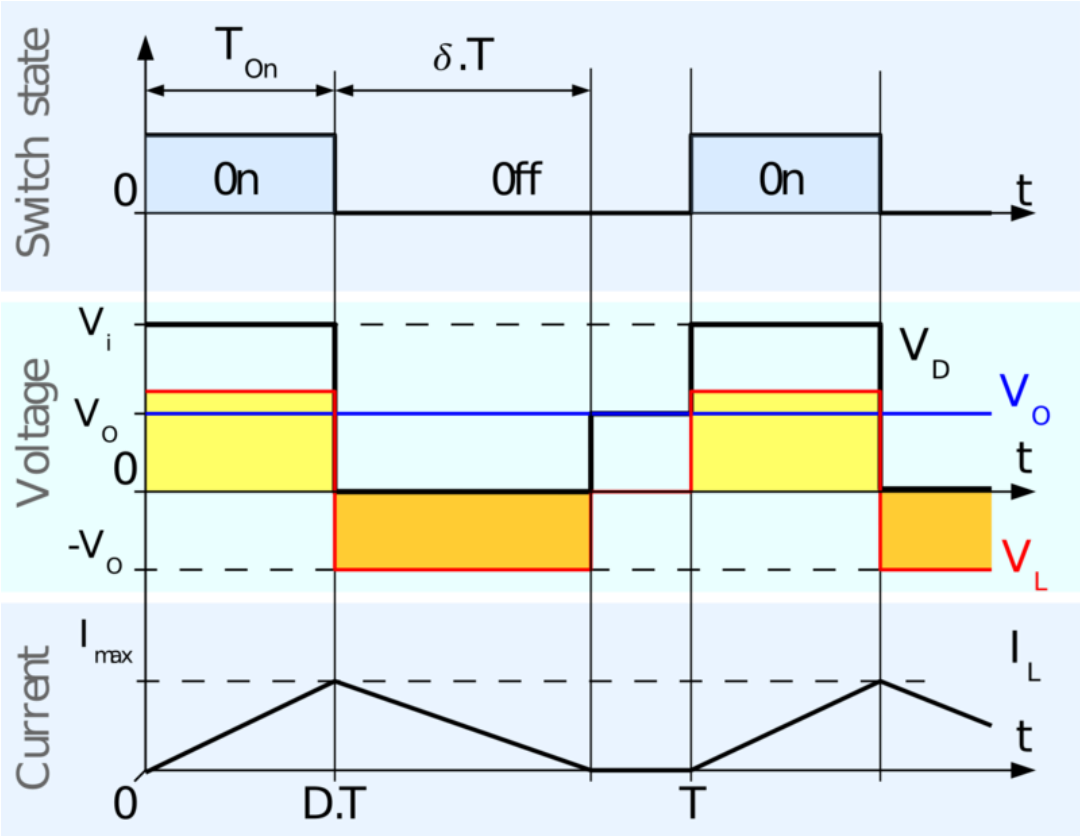


Figure 2.6 Evolution of the voltages and currents with time in an ideal buck converter operating in discontinuous mode.

$$(V_i - V_o)DT - V_o\delta T = 0$$

So the value of δ is:

$$\delta = \frac{V_i - V_o}{V_o} D$$

The output current delivered to the load (Io) is fixed; considering that the output capacitor is large enough so that it can maintain a constant voltage across its output terminals during a conduction cycle. This suggests that the current passing through the capacitor has a zero average value. So, we have:

$$\bar{I}_L = I_o$$

Where $\bar{I}_L$ is the average value of the inductor current. As can be seen in figure 2.5, the current waveform of inductor has a triangular shape. Therefore, the average value of inductor current I_L can be sorted out mathematically as follow:

$$\bar{I}_L = (\frac{1}{2} I_{L_{max}} DT + \frac{1}{2} I_{L_{max}} \delta T) \frac{1}{T}$$

$$= \frac{I_{L_{max}}(D + \delta)}{2}$$

$= I_o$

The inductor current is considered zero at the stsrting and rises during t_{on} up to $I_{L_{max}}$. That means that $I_{L_{max}}$ is equal to:

$$I_{L_{max}} = \frac{V_i - V_o}{L} DT$$

Substituting the value of $I_{L_{max}}$ in the previous equation leads to:

$$I_o = \frac{(V_i - V_o)DT(D + \delta)}{2L}$$

Replacing δ by the expression specified above yields:

$$I_o = \frac{(V_i - V_o)DT(D + \frac{V_i - V_o}{V_o} D)}{2L}$$

This expression can be rewritten as:

$$V_o = V_i \frac{1}{\frac{2LI_o}{D^2 V_i T} + 1}$$

It can be realized that the output voltage of a buck dc-dc converter working in discontinuous conduction mode is much more complex than its complement of the continuous conduction mode. Besides, the output voltage is a function not only of the input voltage (Vi) and duty cycle D, but also of the value of inductor (L), the conduction period (T) and the output current (Io).

2.4.2 The BOOST Converter

A boost converter (step-up converter) is a power converter with an output DC voltage greater than its input DC voltage. It is a class of switching mode power supply (SMPS) containing at least two semi-conductors switches and at one energy storage element. Filter with capacitor are sometime added to the output of the converter to reduce output voltage ripple. A boost dc-dc converter is also called a step-up converter since it “steps up” the input voltage. As power (P = VI) must be unspoiled, the output current is lower than the source current.

A dc-dc boost converter has the same elements as the buck dc-dc converter, but this converter produces an output voltage greater than the source. "Boost" converters start their voltage conversion with a current flowing through the inductor (switch is closed). Then the switch is open leaving the current no other path to go than through a diode (functions as one way valve), the current then wants to slow really fast and the only way it can do this is by increasing it's voltage (akin to pressure) at the end that connects to the diode, and switch. If the voltage is high enough it opens the diode, and one through the diode, the current can't flow back. This is the very basic concept of boost converter.

Circuit analysis: Analysis of the boost converter begins by making these assumptions:

- The circuit is in the steady state mode.
- The inductor current is continuous (always positive)
- The capacitor is learg enough to maintain a constant output voltage Vo.
- The switching cycle is T, the switch is considered closed for time DT and open for time (1-D)T
- The components are ideal

Like Buck converter boost also has two mode of operation. Details are described below:

2.4.2.1 Operating principle of Boost Converter

The main principle of a dc-dc boost converter is the inclination of an inductor to repel changes in current through it. When being charged it works as a load and absorbs energy (a bit like a resistor); when starting discharged it works as an energy source (a bit like a battery). The voltage it generates at the time of the discharge cycle is related to the degree of change of current.

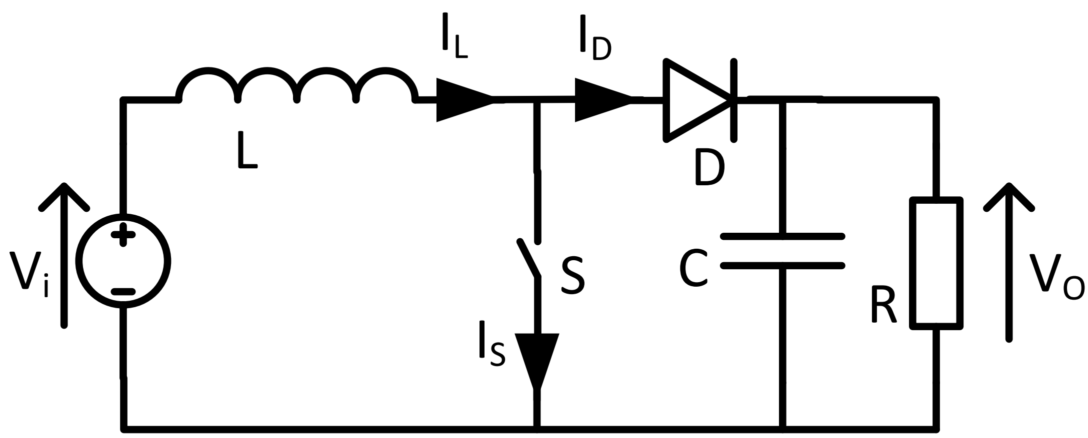
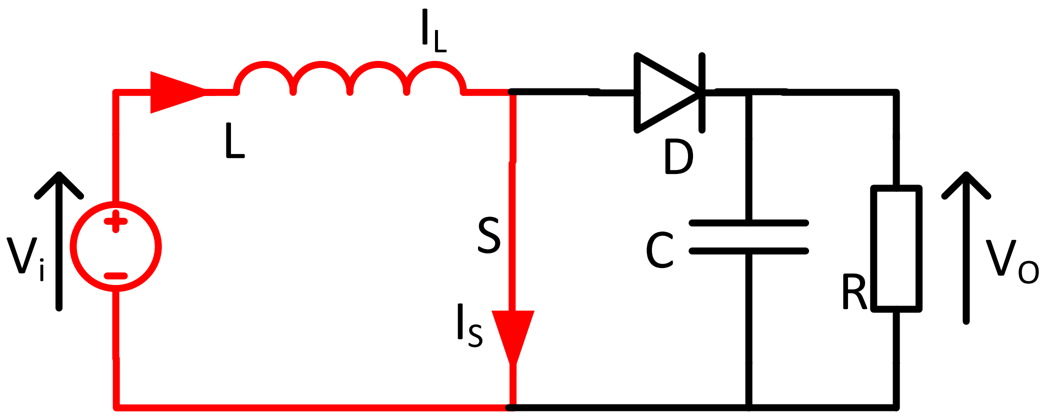
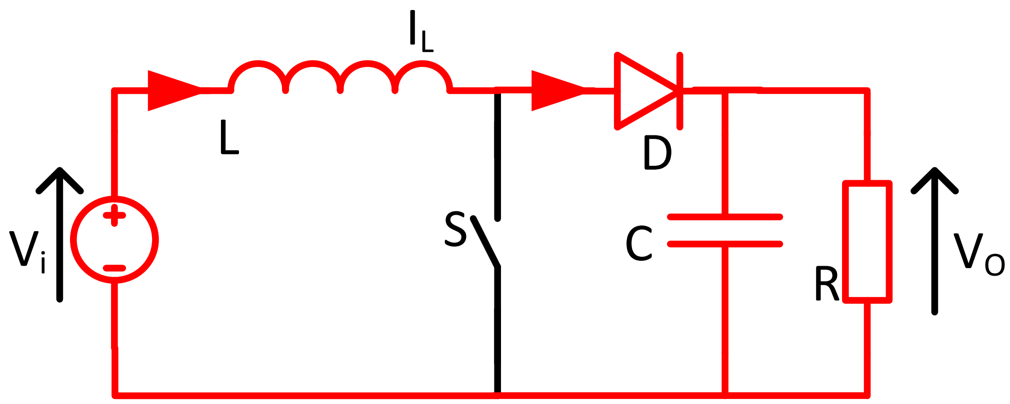


Figure 2.7 Boost Converter Schematic.



(a) On-state



(b) Off-state

Figure 2.8 The two basic configurations of a dc-dc boost converter, conditional on the state of the switch S.

The basic operation of a dc-dc boost converter contains of 2 separate states (Figure 2.8):

- For the On-state, the switch S (shown in the figure 2.8 (b)) is closed, in an increase in the inductor current occurs;
- For the Off-state, the switch is off and the only path provided to inductor current is through the capacitor C, the load R and the flyback diode D. These results in transferring the energy collected during the On-state into the capacitor.
- The input current and inductor current are same which can be seen (in figure 2.8 (b) Off-State). So it is not discontinuous as it was in the buck converter circuit and the necessities on the input filter are relaxed linked to a buck converter.

2.4.2.2 Continuous Conduction Mode (CCM)

When a dc-dc boost converter works in continuous mode, the current through the inductor (I_L) never drops to zero. Figure 2.9 displays the general waveforms of voltage and current in a converter operating in the continuous mode. The output voltage can be determined as follows, in that case of an ideal dc-dc converter (i.e. using all the components with an ideal performance) operating in steady state conditions:

At the time of On-time, the switch S is closed, which makes the supply voltage (V_i) seems across the inductor, which causes a change in inductor current (I_L) passing through the inductor during the time period (t) by the formula:

$$\frac{\Delta I_l}{\Delta t} = \frac{V_i}{L} \tag{2.1}$$

At the finish of the On-time, the increase of inductor current I_L is therefore:

$$\Delta I_{L_{on}} = \frac{1}{L}\int_0^{DT} V_i\, dt = \frac{DT}{L} V_i \tag{2.2}$$

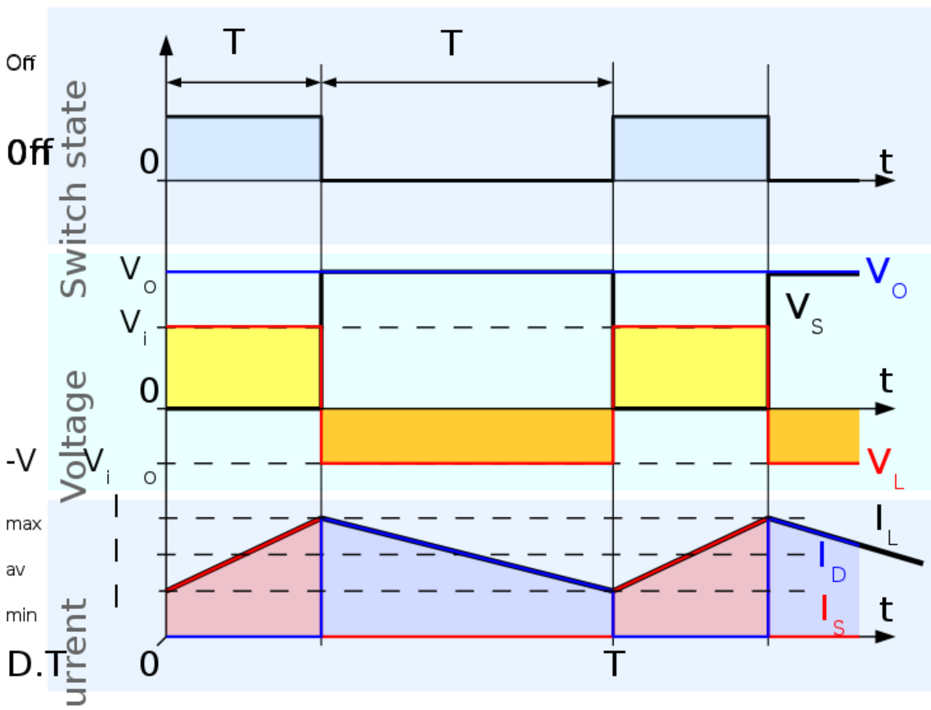


Figure 2.9 Waveforms of current and voltage in a boost converter operating in continuous mode.

D is called duty cycle. It signifies the portion of the commutation period T during on time of the switch. Consequently D ranges between 0 (S is never on) and 1 (S is always on).

During the Off-time, the switch is open, so the current of the inductor flows through the load. If we consider no voltage drop accross the diode, and a capacitor is large enough to maintain constant output voltage, the evolution of IL is:

$$V_i - V_o = L\frac{dI_L}{dt} \tag{2.3}$$

So, the change of inductor current I_L during the Off-time is:

$$\Delta I_{L_{off}} = \int_{DT}^{T} \frac{(V_i - V_o)dt}{L} = \frac{(V_i - V_o)(1-D)T}{L} \tag{2.4}$$

When the converter works in steady-state situation, the amount of energy stored in each of its components should be the same at the starting and at the finish of a commutation period. In exact, the total electrical energy stored in the inductor is given by:

$$E = \frac{1}{2}LI_L^2 \tag{2.5}$$

So, the inductor current should be the same at the biginning and end of the commutation period. This means the overall variation in the inductor current (the sum of the changes) is zero:

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = 0 \tag{2.6}$$

Substituting $\Delta I_{L_{on}}$ and $\Delta I_{L_{off}}$by their expressions yields:

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = \frac{V_i DT}{L} + \frac{(V_i - V_o)(1-D)T}{L} = 0 \tag{2.7}$$

This can be written as:

$$\frac{V_o}{V_i} = \frac{1}{1-D} \tag{2.8}$$

This in turns reveals the duty cycle to be:

$$D = 1 - \frac{V_i}{V_o} \tag{2.9}$$

From the above formula it can be observe that the output voltage is always greater than the input voltage (increases as duty cycle goes from 0 to 1), and that it increases with D, theoretically it can be infinite as D approaches 1. This is why this dc-dc converter is sometimes mentioned as a *step-up* converter.

Sometimes, the required amount of energy demanded by the load is vary small and required a part of whole commutation period to transferre the energy. In this situation, the current through the inductor drops to zero during part of the commutation period. The only difference in the operation stated above is that the inductor is fully discharged at the completion of the commutation period (shown as waveforms in figure 2.5). Although, slight change has a strong effect on the output voltage equation. This can be calculated as follows:

The inductor current at the starting of the cycle is zero, its extreme value $I_{L_{max}}$ $(at\ t = DT)$ is:

$$I_{L_{max}} = \frac{V_i DT}{L} \quad (2.10)$$

During the period when the switch is off, I_L falls to zero after δT:

$$I_{L_{max}} + \frac{(V_i - V_o)\delta T}{L} = 0 \quad (2.11)$$

Using the two previous equations, δ is:

$$\delta = \frac{V_i D}{V_o - V_i} \quad (2.12)$$

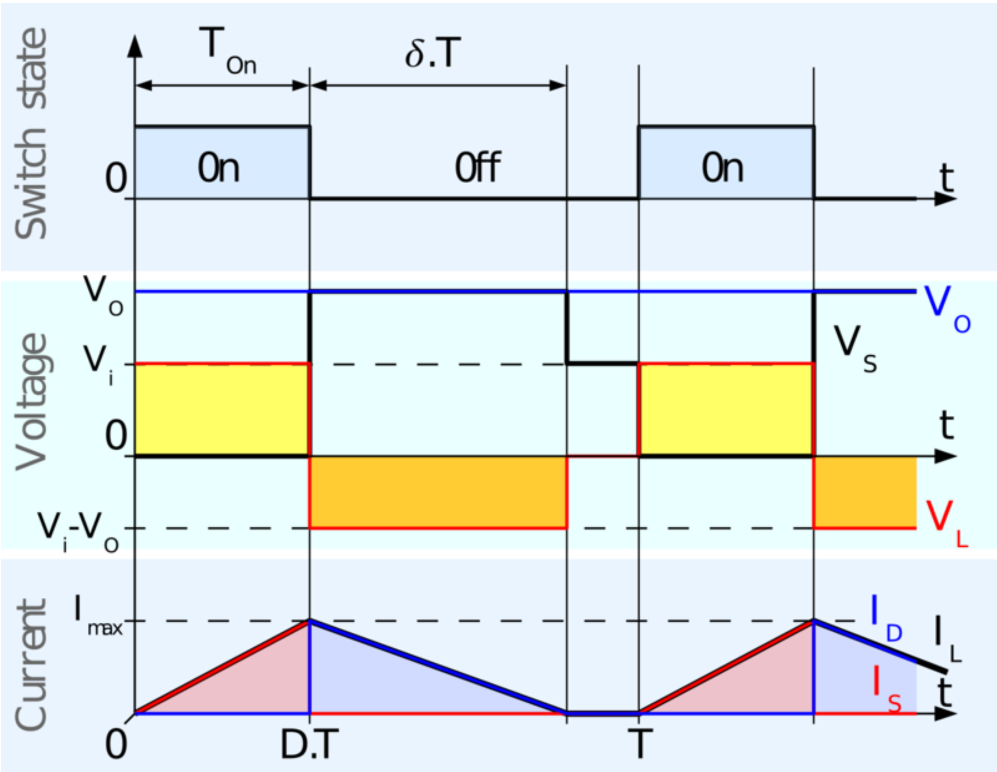


Figure 2.10 Waveforms of current and voltage in a boost converter operating in discontinuous mode.

The current of the load I_o is considered as equal to the average diode current (I_D). From the figure 2.5, the diode current is same to the inductor current during the off-period. So the output current can be express as:

$$I_o = \bar{I_D} = \frac{I_{L_{max}}}{2}\delta \quad (2.13)$$

Replacing $I_{L_{max}}$ and δ by their respective expressions yields:

$$I_o = \frac{V_i DT}{2L} = \frac{V_i D}{V_o - V_i} = \frac{V_i^2 D^2 T}{2L(V_o - V_i)} \quad (2.14)$$

So, the output voltage gain can be express as follows:

$$\frac{V_o}{V_i} = 1 + \frac{V_i D^2 T}{2LI_o} \quad (2.15)$$

Considering the output voltage expression for the continuous mode, this expression for discontenious mode is much more complicated. Also, in discontinuous operation, the gain of output voltage is not only depends on the duty ratio, but also on the value of inductor, input voltage, switching frequency, and the output current.

2.4.3 BUCK-BOOST Converter

Another basic switched mode converter is the buck-boost converter. The output of the buck-boost converter can be either higher or lower than the input voltage. Assumption made about the operation of this circuit is same as it was for the previous converter circuits.

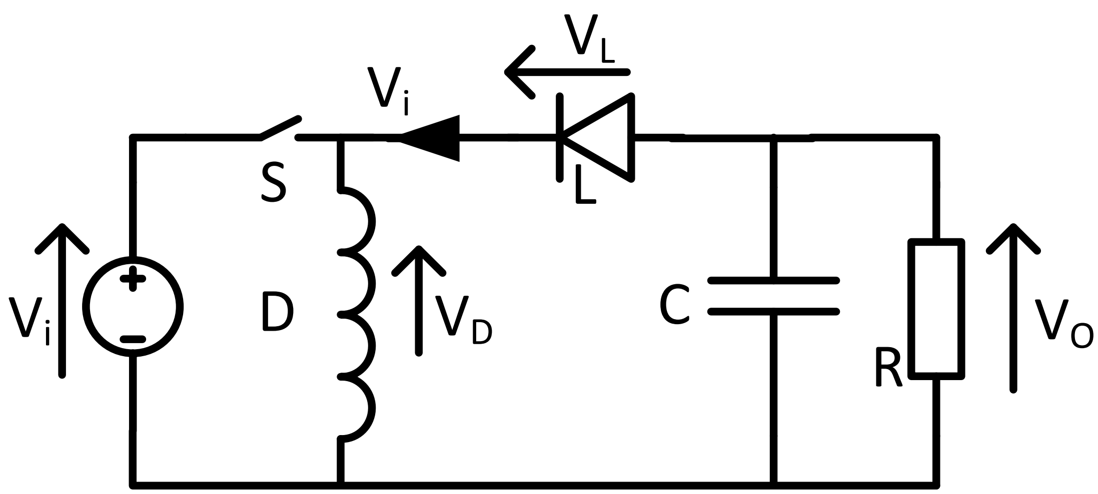
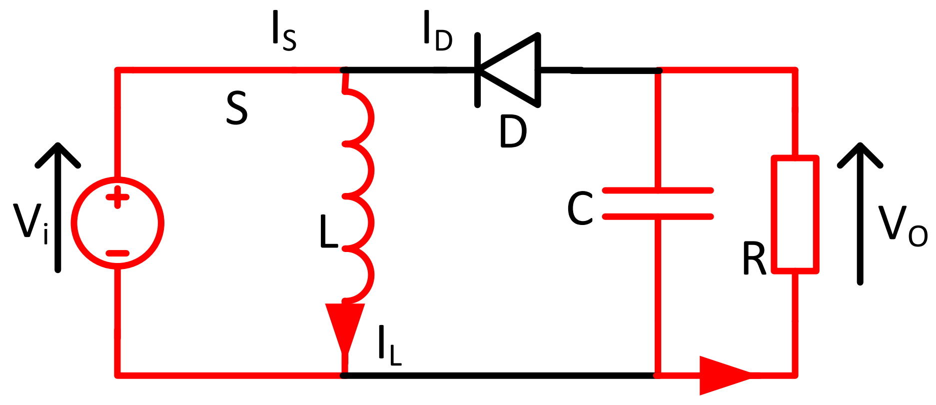


Figure 2.11 Schematic of buck-boost converter

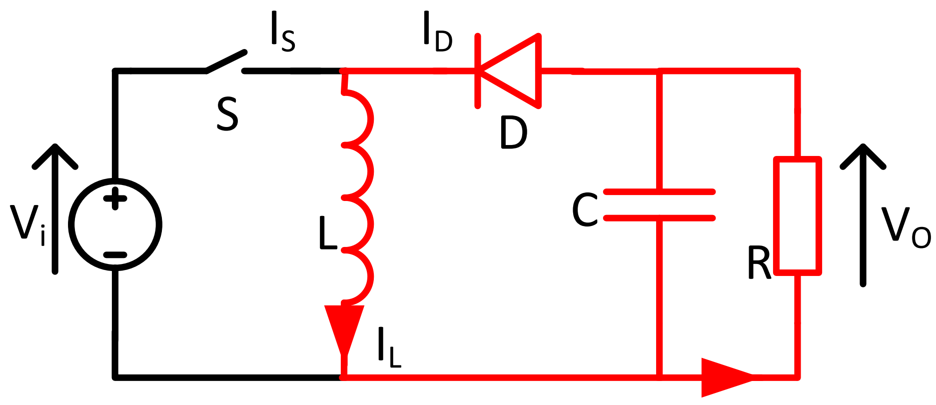
When the switch is turned-on, the input voltage source supplies current to the inductor, and the capacitor supplies current to the resistor (output load).When the switch is opened, the inductor supplies current to the load via the diode D.

The basic principle of the buck–boost converter is fairly simple (Figure 2.11):

- For the On-state, the input voltage source is proportional to the inductor (L). Inductor gatheres energy and the capacitor supplies energy to the output load.



(a) On-state



(b) Off-state

Figure 2.12 The two operating states of a buck–boost converter:

- In the Off-state, the inductor is connected to the capacitor and load, so energy is transferred from inductor to capacitor and load.
- Output voltage polarity is opposite to that of the input;

2.4.3.1 Continuous Mode of BUCK-BOOST converter

In continuous conduction mode the inductor *L* never falls to zero during a commutation period. The voltage and current waveforms in an ideal buck-boost converter is shown in figure 2.13.

Starting from t = 0 upto t = DT, the converter is in On-State, so the switch *S* is on. The inductor current (*I*L) changing rate is therefore given by

$$\frac{dI_L}{dt} = \frac{V_i}{L} \tag{2.16}$$

At the end of the On-state, the increase of I_L is therefore:

$$\Delta I_{L_{on}} = \int_0^{DT} d\, I_L = \int_0^{DT} \frac{V_i}{L} dt = \frac{V_i DT}{L} \tag{2.17}$$

D is called as duty cycle. It signifies a portion of the commutation period *T* for which the switch is on. Therefore *D* changes between 0 (*S* is never on) and 1 (*S* is always on).

During the Off-period, the switch *S* is open and the inductor current flows through the load. Asuming no voltage drop in the diode, and considering a large enough capacitor to maintain a constant voltage, the evolution of I_L is:

$$\frac{dI_L}{dt} = \frac{V_o}{L} \tag{2.18}$$

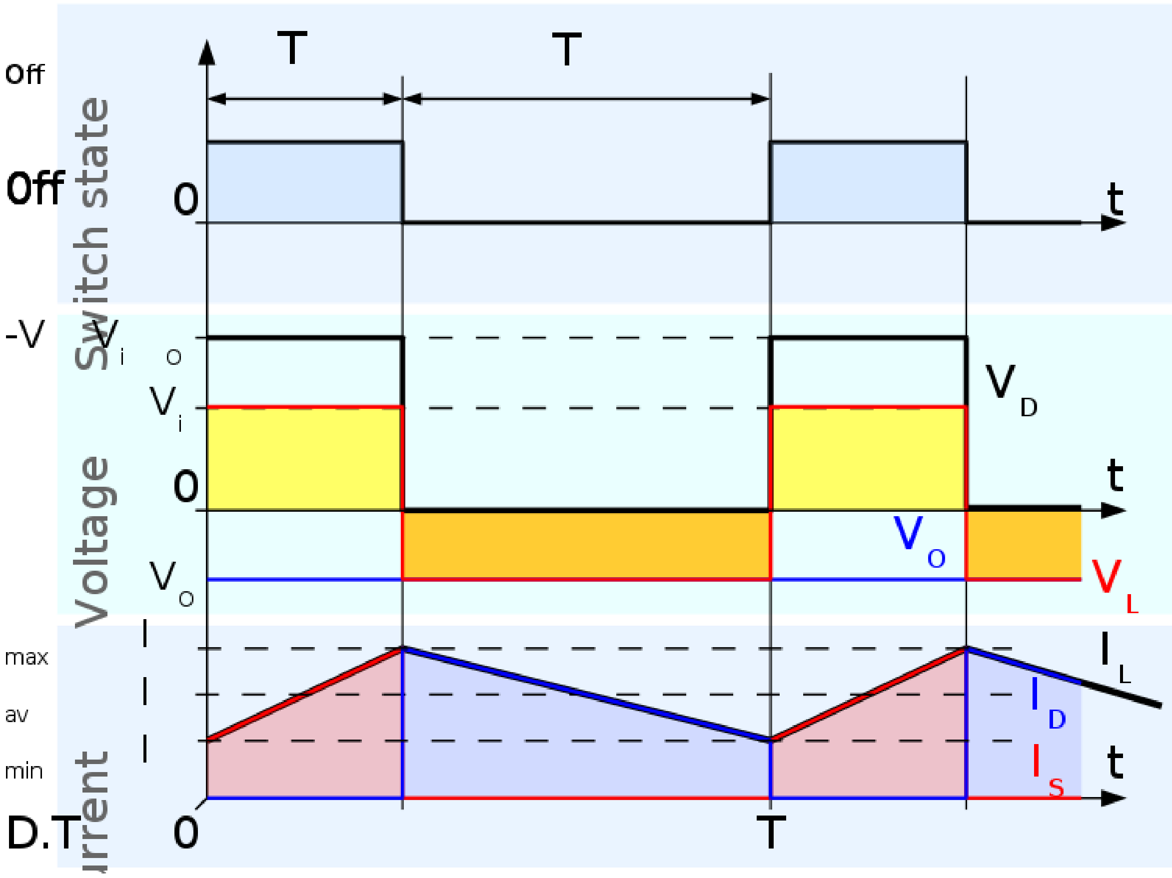


Figure 2.13 Waveforms of current and voltage in a buck–boost converter operating in continuous mode.

Therefore, the change of I_L for the Off-period is:

$$\Delta I_{L_{off}} = \int_0^{(1-D)T} dI_L = \int_0^{(1-D)T} \frac{V_o dt}{L} = \frac{V_o(1-D)T}{L} \qquad (2.19)$$

Assuming the steady-state operation of the converter, the amount of total energy stored in each of its inductor and capacitor has to be the same at the starting and at the completion of a commutation cycle. So, the energy in an inductor is given by:

$$E = \frac{1}{2} L I_L^2 \qquad (2.20)$$

It is obvious that the value of IL at the end of the Off state must be the same as the value of IL at the beginning of the On-state, i.e. the sum of the variations of IL during the on and the off states must be zero:

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = 0 \qquad (2.21)$$

Substituting $\Delta I_{L_{on}}$ and $\Delta I_{L_{off}}$ by their expressions yields:

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = \frac{V_i DT}{L} + \frac{V_o(1-D)T}{L} = 0 \qquad (2.22)$$

This can be written as:

$$\frac{V_o}{V_i} = \frac{-D}{1-D} \qquad (2.23)$$

This in return yields that:

$$D = \frac{V_o}{V_o - V_i} \qquad (2.24)$$

From the above expression we found that output voltage is alwys negative an the absolute value increases with the increase of duty cycle D. Apart form the polarity the converter can either be operated as step up or step down converter.

2.4.3.2 Discontinuous Mode of BUCK-BOOST converter

When the load demand very small current it can ve transfer in a fraction of the total commutation period. In that case inductor current may fall to zero for a part of a period and inductor may be completely discharge at the end of the commutation period.

As the inductor current at the starting is zero, its extreme value $I_{L_{max}}$ (at t=DT) is

$$I_{L_{max}} = \frac{V_i DT}{L} \qquad (2.25)$$

During the off-period, inductor current I_L drops to zero after δ.T:

$$I_{L_{max}} + \frac{V_o \delta T}{L} = 0 \tag{2.26}$$

Using the two previous equations, δ is:

$$\delta = -\frac{V_i D}{V_o} \tag{2.27}$$

The load current *and* average diode current is same. From figure 2.14, it can be observed that the diode current and inductor current is equal during the off-state. So, the output current can be express as:

$$I_o = \overline{I_D} = \frac{I_{Lmax}}{2}\delta \tag{2.28}$$

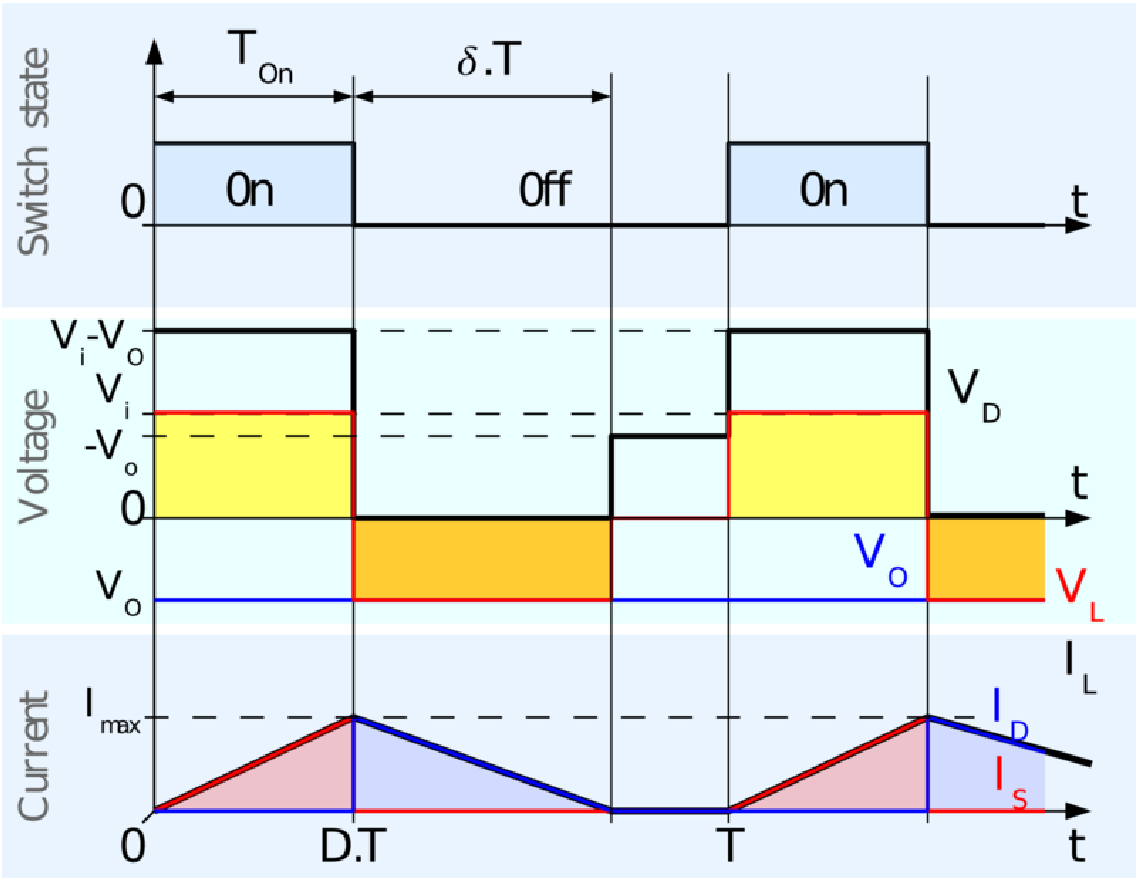


Figure 2.14 Waveforms of current and voltage in a buck–boost converter operating in discontinuous mode.

Replacing $I_{L_{max}}$ and δ by their respective expressions yields:

$$I_O = -\frac{V_i DT}{2L}\frac{V_i D}{V_o} = -\frac{V_i^2 D^2 T}{2LVo} \tag{2.29}$$

Therefore, the gain of the output voltage can be written as:

$$\frac{V_o}{V_i} = -\frac{V_i^2 D^2 T}{2 L I_o} \tag{2.30}$$

Comparing to the equations of the output voltage gain for the continuous conduction mode, this expression for discontinuous mode is much more complex. Besides, in discontinuous operation mode, the output voltage isnot only dependent on duty cycle, but also on the value of inductor, input current and output voltage.

As told at the beginning of this section, the converter operates in discontinuous mode when low current is drawn by the load, and in continuous mode at higher load current levels. The limit between discontinuous and continuous modes is reached when the inductor current falls to zero exactly at the end of the commutation cycle. With the notations of figure 2.15, this corresponds to:

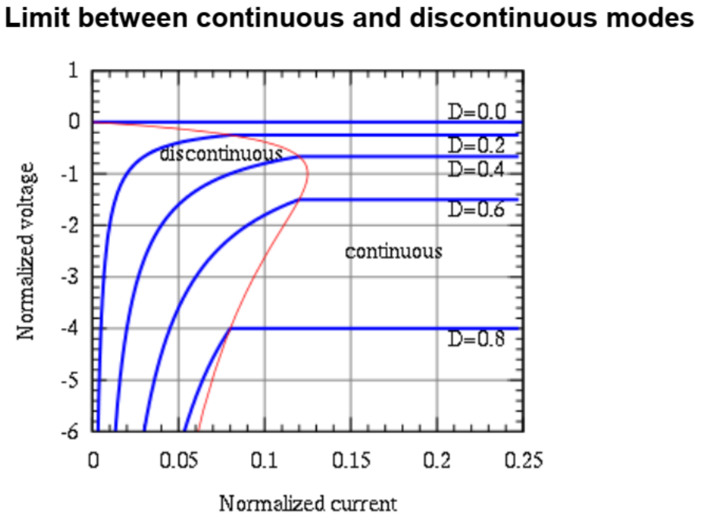


Figure 2.15 Evolution of the normalized output voltage with the normalized output current in a buck–boost converter.

$$DT + \delta T = T \tag{2.31}$$

$$D + \delta = 1 \tag{2.32}$$

Here, the output current can be given by:

$$I_{o_{lim}} = \bar{I}_D = \frac{I_{Lmax}}{2}(1 - D) \tag{2.33}$$

Replacing by the equation given in the *discontinuous conduction mode* section yields:

$$I_{o_{lim}} = \frac{V_i D T}{2L}(1 - D) \tag{2.34}$$

This is the limit between continuous conduction mode and discontinuous conduction modes, and it fulfils the expressions of both modes. Thus, using the output voltage expression of continuous mode, the previous expression can be written as:

$$I_{o_{lim}} = \frac{V_i DT}{2L} \frac{V_i}{V_o}(-D) \quad (2.35)$$

2.4.4 Interleaved Boost Converter

A boost or step up converter is a power converter which has a higher DC voltage at the output than at the input. Owing to the large ripple content in the current, conventional boost converters are incompatible in application involving high power. Rather interleaved boost converter is suited for high power application due to lower ripple content in current. Multiple identical step up converters having same phase shift and switching frequency is assembled parallelly to construct an interleaved boost converter. IBC has lower ripple in input-output current and voltage waveforms. It can operate on higher switching frequency and thus reduces loss and scale down the converter. The circuit diagram of a two- phase IBC is given in "Fig. 2.16".

In a two-phase boost converter, a pair of boost converters is kept 180° apart in phase. Current at the input is the summation of individual inductor current (e.g. $IL_1 \& IL_2$). Since the converter operates 180° out of phase, each inductor cancels the ripple of the other and thus the total input current ripple is reduced.

When switch S_1 is on and switch S_2 is off, the current IL_1 and IL_2 of the inductor is,

$$\frac{dIL_1}{dt} = \frac{V_{in}}{L_1} \quad (2.36)$$

$$\frac{dIL_2}{dt} = \frac{V_0 - V_{in}}{L_2} \quad (2.37)$$

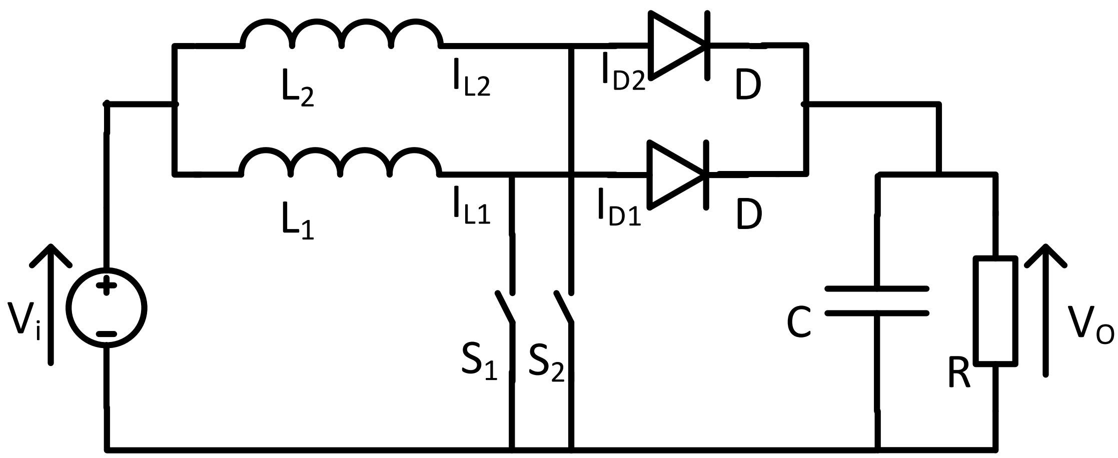


Figure 2.16 Interleaved Boost Converter

Considering first phase when one switch ($e.g. S_1$) is off and other switch (e.g. S_2) is on, the inductor current is,

$$\frac{dIL_1}{dt} = \frac{V_0 - V_{in}}{L_1} \quad (2.38)$$

$$\frac{dIL_2}{dt} = \frac{V_{in}}{L_2} \quad (2.39)$$

$$\frac{V_{in}}{L_1} = \frac{V_0 - V_{in}}{L_2} \quad (2.40)$$

$$\frac{V_0 - V_{in}}{L_1} = \frac{V_{in}}{L_2} \quad (2.41)$$

The current of the inductors is out of phase and cancels the ripple of one another. From equation “Eq. 2.20”and “Eq. 2.21” the value of the inductor can be calculated for known value of input and output voltage. The duty cycle, can be found using “Eq. 2.22” given below.

$$D = 1 - \frac{V_{in}}{V_{out}} \quad (2.42)$$

Duty cycle is expressed in percentage and is the ratio of time the circuit is ON to the total time period. It is generated by a reference DC signal along with a saw-tooth waveform is fed to the input of a comparator to generate a pulse with desired duty cycle. The value of the capacitor, C_{min} can be found using “Eq. 2.23” shown below.

$$C_{min} = \frac{V_{out}\, D}{\Delta V_{out}\, Rf} \quad (2.43)$$

Where, output voltage change is denoted by ΔV_{out}, load resistance by R and the the switching frequency by f. To calculate the basic parameters (e.g. value of inductor, capacitor, duty cycle) all the above equations are used.

Interleaved boost converter can be employed in power factor correction circuits, photovoltaic system, fual cell system etc[47]-[49]. Design methodology of IBC bas been explained in this paper. The calculation of the value of inductor and the capacitor have been done. The ultimate objective of this report is to design an IBC with reduced input current ripple and thye output voltage ripple.

2.4.4.1 Design Aspect of IBC

At the beginning of the design of Interleved Boost Converter it needs to select the number of phases, inductors, power switches, duty ratio etc [50]. This requires a good knowledge of the peak currents. The inductors and the diodes in all channels should be kept identical. Designing the components in the power path is similar to that of the single boost converter with which operates at 1/n times the power.

A. Selection of number of phases: It has been observed that the ripple in the input current decreases with increase in the number of phases. On the other hand, the cost and complexity of the circuit also increases. So, a compromise had to be made between them. In this paper, the number of phases was chosen to be two to reduce the input ripple content without increasing the complexity and cost drastically.

B. Selection of duty ratio: Duty ratio directly effect the ripple of input current and hence it has to be selected carefully. From the above plot of the input current vs the duty ratio, it can be observed that for an N-phase IBC, the ripple of input current can be zero at a particular values of duty ratio and inductor value. For example for a 3- phase converter, the ideal duty ratio at which the ripple is zero is 0.7.

C. Choosing suitable inductance and Capacitance: The value of the nominal capacitor to be employed can be computed using the equation (2.44),

$$C = V_s \times D \times f \times R \times \Delta V_o \quad (2.44)$$

where, V_o and V_s represent the output and input voltage respectively, D is the duty cycle, R is the load resistance, f is the switching frequency and ΔV_o is the ripple in the output voltage.

Similarly, the inductor value can be calculated using equation (2.45),

$$L = V_s \times D \times f \times \Delta I_L \quad (2.45)$$

In above equation, ΔI_L signifies the ripple in the inductor current, IGBT was used for switching and the conduction losses related with the device is less when compared to MOSFET. In general, they are used in high current ,high voltage, and low switching frequency applications.

CHAPTER 3

MODEL BUILDING

Due to the low DC voltage generated by solar PV in the range 12~75V power converter like DC-DC converter is mandatory to upscale the output voltage from Solar PV system as per requirement of the the utility grid or any convenient utilization voltage[11]. The charging voltage or current output from the PV modules or arrays will be reglated by the DC-DC converter and this has inturn sparked the appeal of highly efficient DC-DC[12, 13]. PV array generated voltages widely varies due to solar irradiation, ambient temperature, unanticipated alteration in shadows, the neatness level of the surface of the PV module, disproportionate PV modules, etc.[9, 14, 15]. Hence, to address the unpredictable and low DC voltage output from PV array, a design of DC-DC boost converter becomes a pressing need.

3.1 Finding Suitable Topologies of Boost Converter for Photovoltaic System

Although the amalgamation of DC-DC converter with the PV systems or alternative renewable energy souces will result in efficient application, the various topology of the the former has not yet been examined particularly. Thus, this section presents topologies of DC-DC converter in various solar PV application systems.

The distinct requirements of the DC loads are met by various designed topologies of DC-DC converter. Different topologies of DC-DC converter can be operated as switching mode regulators which are able to convert uncontrolled DC voltage to useful utilization voltage. This can be made possible by carrying the DC voltage output through power switching devices for PWM switching. This is achievable by buck, boost, buck-boost,cuk, Single Ended Primary Inductor Converter (SEPIC) and flyback-boost converter [1, 15, 22]. Turn-on and Turn-off is required from the power switching devices for each of the converters. Applications and diffterent parameters of the designed circuit determines the use of various power switching devices such as, BJTs, MOSFETs, thyristors and IGBTs. A gate dive circuit is used to generate the required gating signal for the power switching devices[22]. The output voltage, frequency and phase delay of the DC-DC converters are controlled by the Pulse Width Modulation (PWM) switching of the DC-DC converter [2, 23].

3.2 Choosing Interleaved Boost Converter for PV application

Basic DC-DC boost converter is the preferred for PV applications. This is due to topology of this converter. The inductor in the input side reduces the ripple in the current drawn from PV and hence its losses. Moreover, the diode in the basic cell protects the PV module from reverse current. However, for reduced ripple level in the PV current, a volumetric inductor has to be used [2] - [4]. Since the efficiency and weight is effected by the inductor, an interleaved boost converter with two cells of basic converter connected in parallel, could be used as a solution. The interleaved boost converter is capable of minimizing the PV current ripple without the need of hefty inductors or high switching frequencies. This is achieved by the introduction of phase shift between the signals at the switched of the parallel cells. The converter can also effectively lower Electromagnetic Interference (EMI). [5]-[8] investigates the application of non-isolated interleaved boost converter. Although the limitations of interleaved boost converter are not featured in the research, the condtion for ripple-free input has been indentfied.

3.3 Traditional IBC

A boost or step-up converter is a power converter which has a higher DC voltage at the output than at the input. Owing to the large ripple content in the current, conventional boost converters are incompatible in applications involving high power. Rather interleaved boost converter is suited for high power application due to lower ripple content in current.

Multiple identical step-up converters having same phase shift and switching frequency is assembled parallelly to construct an interleaved boost converter. IBC has lower ripple in input-output current and voltage waveforms. It can operate on higher switching frequency and thus reduces loss and scale down the converter. The circuit diagram of a two- phase IBC is given in "Fig. 3.1".

In a two-phase boost converter, a pair of boost converters is kept 180° apart in phase. Current at the input is the summation of individual inductor current (e.g. $IL_1 \& IL_2$). Since the converter operates 180° out of phase, each inductor cancels the ripple of the other and thus the total input current ripple is reduced.

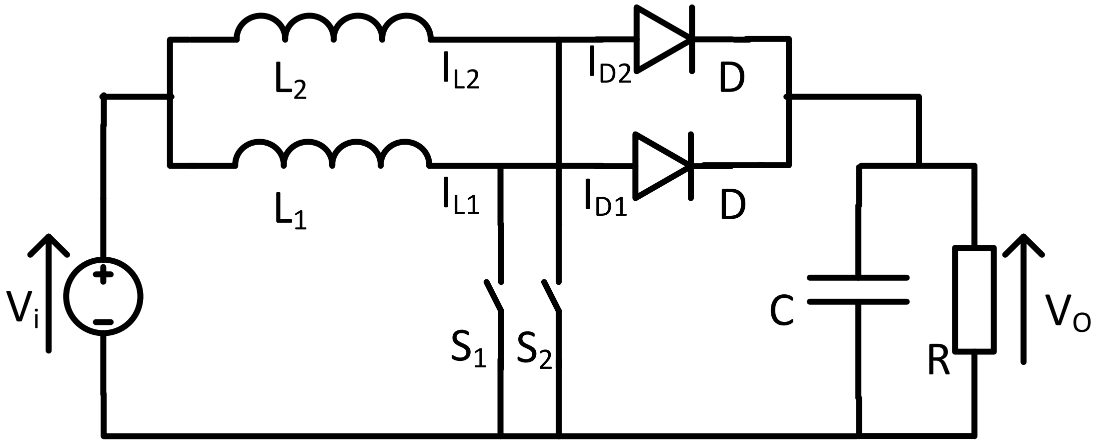


Figure 3.1 Circuit Diagram of IBC

Duty cycle is expressed in percentage and is the ratio of time the circuit is ON to the total time period. It is generated by a reference DC signal along with a saw-tooth waveform is fed to the input of a comparator to generate a pulse with desired duty cycle. The value of the capacitor, C_{min} can be found using "Eq. 3.8" shown below.

$$C_{min} = \frac{V_{out}\,D}{\Delta V_{out}\,Rf} \tag{3.8}$$

Where, output voltage change is denoted by ΔV_{out}, load resistance by R and the switching frequency by f. To calculate all the basic parameters, (e.g. value of inductor, capacitor, duty cycle) the above equations are used.

3.4 Why Two Phase IBC

Interleaved boost converter may have multiple phase and the performance depends on the number of phases. Usually the input and output ripple of the converter decrease with the increase of phase. But at the same time the complexity and the cost of the converter increase also increase. It is advantage to use multi-phase IBC when the difference between input and output voltage is huge. For typical photovoltaic application output voltage may be two or three times of the input voltage. For that case two phase IBC was selected for this research where input voltage is 33V to 70V and the output voltage is 90V.

3.5 Selecting Suitable Components for IBC

For a two phase interleaved boost converter two single-phase soft-switching boost converters are connected in parallel and then to a single output capacitor. So one additional inductor, one additional diode and two switch is required for an IBC. The performance of the converter depends on the value of capacitor and inductor. This paper investigates the performance variation of IBC with the change of inductor value because inductance has a big impact on input current ripple and output voltage ripple.

3.6 Output Voltage vs Duty Ratio for IBC

Output voltage of the boost converter depends on input voltage and duty cycle. If the input voltage is constant then for a constant output voltage a constant duty cycle is required. But the output voltage of a solar PV system is variable in nature so for a constant output voltage a variable duty cycle for boost converter is required and it depends on the input voltage of the PV module. If input voltage is increase then duty cycle should decrease to maintain a constant output voltage and vice versa. As the range of the input voltage variation increase the range of the duty cycle variation also increase. But changing duty cycle is not straight forward and some important aspect should keep in mind. The duty ratio has effect on following parameters:

1. Output voltage: With the increase of duty ratio output voltage increase and in decrease in duty ratio output voltage decrease for same input voltage.
2. Output current: With the increase in duty ratio output current decrease and vice versa.
3. Effective input impedance: The effective input impedance of the converter increase with the decrease of duty ratio. The impedance value is very high for duty ratio in the range 0 to 0.5.
4. Minimum inductance: The minimum inductance required decrease exponentially with the increase in duty ratio.
5. Minimum capacitance: The minimum capacitor required increase linearly with the increase in duty ratio.

Above figure (figure 3.2) shows the minimum inductance and capacitance required for a specific duty cycle. From the graph it is clear that minimum inductance value required reduces when operate in higher duty cycle. The relation is not linear but it reduces exponentially. Unlike inductance at higher duty cycle higher capacitance is required and the relation is linear. For lower input voltage higher duty ratio is required to maintain a constant output voltage. So, it is clear that the minimum inductance required is indirectly related to the input voltage and not fixed with the input voltage variation.

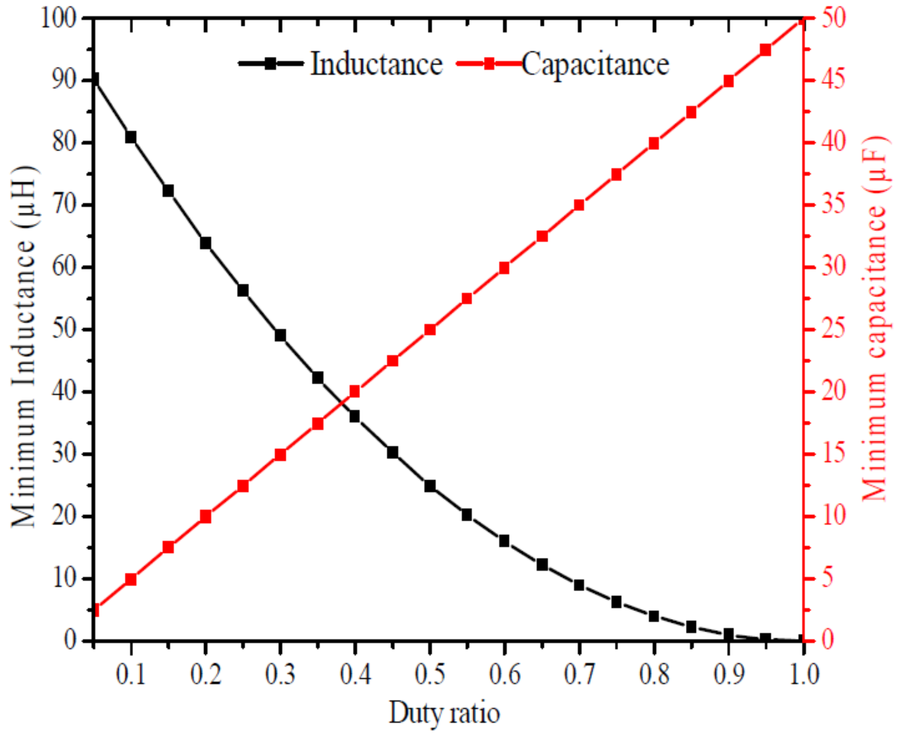


Figure 3.2 Effect of duty ratio on the minimum inductance and capacitance for IBC [51]

Figure 3.3 shows the relation between the input impedance and the duty ratio and the graph is exponential with negative slop. So, it can be said that the input current is directly related to the duty ratio and increases with the increase with duty ratio.

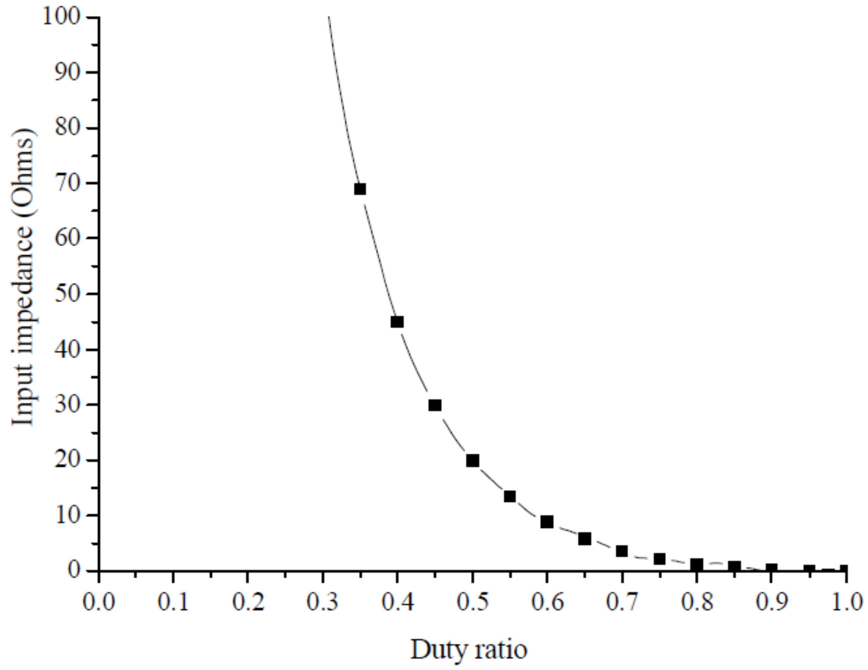


Figure 3.3 Effect of duty ratio variation on the effective input impedance of a buck-boost converter [51]

3.7 Effect of Inductance on IBC

Inductor value has a big impact on performance, size and price of boost converter. Choosing an appropriate inductor for boost convert is very important. With the increase in inductor value parasitic resistance, dc resistance and cost increase. As the resistance increases and saturation current decrease with the increase in inductance, large inductor leads to less conversion efficiency [52].

Smaller inductor has smaller dc resistance, which means smaller dc conducting loss. However, the current ripple becomes larger which causes larger AC loss or core loss [53].

Inductor is also a determinant of the operating mode of a boost converter. Whether a converter will operate in continuous conduction mode (CCM) or discontinuous conduction mode (DCM) or both will depends on inductor value. A superier understanding of the modes of operation of the boost converter can be achieved by accurately sizing the inductor which helps to avoid unpredictable issues.

The current through the inductor in DCM goes from zero during FET on time and is discharged fully to zero before next switching period. However, the current through the inductor in CCM boost is always greater than zero when the current is going up or down due to the stored energy being discharged into the capacitor and load. CCM operation is more commonly used for high power boost converter while DCM is used for low power converter.

The duty cycle in CCM may be changed by varying the input voltage but remains fixed during loading. The operating mode of nearly all CCM Designs usually reverts back to DCM under a certain minimum minimum load since the current through the inductor reaches zero befor the subsequent switching period.

3.8 Finding Optimum Inductor Value for IBC

Considering above advantages and disadvantages of large and small inductance it is clear for best performance a optimum inductor value is required for dc-dc boost converter. Input current ripple is a very important performance parameter of any boost converter. The lower the input current ripple the better the converter is. This input current ripple depends on the inductance of the boost converter in a great extent. In paper [56] the way of calculation of input current ripple for different duty cycle is shown. Figure 3.4 shows the profile of the inductor current according to the switching pattern in DCM. The input current ripple can be calculated using the following formulas shown in Fig. 3.5.

DT means the switching-on time, and $D_A T$ indicates that the phase current becomes zero. Using *D* and D_A, the voltage gain of each phase boost converter and the rising and falling slopes of the inductor current can be expressed.

D_A is varied according to the switching frequency *fs* (1/*T*), the inductance *L*, the duty ratio, and the output current of each phase *io/N*. D_A is expressed as:

$$D_A = D + \frac{2Li_o}{N.TDV_{in}} \quad [56]$$

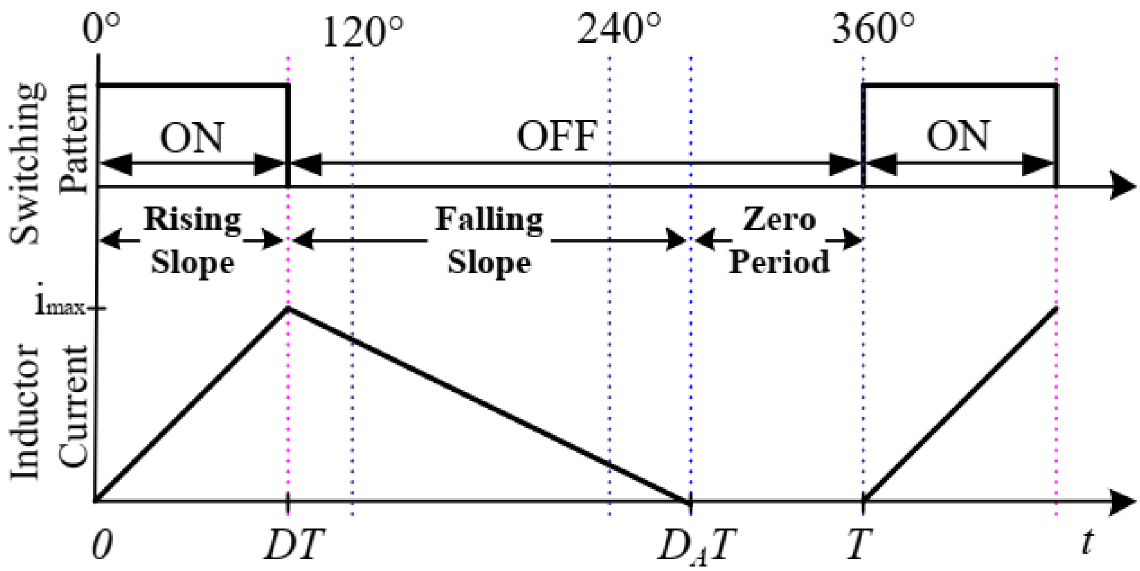


Figure 3.4 Input phase current and switching pattern [56]

Because D_A is determined by several factors, the analysis of the input current in a DCM operation becomes very complicated. Figure 3.5 (a) and (b) show the phase inductor current and input current according to the switching pattern in CCM and DCM of a 3-phase IBC. For CCM, the input current has two slopes, one rising and one falling. The input current of the IBC in CCM is easily analyzed. However, the slope of the phase current in DCM can be one rising and two falling slopes, or two rising and one falling slope, which makes the analysis difficult. In order to analyze the input current, *D*, D_A, and the rising and falling slopes are selected as the analysis criteria.

Using the above current ripple equation the inductor value for different duty ratio can be calculated using the following formulas.

a. For duty ratio D from 0 – 1/3 inductor value can be calculated as:

$$L = \frac{NTV_{in}}{i_0}.D^2 = \frac{TV_{in}}{3i_0} \quad (3.9)$$

Where, L is the required inductor, T is the time period, i_0 is the input current ripple.

b. For duty ration D from 1/3 – 2/3 inductor value can be calculated as:

$$L = \frac{NTV_{in}}{4i_0}.D^2 = \frac{TV_{in}}{3i_0} \quad (3.10)$$

c. For duty ration D from 2/3 – 1 inductor value can be calculated as:

$$L = \frac{NTV_{in}}{2i_0}.D^2 = \frac{TV_{in}}{6i_0} \quad (3.11)$$

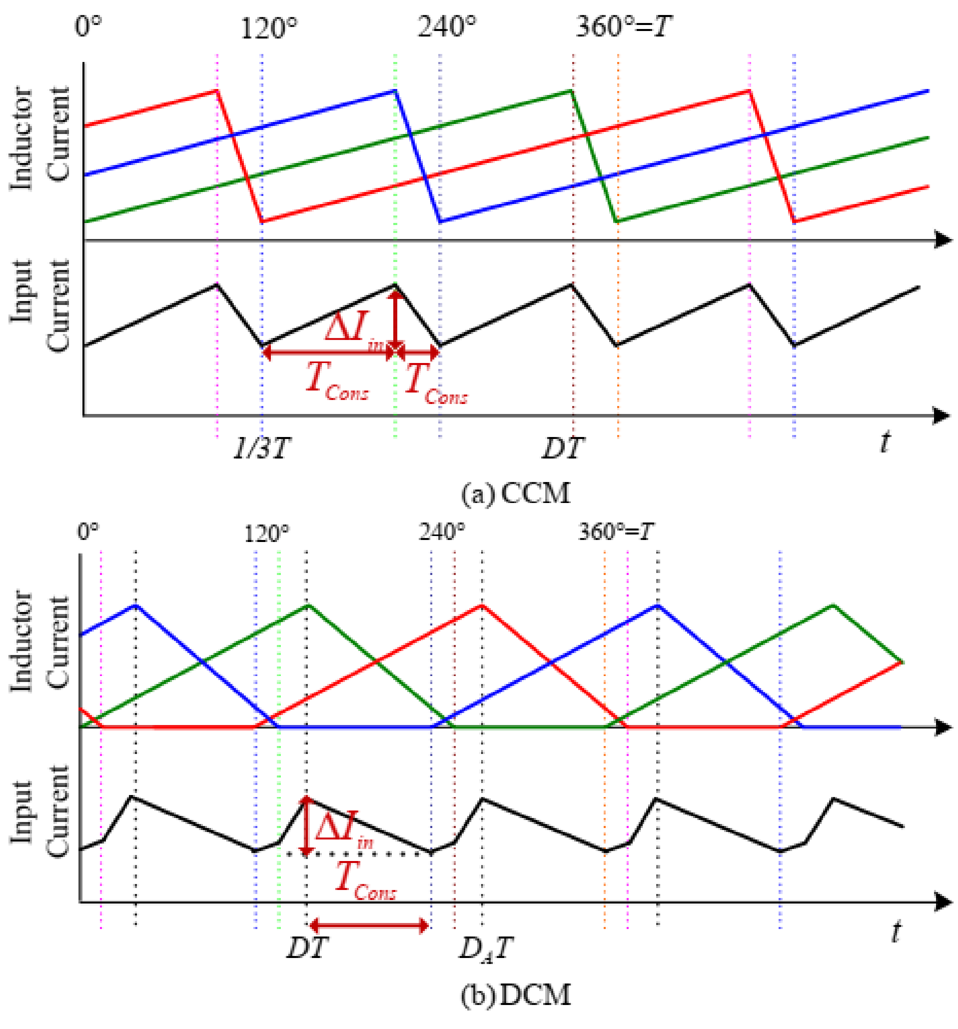


Figure 3.5 Inductor current and input current according to the switching pattern [56].

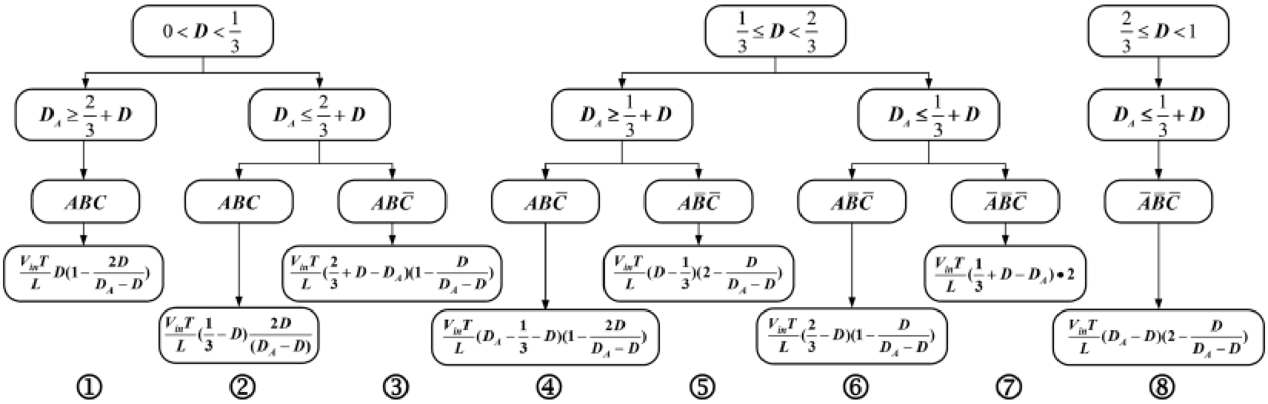


Figure 3.6 Input current ripple magnitude equations for different duty ratio [56]

From the above equations (3.19, 3.10, 3.11) following input current ripple vs input voltage graph can be generated.

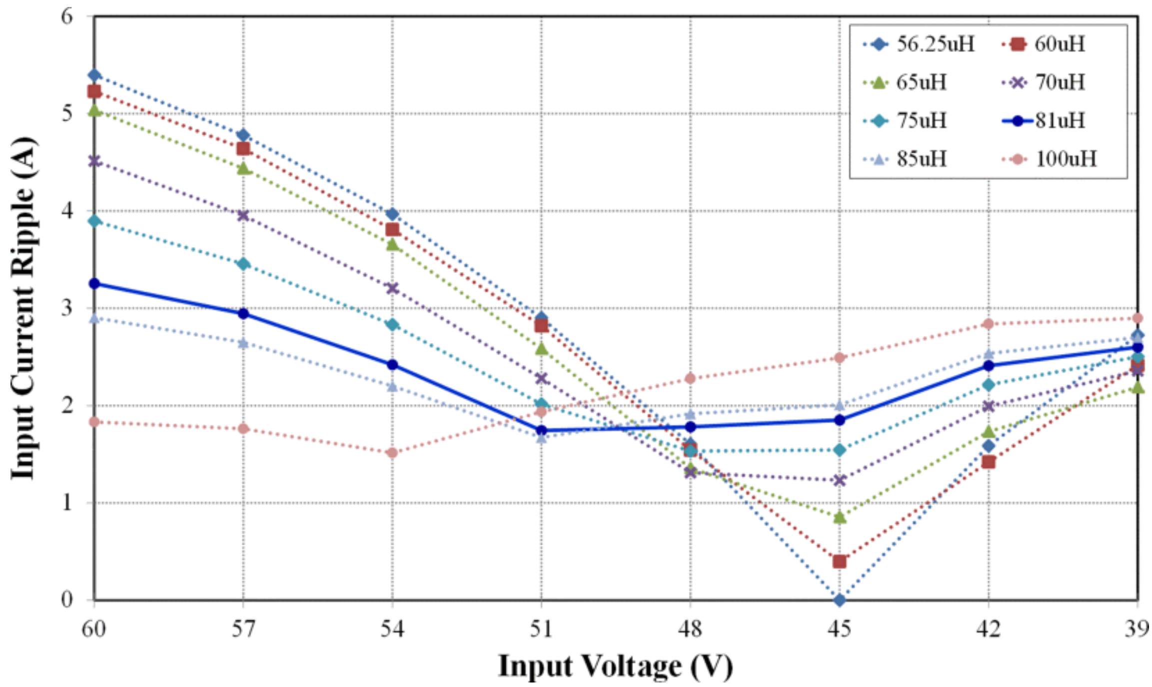


Figure 3.7 Input current ripple vs Input voltage graph [56]

From the figure 3.7 a clear relation between input voltage and input current ripple can be found. It is depicted that for a specific inductor, input current ripple is different at different input voltage. Every inductor has a minimum input current ripple for a specific input voltage and it increases for increasing or decreasing of the input voltage. So, from the above graph we can conclude that, an IBC can generate minimum current ripple for a specific input voltage only. So for minimum input ripple an IBC required different inductance at different input voltage and this is not possible to implement practically.

To make it practical Dong-Hee Kim and G. Choe find an optimized value of the inductor for an input voltage range which is shown in figure 3.7 using the solid blue line. From a careful look on the graph it can be found that actually infinite inductor value is not require for a range of input voltage to keep input current ripple at minimum. Only three different inductors are required to do the job. Three separate inductor value for three different range of duty ratio are given in the following table 3.1. If only one inductor is chosen for the converter than the optimum inductor for the conductor is 81uH.

Table 3.1 Optimum inductor value and duty cycle

Input Voltage Range	Output Voltage	Duty Ratio	Switching Frequency	Inductance	Capacitance
60 V to 51 V	90 V	0 to 1/3	20 KHz	100 uH	940 uF
51 V to 42 V		1/3 to 2/3		75 uH	
42 V to 33 V		2/3 to 1		65 uH	

So, a more efficient IBC can be developed using three separate inductors in case of one optimized inductor. Considering the above fact following new topology (figure 3.8) for interleaved boost converter is proposed in this paper.

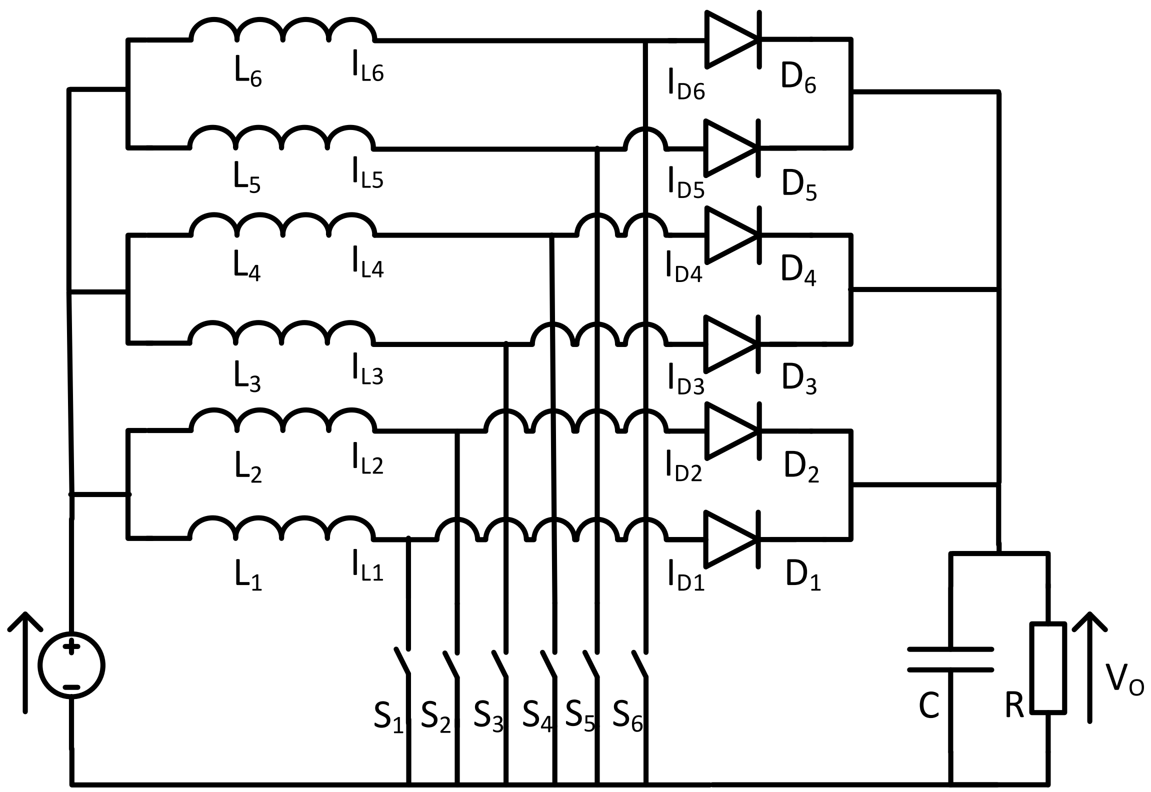


Figure 3.8 Proposed IBC with three separate inductors

In the converter three separate branches are included containing different inductor in each branch and automatic switching occurred in different branches based on input voltage. For generating required switching pulse PWM technique will be used and a control algorithm will be required to maintain the sequence.

3.9 Operation of Proposed Converter

For the edge of illustration a time varying input voltage was chosen. For zero to 4 seconds the input voltage is 45V. According to the table 3.1 the most suitable inductor for this input voltage is 75uH. So, the controller will activate 75uH inductor brunch and corresponding switches are S3 and S4. Generated pulse for S3 and S4 are shown in figure 3.9. The duty cycle is also calculated by the controller and also depends on the input

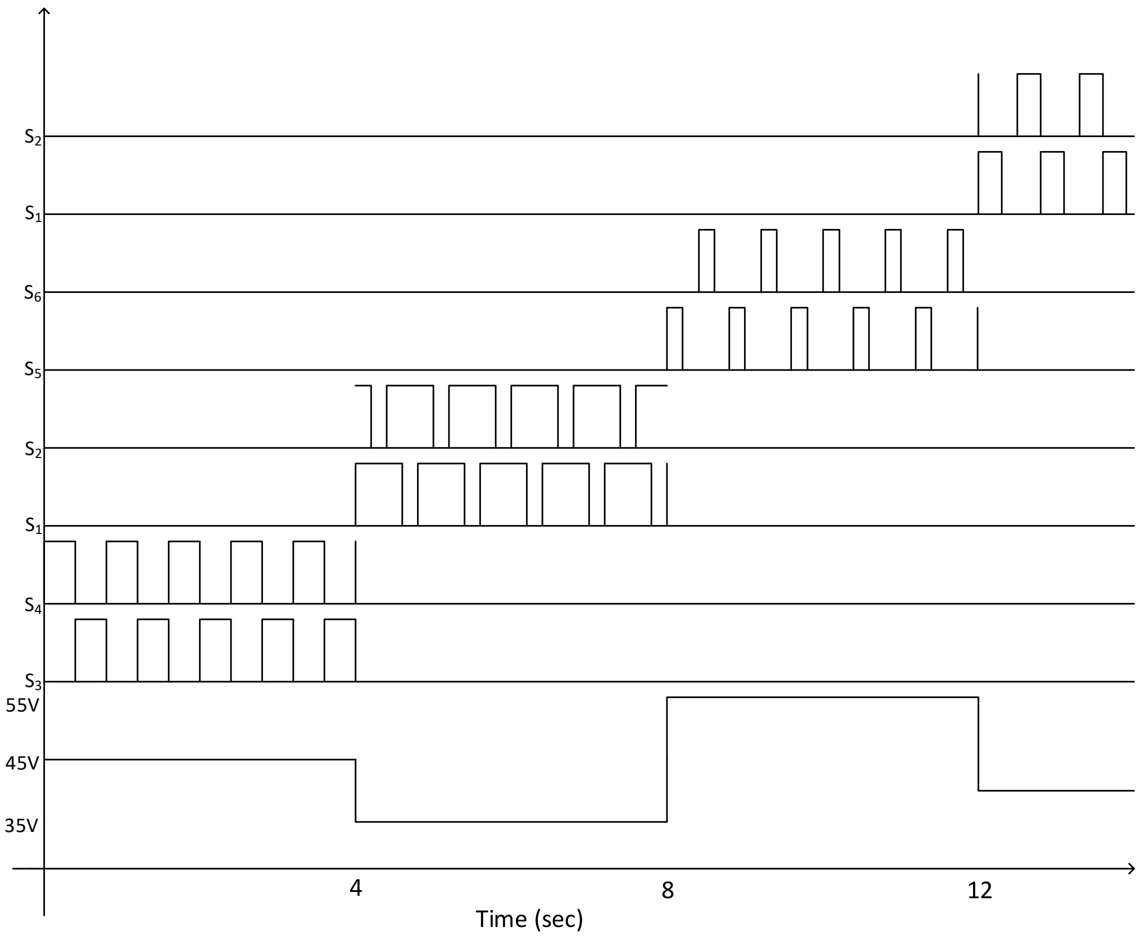


Figure 3.9 Timing diagram of the proposed converter

voltage. The activated branch of the converter is shown in the figure 3.10 with red line. For 4 to 8 seconds the input voltage is 35 volts. As per the calculated inductance 65uH is the optimum inductor for this voltage. The controller activates 65uH branch automatically and the timing pulse for switch S1 and S2 are given in the figure 3.9. The active branch for this voltage is shown in figure 3.12. When the input voltage is 55V then

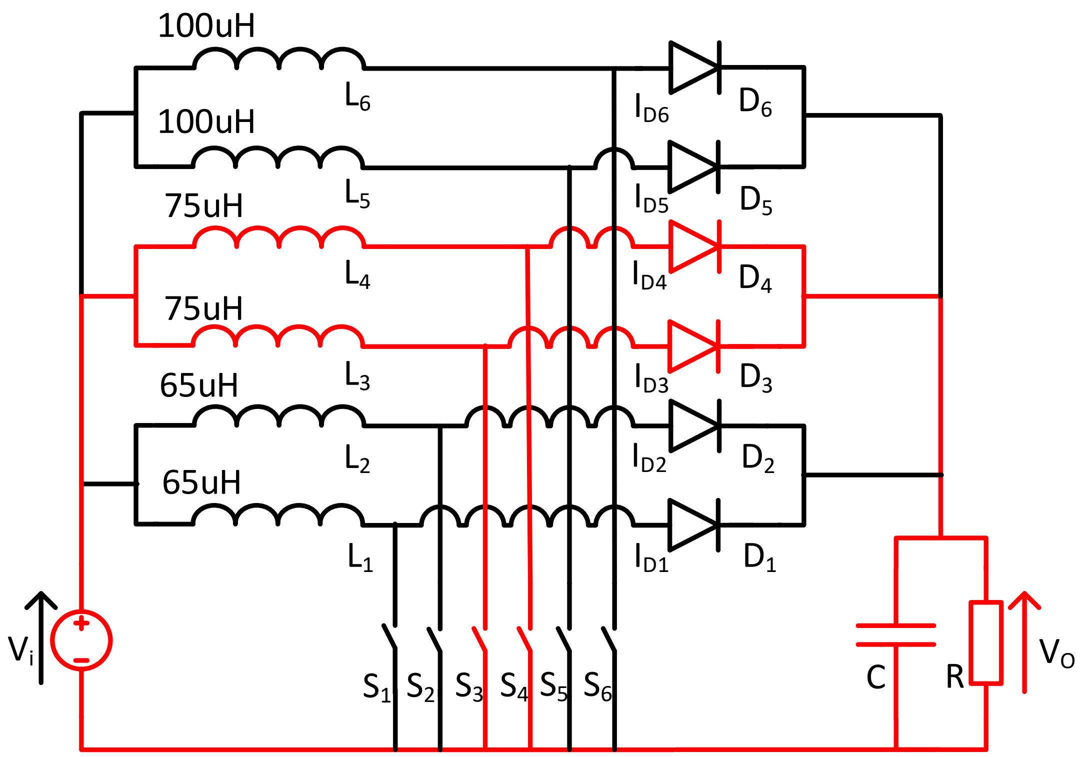


Figure 3.10 Operation state for 45V input

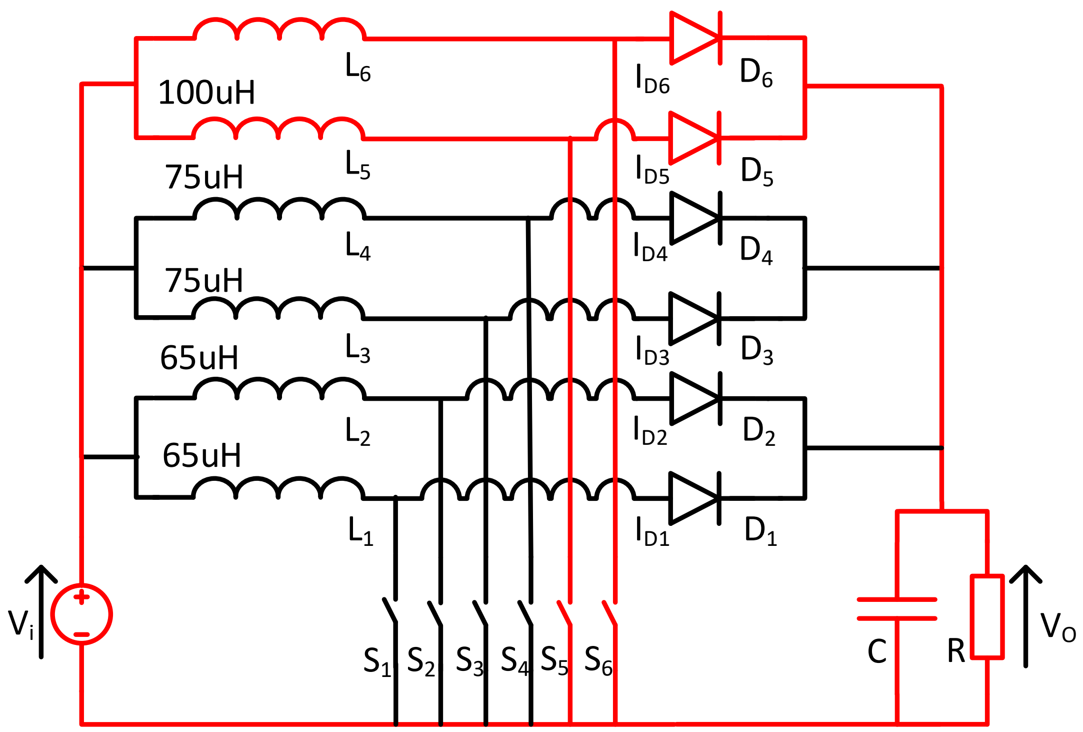


Figure 3.11 Operation state for 55V input

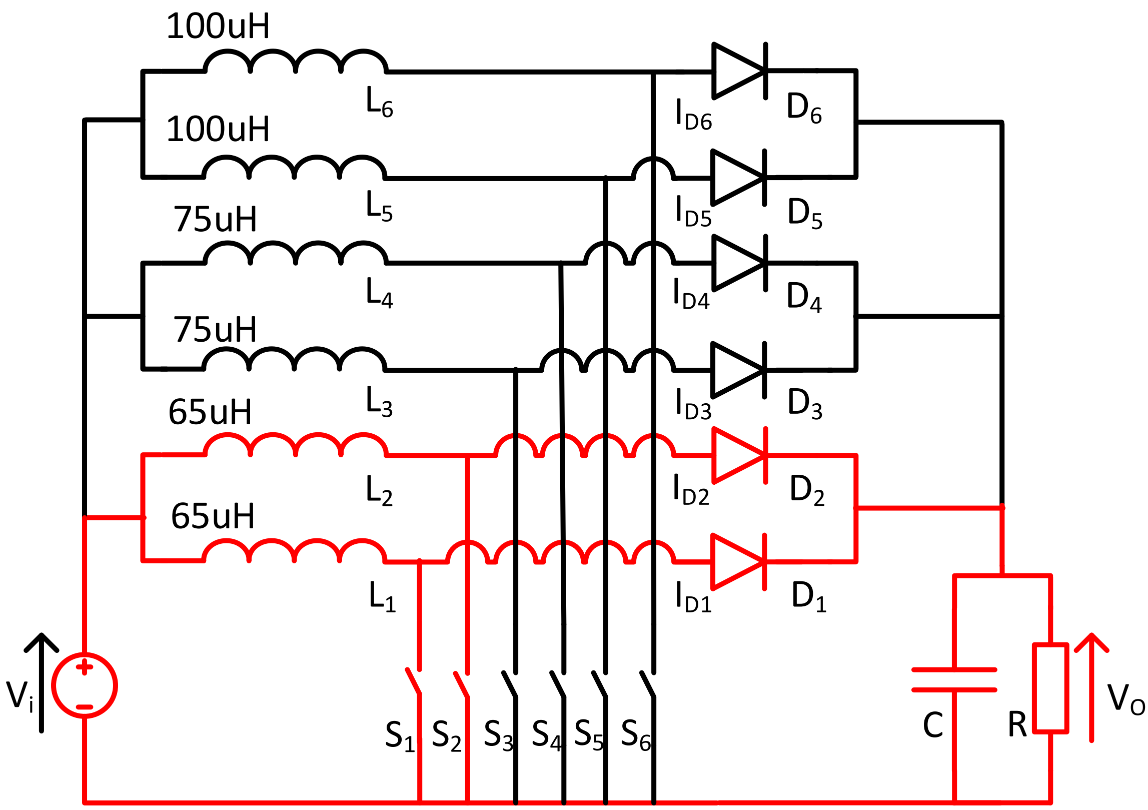


Figure 3.12 Operation state for 35V input

3.10 SIMULINK Model for Simulation

The proposed circuit is modeled in SIMULINK for simulating the circuit. A solar PV module is included as input source of the Boost Converter. A repeating signal table was chosen for creating a variable solar irradiance and fed to the solar PV module as Ir input. Temperature is kept constant as 25 degree Celsius. Simulink If block was used to implement the switching logic for switching among three different inductor branches according to the input voltage. The model is given below in figure 3.13. The algorithm for switching logic is shown in figure 3.14. The circuit is simulated for three different input voltage for better understanding of the response of the controller. According to the input voltage the corresponding switching pulse is generated with the appropriate duty cycle. The timing signals are shown in figure 3.9 where input voltage and corresponding switching pulse was given. Table 3.2 shows the optimum inductor value for each specific input voltage range with the range of duty cycle. Table 3.2 shown the specification of the solar cell used in the circuit. Two 36 volts solar module was connected in series and the maximum input voltage can reach to 72 volts at 1000w/m^2 solar irradiance.

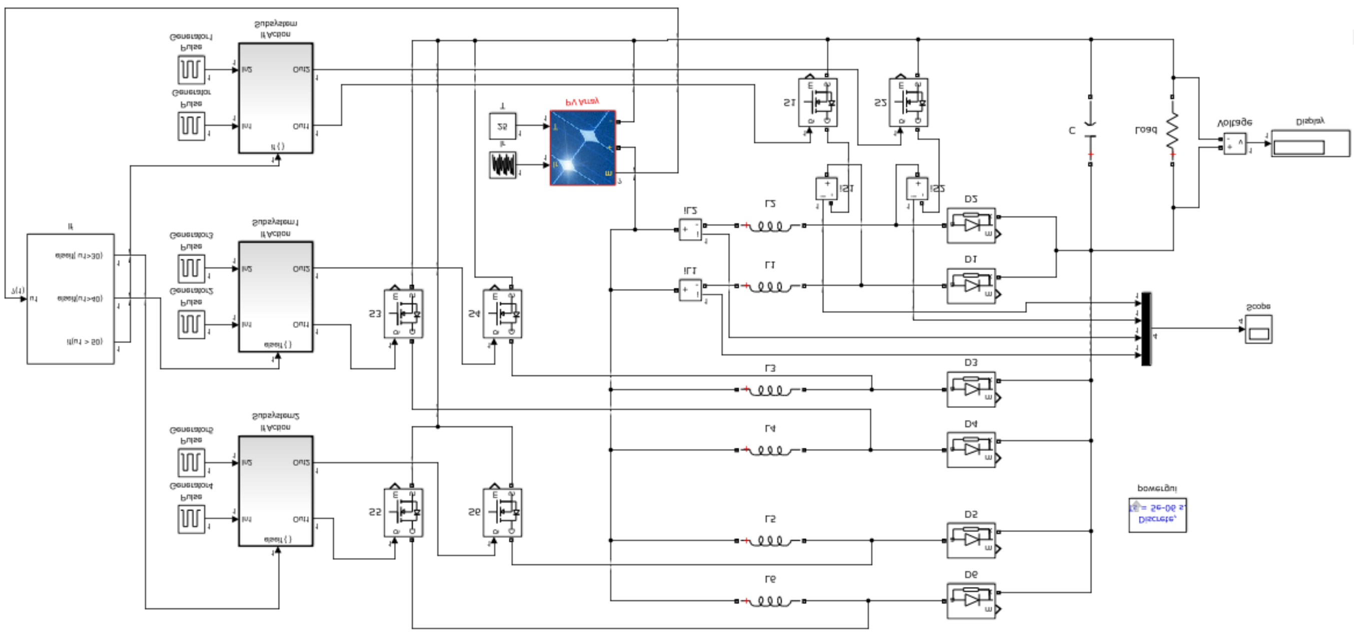


Figure 3.13 Simulink Model for Proposed IBC

Table 3.2 Optimum inductor value for different branches

Sl. No.	Component	Value	Branch	Duty Ratio
1.	L1 & L2	100uH	a	0 to 1/3
2.	L3 & L4	75uH	b	1/3 to 2/3
3.	L5 & L6	65uH	c	2/3 to 1

Table 3.3 Solar Module Specification

Sl. No.	Parameter	Value
1	Maximum Power (W)	213.15
2	Open circuit voltage Voc (V)	36.3
3	Cells per module (Ncell)	60
4	Short-circuit current Isc (A)	7.48
5	Voltage at maximum power point Vmp (V)	29
6	Current at maximum power point Imp (A)	7.35

3.11 Controller of the Proposed IBC

Traditional IBC required two switches to control the branches. As the proposed IBC has 4 additional branches so 4 additional switches is also required for switching the inductors. The switching sequence and duty ratio is dependable on the input voltage. So, for perfectly switching a specific algorithm should be followed. Figure 3.13 shows the switching algorithm of the controller. There is no basic difference of operation between traditional IBC and the proposed IBC. Proposed IBC require to generate switching pulse for three separate inductor branches (each branch contain two inductors) according to input voltage/duty ratio where traditional IBC generate switching pulse only for two inductor. The switching pulse generating unit or controller must sense the input voltage to determine which inductor should be switched to generate the expected output voltage maintaining minimum ripple current.

For maintaining a constant voltage all the time for all the input voltage in the range duty ratio must be adjusted with the variation of the input voltage. So, a controller circuit is required to generate appropriate duty cycle according to input and output voltage. A close loop controller like PID controller can give the better result on calculating perfect duty ratio regarding input voltage. For a solar PV system the voltage is variable in nature and may affected by cell temperature, irradiance and shading on the cell. So, the controller must be able to take care of this long variation of input voltage and must calculate exact duty ratio to maintain desirable output voltage keeping the input ripple current minimum.

The switching controller shown in figure 3.13 is very simple. It senses the input voltage from the PV output and read the value of desire output voltage. According to the input output voltage difference it calculates the required duty cycle. Base on the duty ratio the controller select a specific inductor to switch to maintain the minimum input current ripple and output voltage ripple. Figure 3.7 shows the flow chart of the controlling algorithm.

It is advantageous to use Silicon Carbide (SiC) diode instead of using Si based diode. The main advantages are high breakdown voltage and small reverse-recovery current. As a result higher efficiency and higher power density can be brought. It also reduces the requirement of the cooling system [57].

For switching the inductor CoolMOS is proposed instead of traditional MOSFET and IGBTs. The advantages of the CoolMOS are low on-state resistance at low-junction temperature and no tail current during the turn-off transient. These result in relatively lower conduction loss and turn-off switching loss compared to IGBTs. Thus higher efficiency can be achieved [57].

3.12 Flow Chart of Switching Algorithm

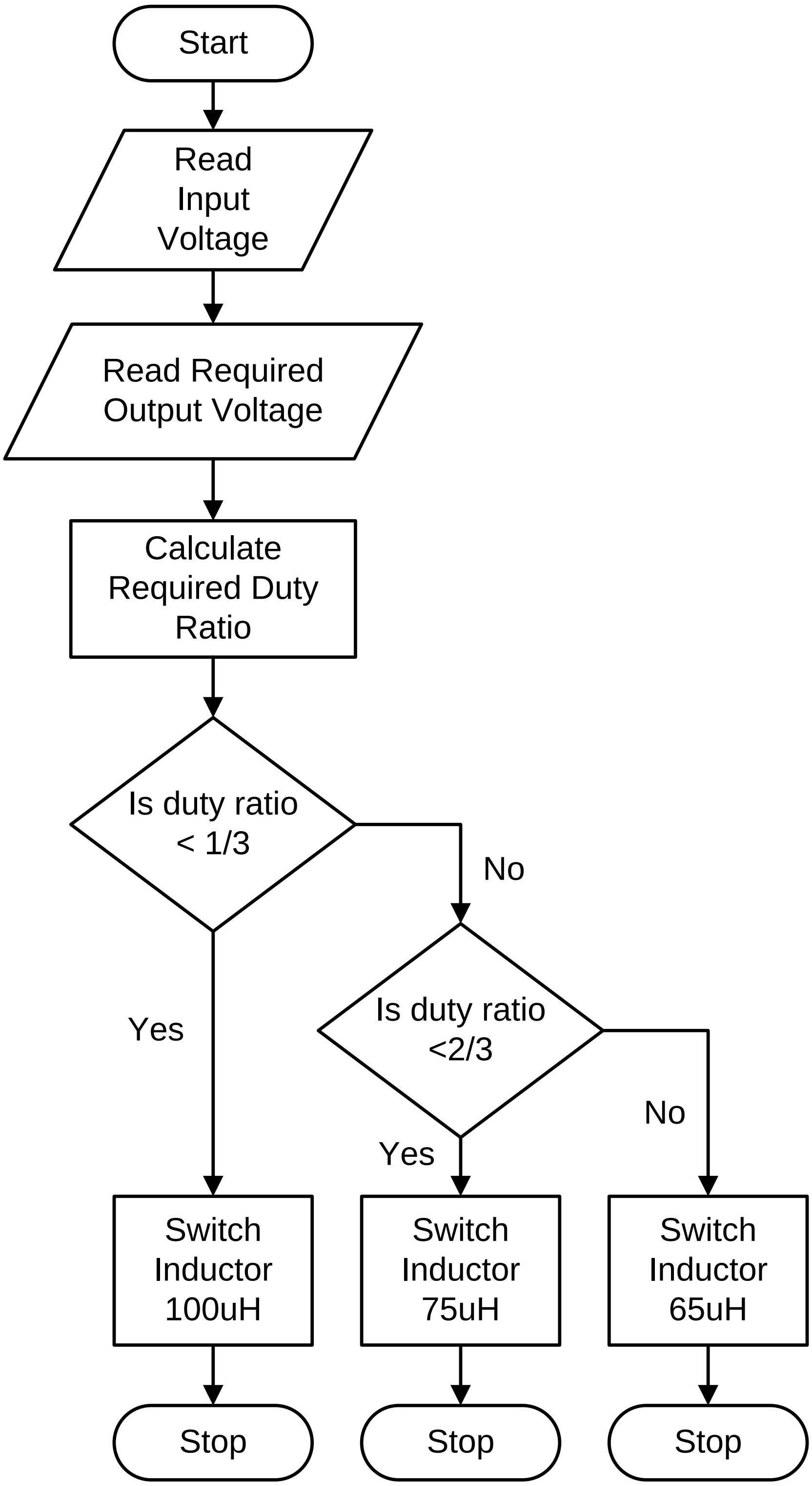


Figure 3.14 Switching algorithm of proposed IBC

CHAPTER 4

SIMULATION AND ANALYSIS

All the simulation work was performed using MATLAB/SIMULINK. So, before starting simulation a SIMULINK model of proposed converter was developed. The system was simulated for input voltage range 35V to 75V by choosing output voltage as 90V. Switching frequency was set to 20kHz and the capacitor value was 940uF. Simulation was performed in two steps. Firstly, traditional IBC was simulated with the chosen inductor values for the proposed converter considering expected output voltage as 90V. Input current ripple for the mentioned input voltage range is observed. Then the proposed IBC was simulated for same input output parameter and the result is observed. Both transient and steady state response was carefully noted.

Simulation was performed for three discrete input voltages like 45V, 35V and 55V. The reason for choosing this three specific value is that, theses three values cover the three ranges of the duty cycle.

4.1 Simulation Result

The goal is to simulate the proposed IBC with solar input. So a solar PV is connected as the input of the IBC. As the solar output is variable and depends on cell temperature, irradiance, and shading so to make the variable output at least one parameter should change. Here, irradiance is changed during simulation time using a repeating signal table. Other parameters e.g. temperature kept constant to make it simple. Figure 4.1 shows the irradiance and figure 4.2 shows the output voltage of the solar PV.

4.1.1 Simulation of IBC with fixed Input Voltage

For better understanding and edge of comparison simulation is done with the calculated inductor with three separate input voltages. For each input the result for different inductor is analyzed. The actual output voltage from the solar panel is far more complex and

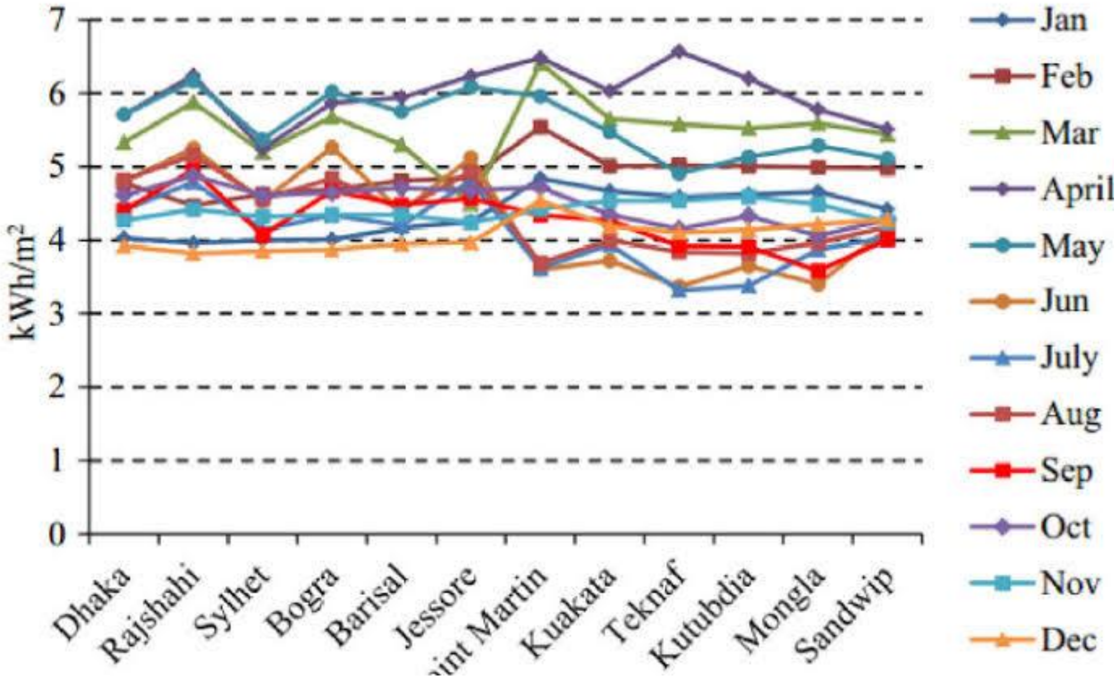


Figure 4.1 Solar Irradiance for different month

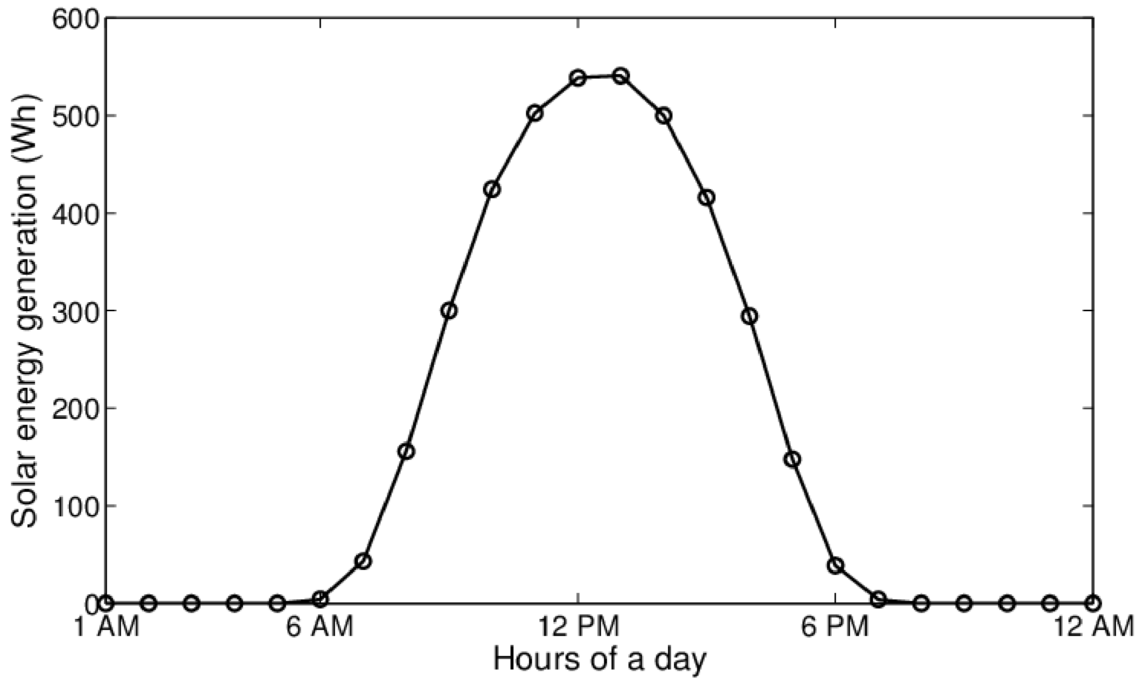


Figure 4.2 Solar Irradiance in a day

it depends on solar irradiance and temperature. Typical solar irradiance in Bangladesh for whole year is shown in the figure 4.1 for different main cities. A typical solar irradiance graph for one day is shown in figure 4.2. Figure 4.2 shows solar irradiance at different time of the day. Figure 4.3 shows the typical output voltage from a solar module for highly varying environment where temperature and irradiance vary frequently. Though the actual output voltage may very frequently and the output voltage shape is totally random the circuit is simulated for a modified input. Before simulating the proposed converter the traditional IBC is simulated with the generated signal and then the proposed converter is simulated.

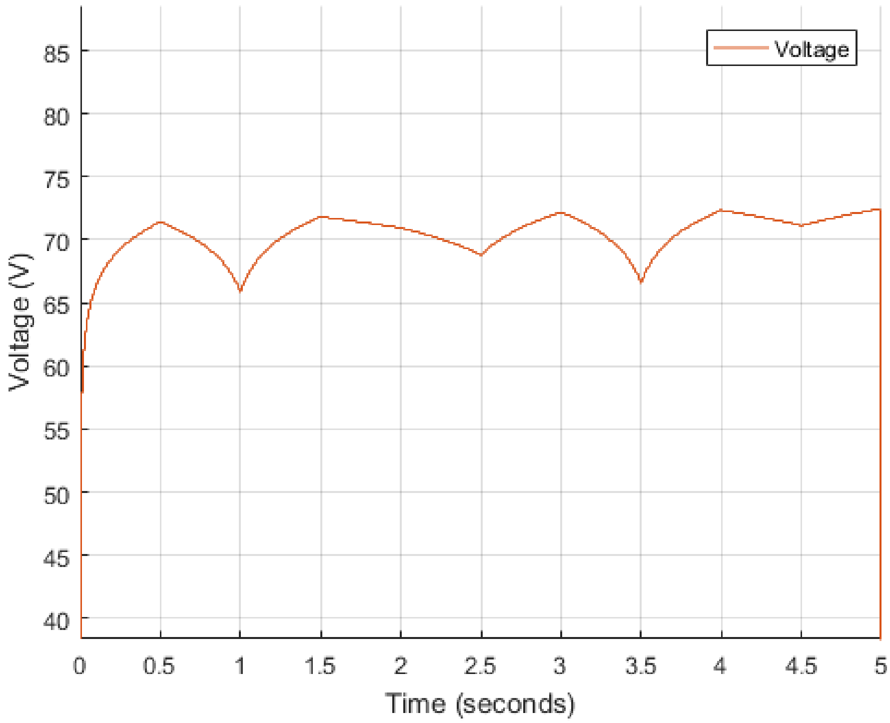


Figure 4.3 Typical output voltage of solar PV

In Fig. 4.4 and Fig. 4.5 transient and steady state input current for three different inductor values (i.e. 100uH, 75uH and 65uH) are shown respectively. For that case input voltage is 45V and the duty cycle required to maintain 90V output is 0.52. From the graph it is clear that 75uH inductor has minimum overshoot of input current and reaches fast to the steady state situation compare to other two inductors. So for input voltage 45V inductor 75uH shows better response.

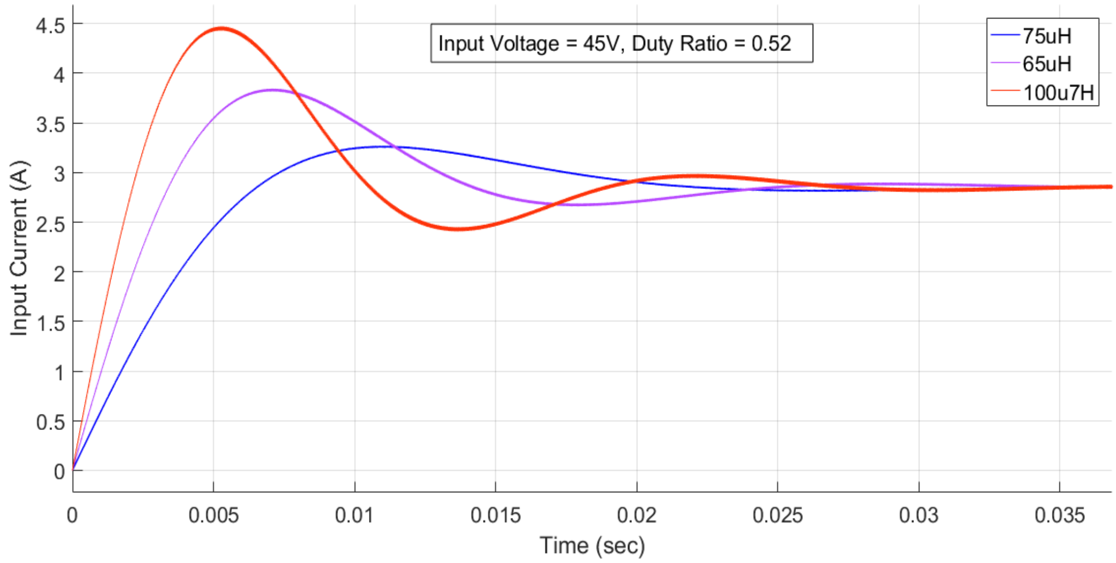


Figure 4.4 Transient response for three different inductor value when input voltage is 45 V.

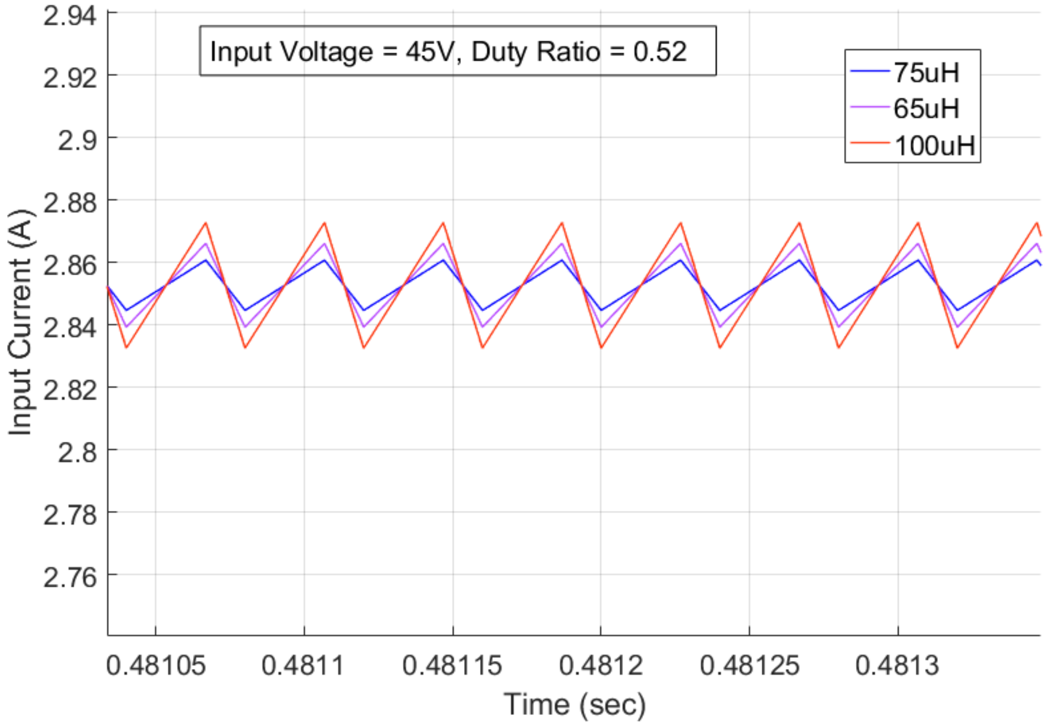


Figure 4.5 Steady state response for three different inductor value when input voltage is 45 V.

From figure 4.6 output voltage for above mentioned inductors can be seen. From the graph it is clear that there is no remarkable change on output voltage for change in inductor value. So, inductor value does not contribute to the output voltage ripple. Actually the output voltage ripple depends on output capacitor and the analysis is out of scope of this research.

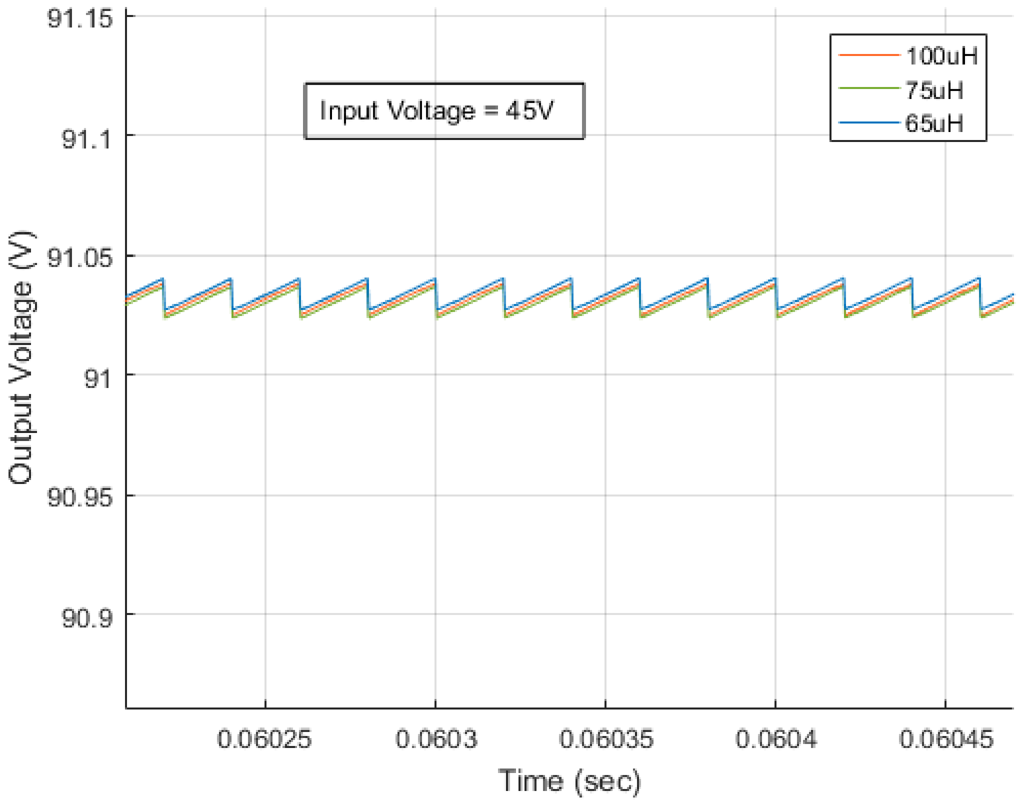


Figure 4.6 Output voltage for different inductor value.

Fig. 4.7 and Fig. 4.8 shows the steady state and transient result for the input voltage 35V. The duty ratio to maintain the 90V output is 0.62. The optimum inductance for this duty ratio was found as 65uH. The simulation result proves the fact.

From the transient and steady state output it is clear that lower inductor has lesser input ripple for the input voltage of 35V.

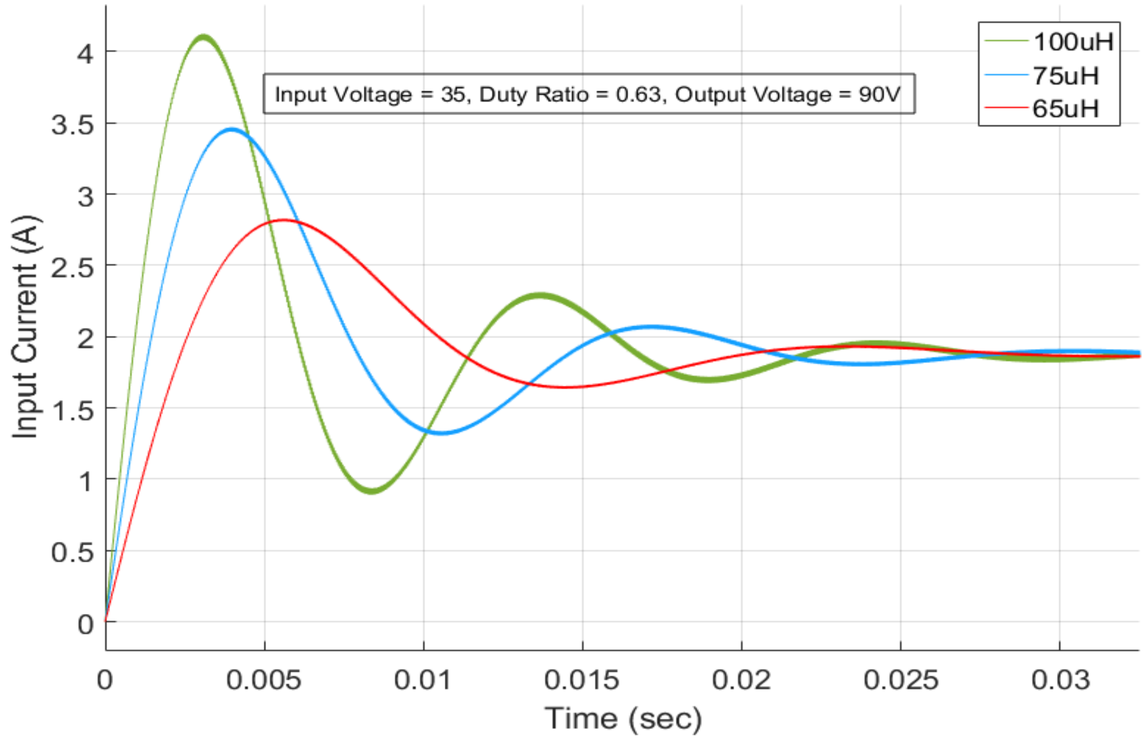


Figure 4.7 Transient response for three different inductor value when input voltage is 35 V

Figure 4.8 Stedy state response for three different inductor value when input voltage is 35 V.

Figure 4.9 shows the transient response for three different inductor value when input voltage is 55V. For input voltage 55V inductor 100uH has better transient response as peak overshoot is less and satteling time is aslo less. Figure 4.10 shows the steady state input current. It is depicted that inductor 100uH has lesser ripple compare to others two inductors. The output voltage ripple is almost same for all three inductors and shown in figure 4.11.

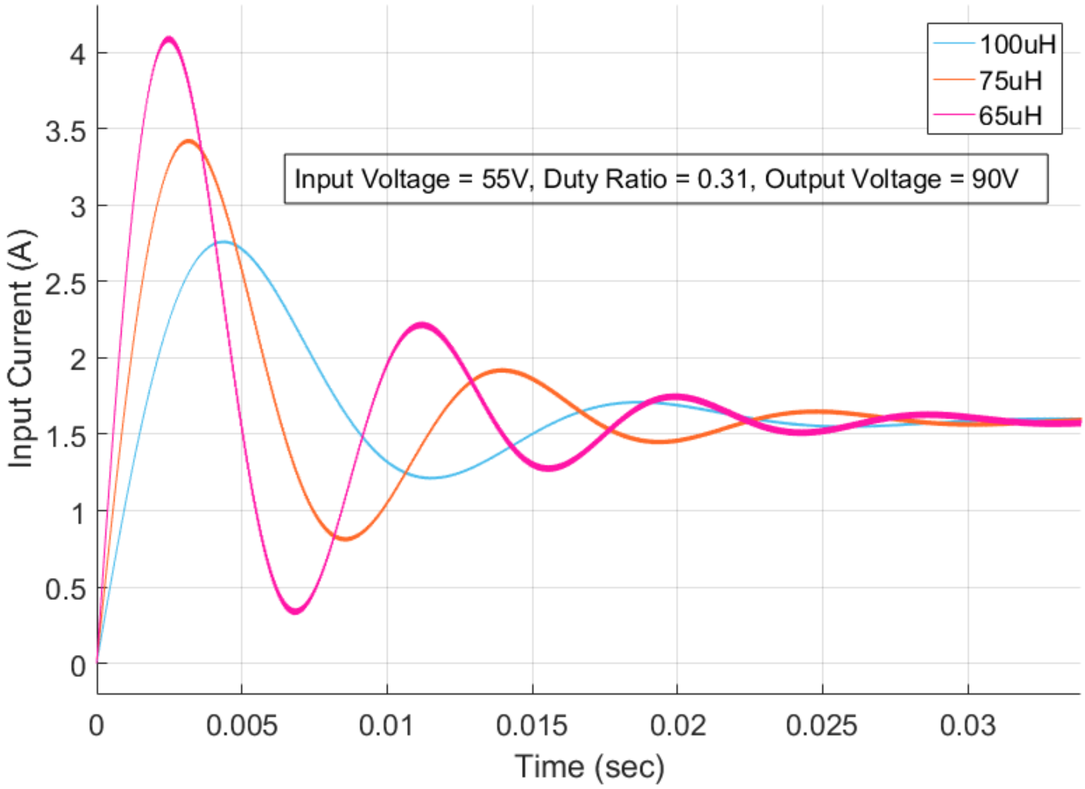


Figure 4.9 Transient response for three different inductor value when input voltage is 55 V.

Figure 4.12 illustrates the input current for three different inductor at three different input voltage. This graph was generated using optimum inductor value for the specific input voltage. For higher input voltage higher input current flows for maintaining same output voltage. For lower input voltage lower input current flows. Figure 4.13 shows the inductor current for different input voltage.

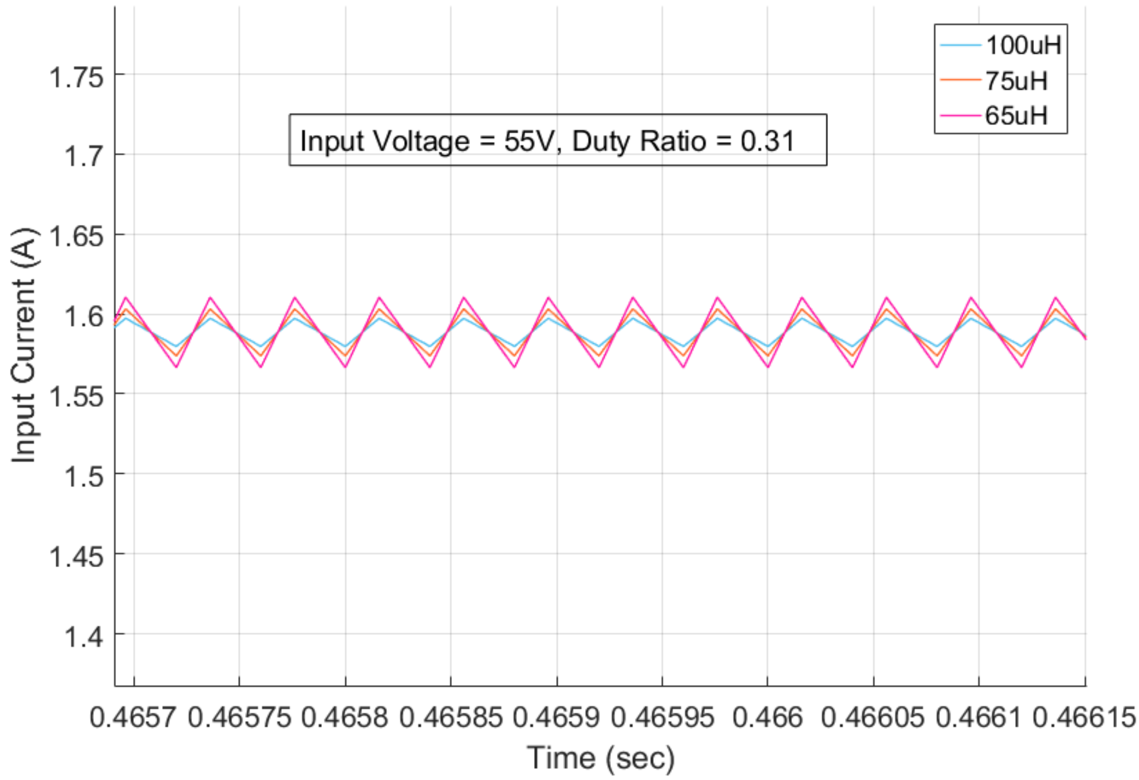


Figure 4.10 Stedy state response for three different inductor value when input voltage is 55 V.

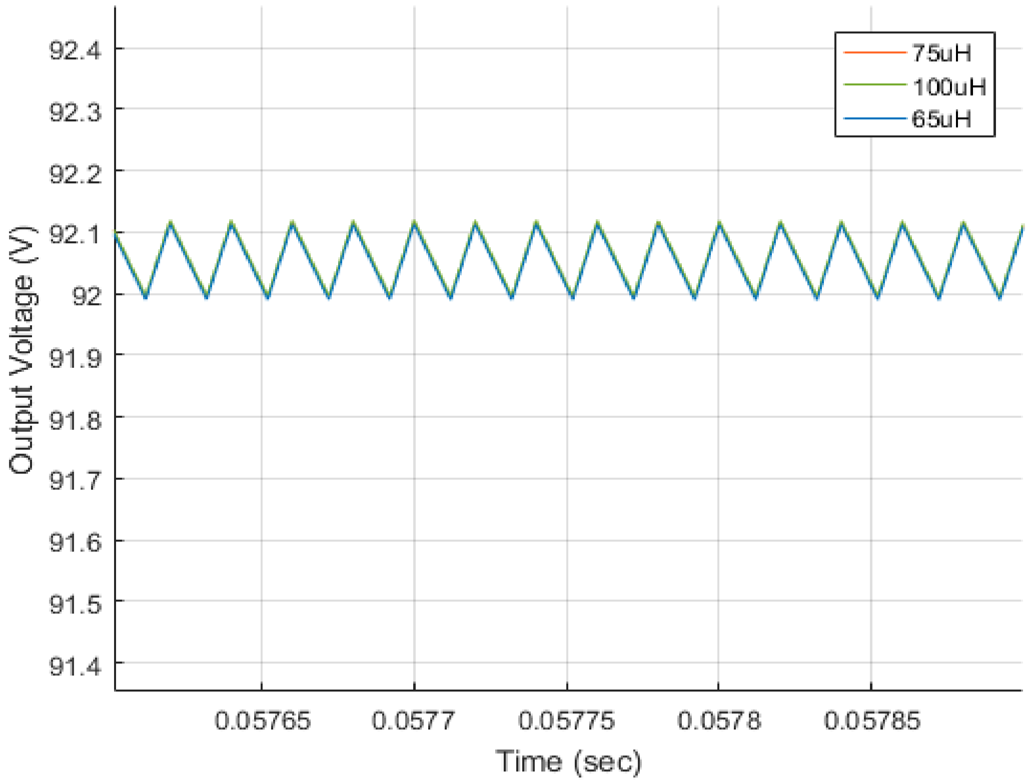


Figure 4.11 Output voltage for different inductor

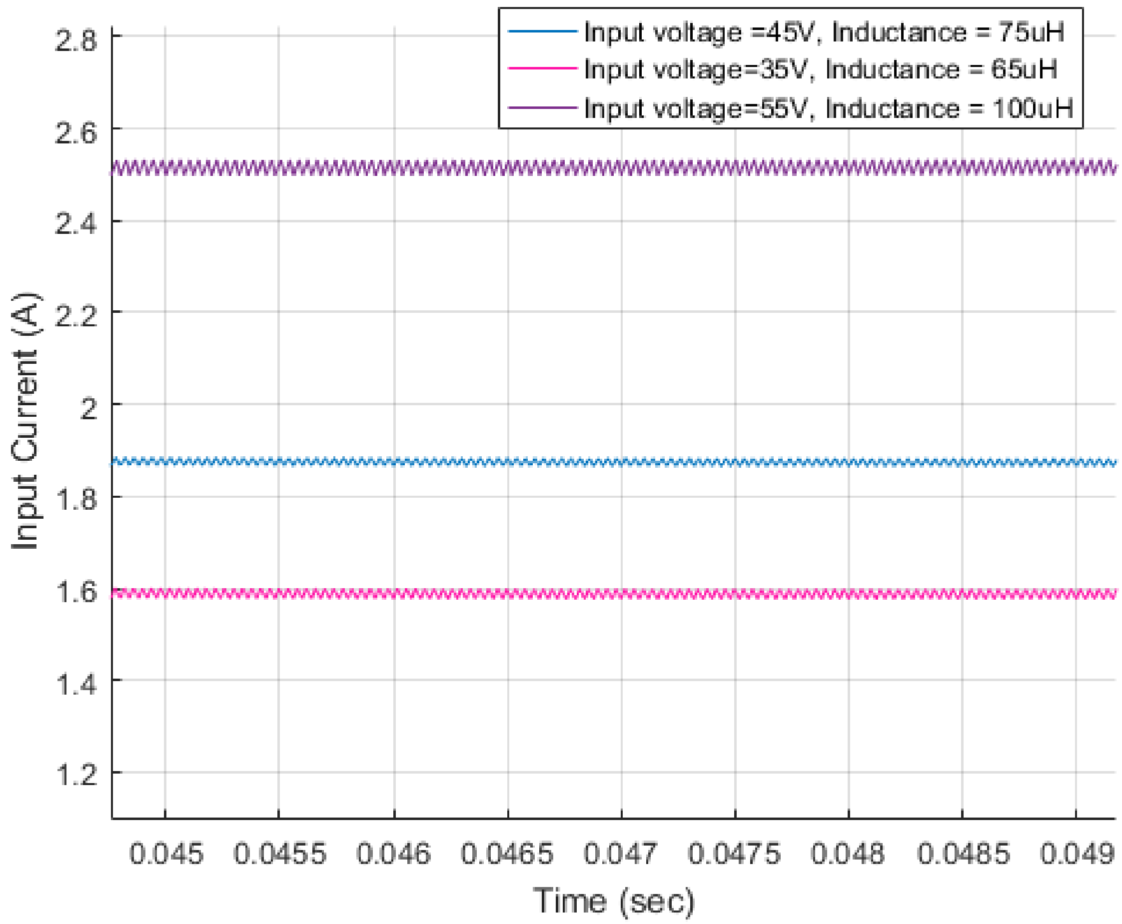


Figure 4.12 Input current for different inductor at different input voltage

4.1.2 Simulation of IBC with Variable Input

After simulating IBC with constant input in this section the result for variable input is presented. The variable input will come from a solar PV in practical case. Infinite variation in input voltage may occur for change in temperature, irradiance and shading in real scenario. But to keep the simulation and analysis simple instead of using actual solar input a variable DC is fed to the IBC which input has three separate levels. This input is enough to understand the practical case.

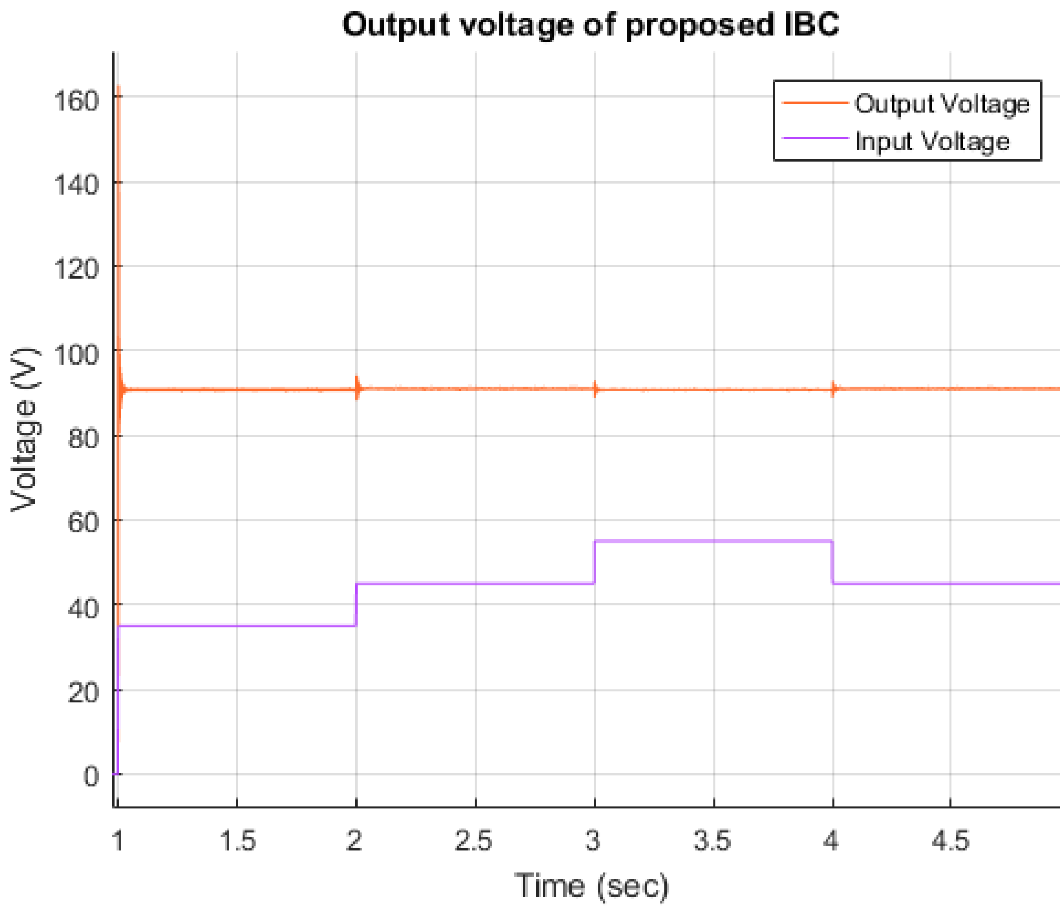


Figure 4.13 Input and Output voltage of proposed IBC

Figure 4.14 shows the output voltage with the variable input voltage for the proposed interleaved boost converter. The exixting IBC also show approximately same result. So, changing inductor for varying input has no remarkable effect on output voltage as already discussed in previous chapter.

In figure 4.15 the input current webform for existing and proposed IBC is presented. From the figure it is shown that the proposed IBC has better result compare to existing IBC.

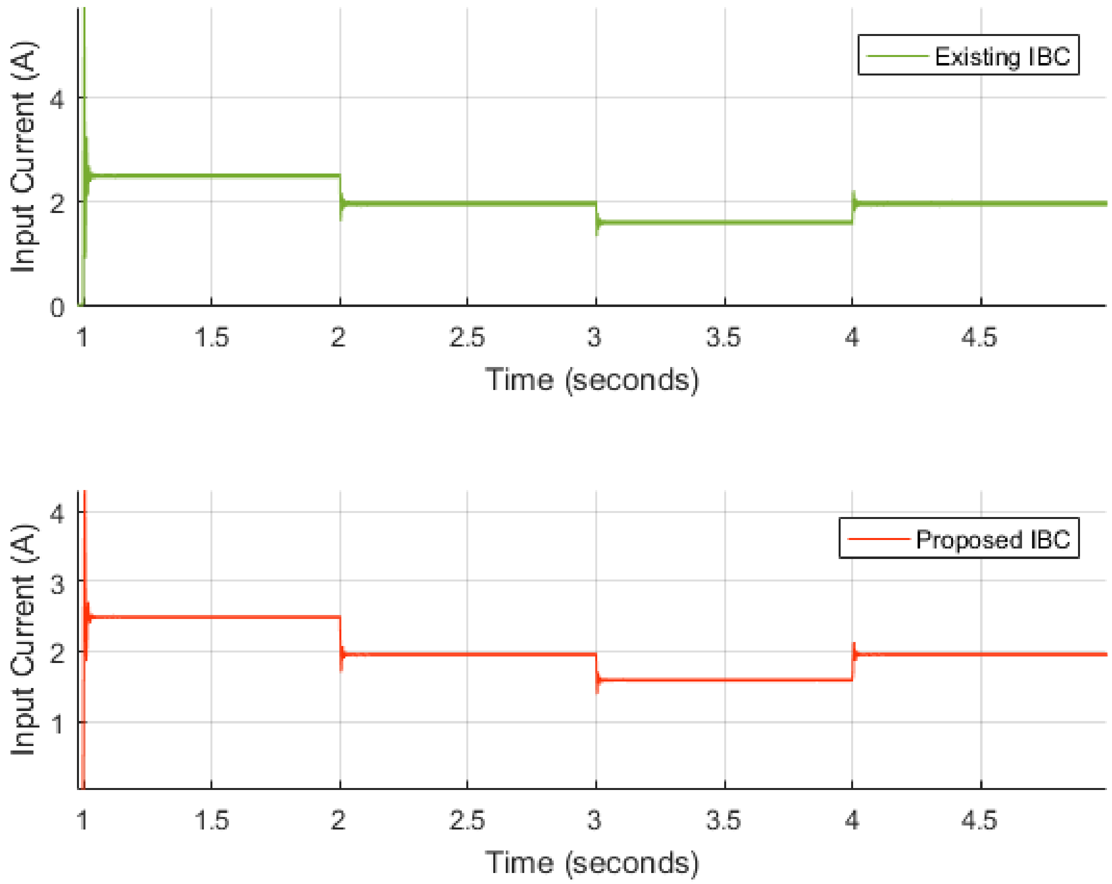


Figure 4.14 Input current for existing and proposed IBC

Figure 4.16 gives a closer view of input current and a clear difference can be visualized. Figure 4.17 shows the transient response of both converter. For the response it is clear that proposed IBC gives better result. The proposed IBC has less overshoot and less setling time.

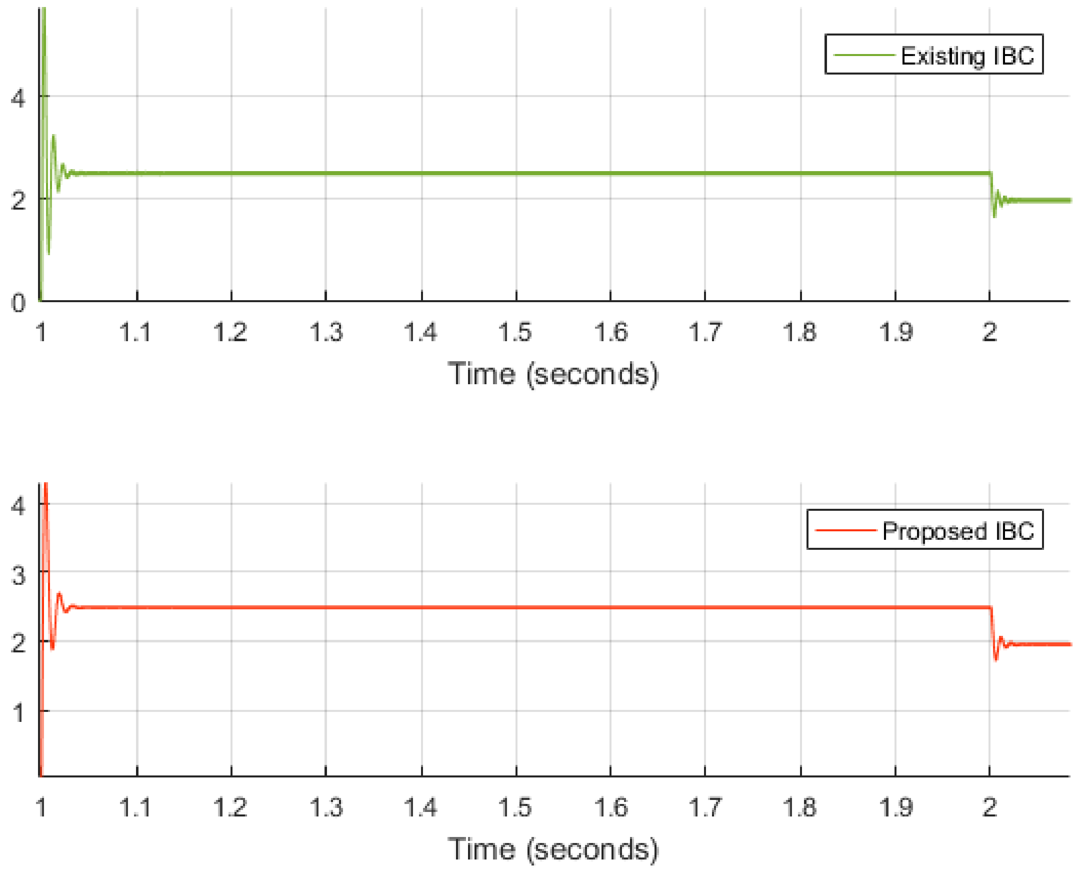


Figure 4.15 Closer response of the input current

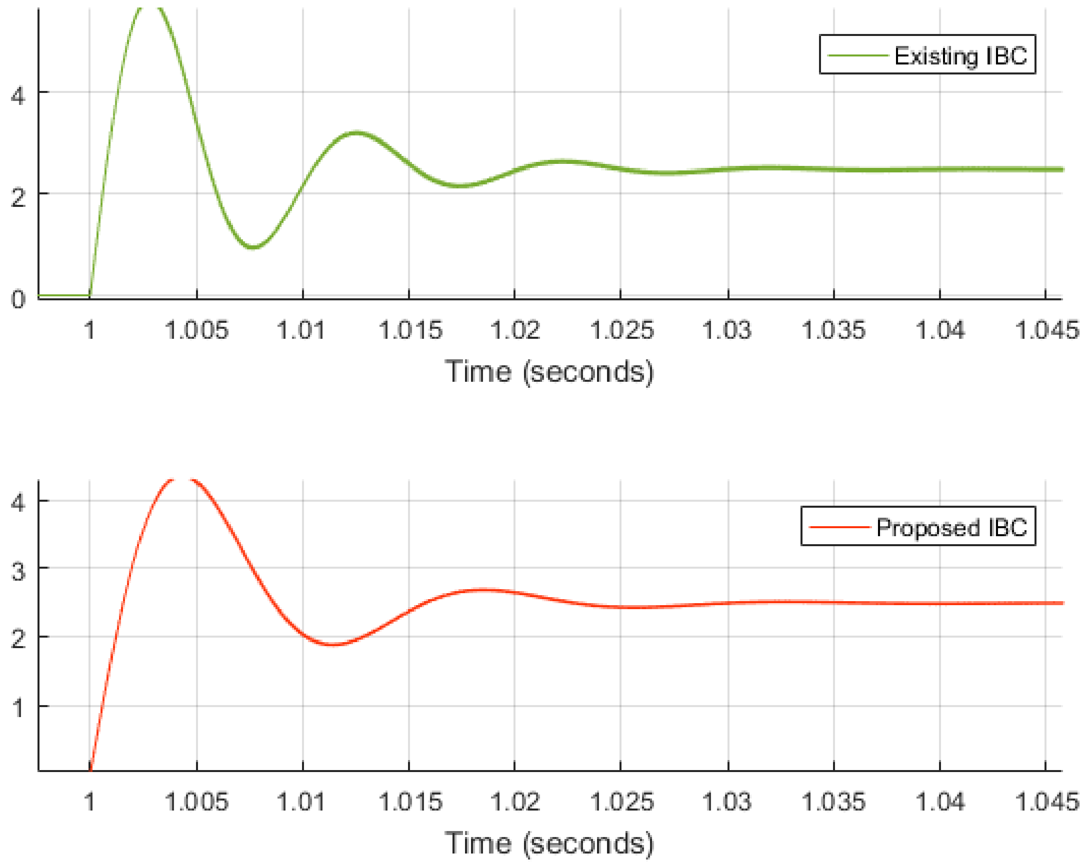


Figure 4.16 Transient response of both converter

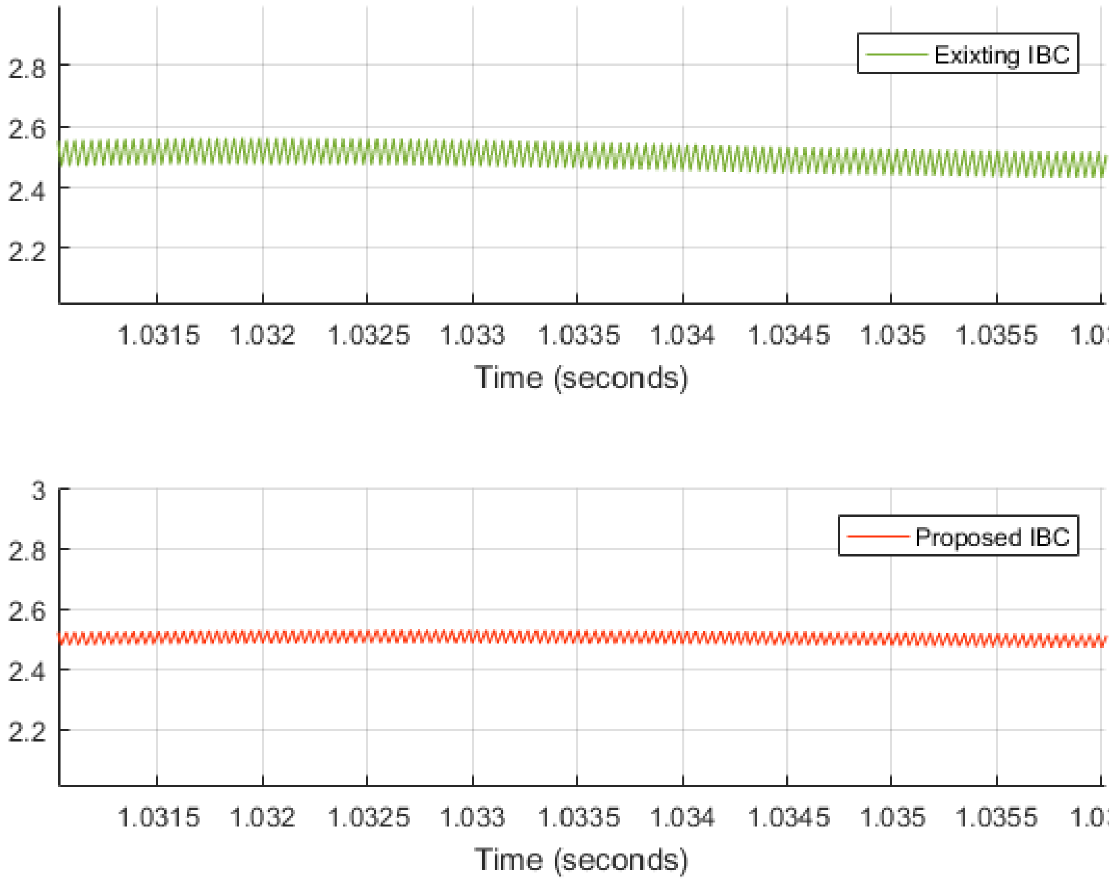


Figure 4.17 Amplified view of ripple current

Figure 4.19 illastrate a transient created when a sharp input change occurred. From the graph it is also clear that proposed IBC gives better response on sudden change in input voltage.

In figure 4.20 input current for existing IBC and proposed IBC is presented in same plot. It is now easily visible and the difference between them is more clearly observed.

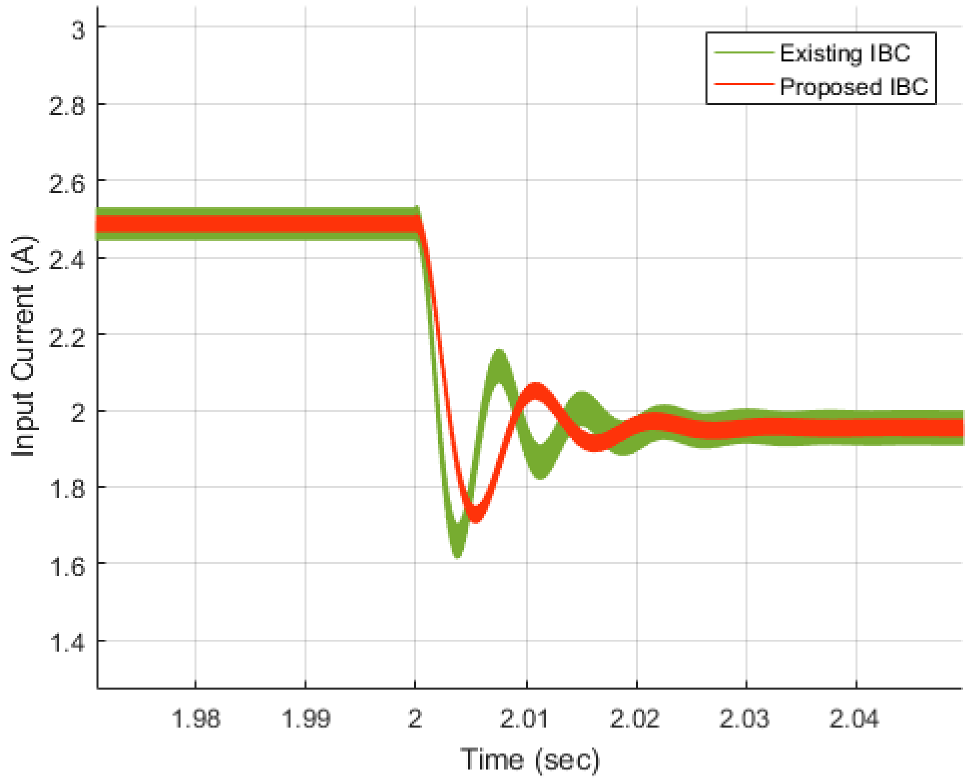


Figure 4.18 Transient created for sharp chang in input voltage

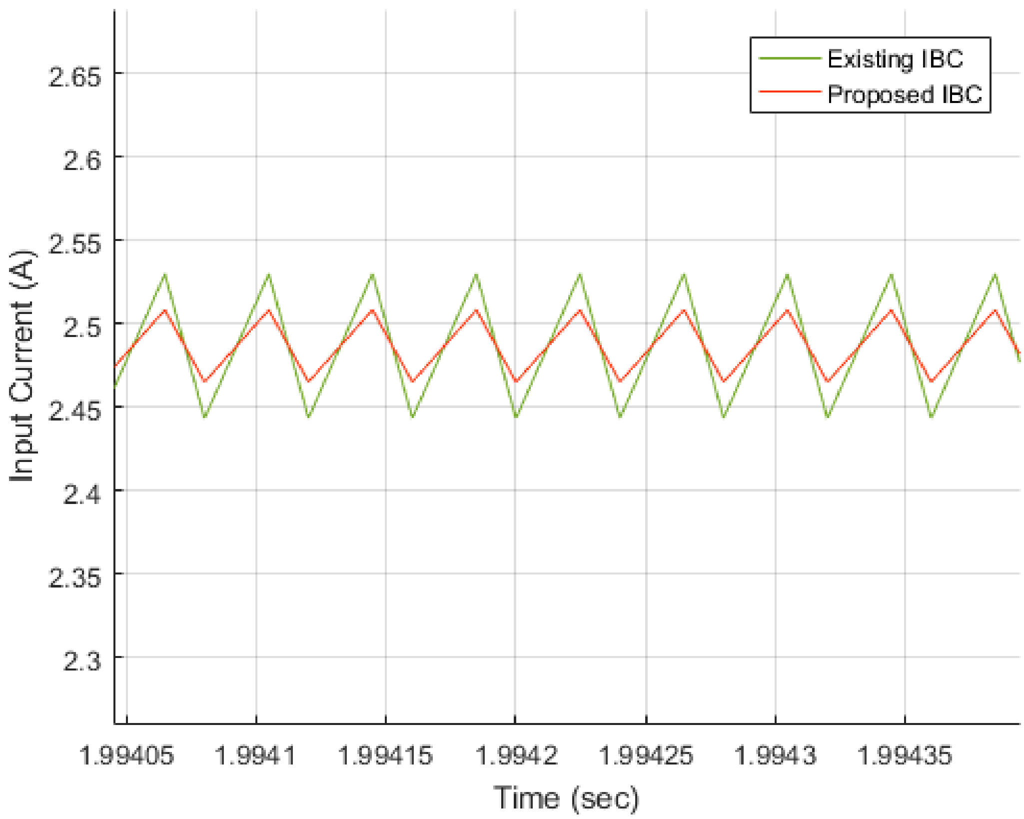


Figure 4.19 Comparison of input current

4.2 Practical Implementation

From figure 3.7 it is clear that if one inductor is used for an IBC when input voltage is form 30 volts to 70 volts then 81uH is the optimum inductor which provides minimum ripple in input current. Using that value a practical circuit was made and the output voltage, input current and inductors currents was observed. The circuit was made using ferrite core power inductor, and IRF520 mosfets. The controller was designed using Arduino microcontroller environment. IRF520 mosfet is Arduino compatible and no mosfet driver is required for this circuit. Input and Output voltage was measured using Arduino analog pin. Arduino supports 10 bit analog to digital converter with is enough accurate for this application. For generating switching pulse with exact duty cycle for producing stable output voltage PID controller was used. Figure 4.21 represents the circuit diagram of the converter. The circuit was design in Eagle CAD.

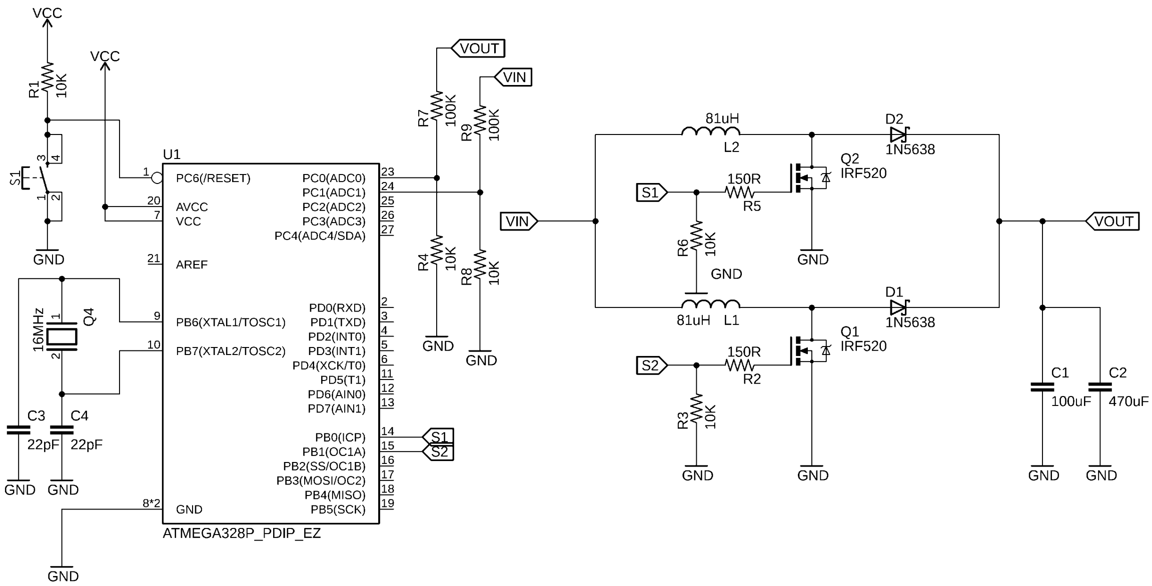


Figure 4.20 Schematic diagram of practical IBC

The Arduino microcontroller was operated from a 16MHz external microcontroller. The switching frequency chosen for the converter was 15KHz and two Arduino digital pins was used for generation the switching pulse. The output from a digital oscilloscope is presented here. Figure 4.22 shows the practical setup of the converter circuit. Arduino Nano was used in the practical circuit.

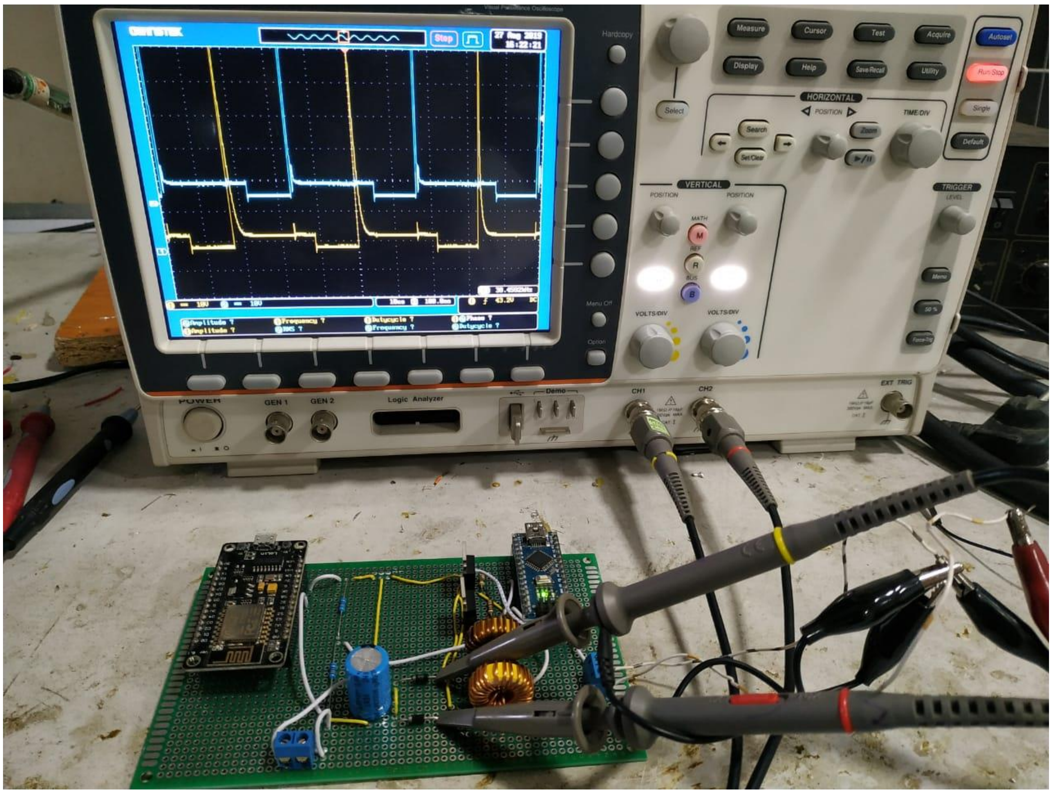


Figure 4.21 Practical setup of the converter

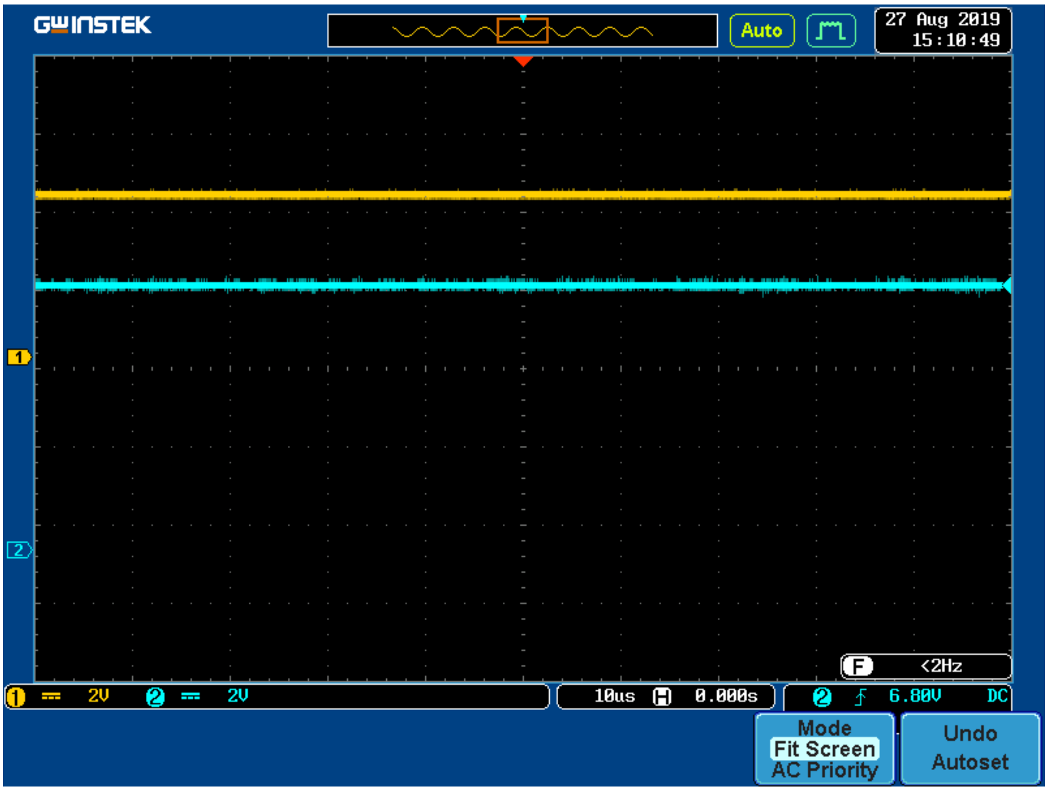


Figure 4.22 Input and Output Voltage

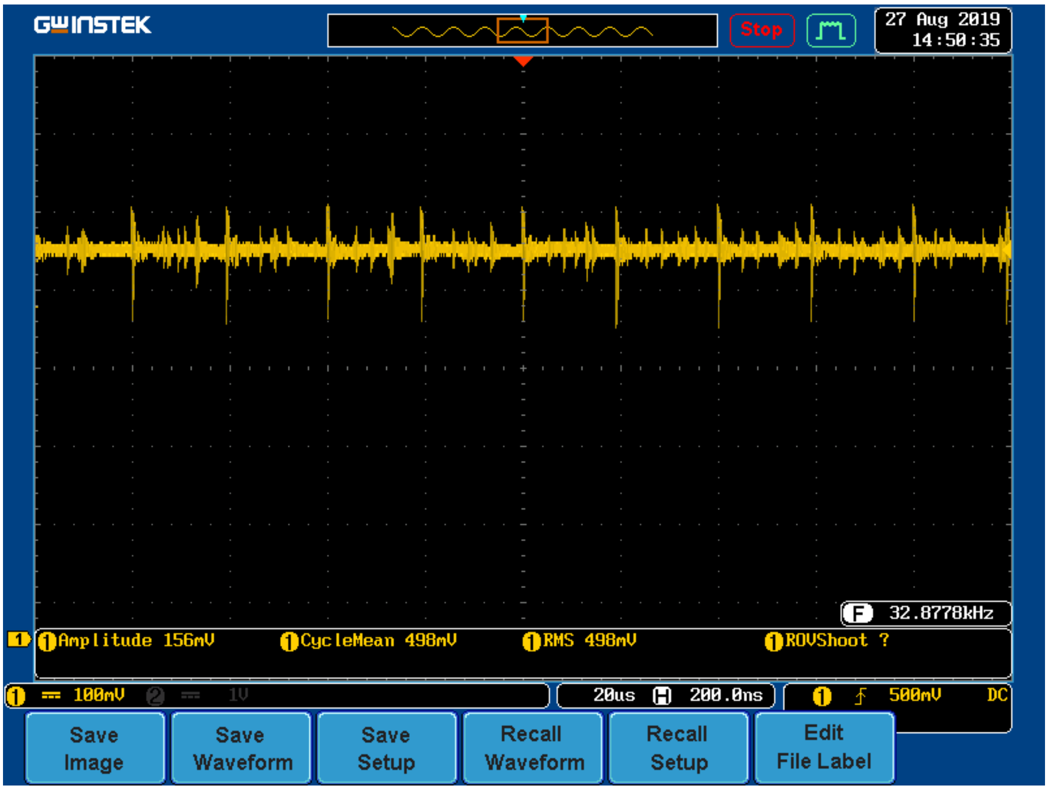


Figure 4.23 Input current

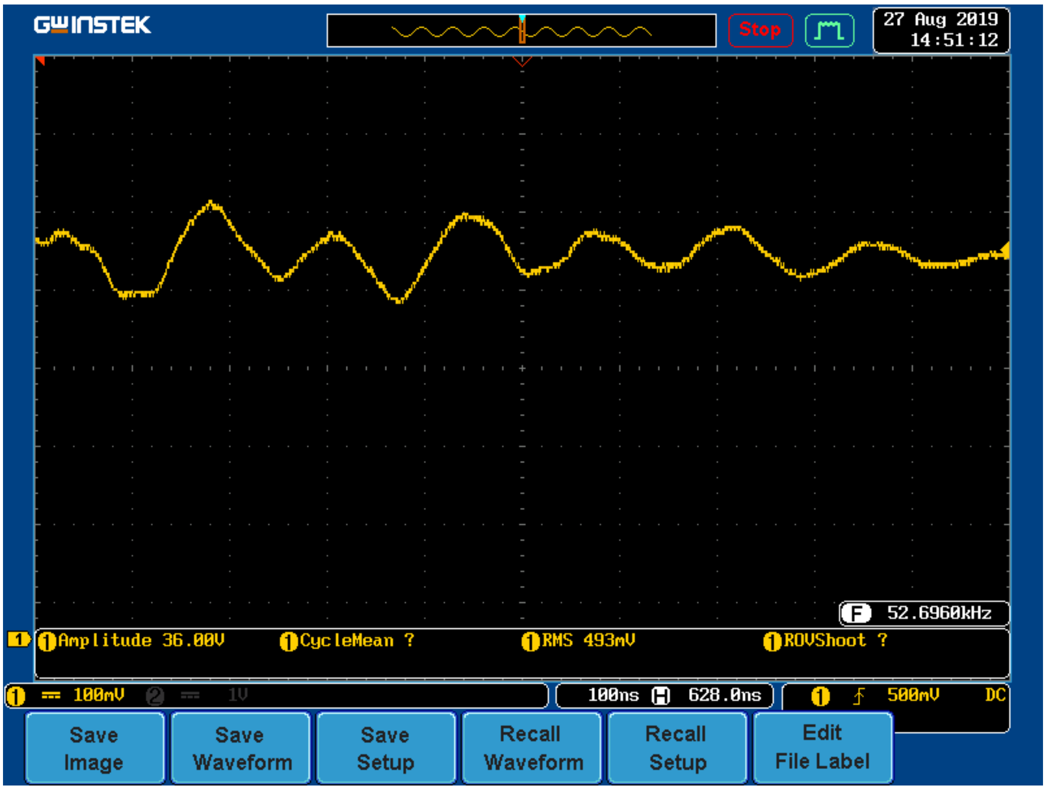


Figure 4.24 Output voltage from solar panel

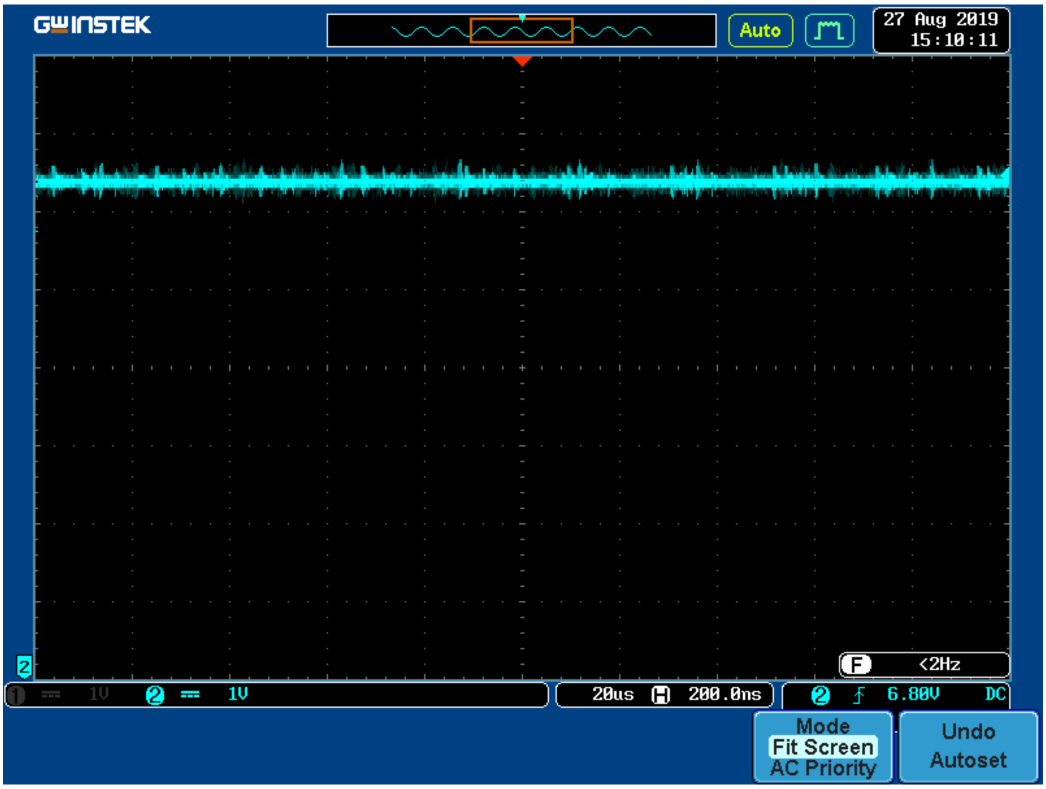


Figure 4.25 Output voltage from the IBC

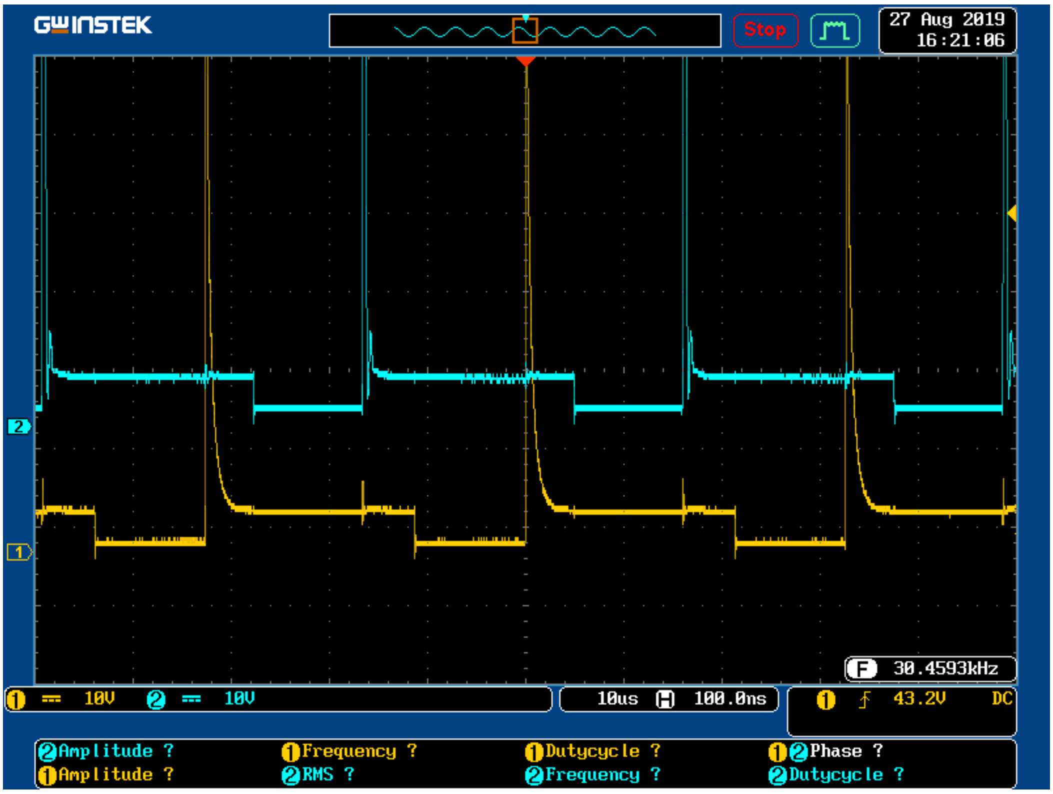


Figure 4.26 Inductor current of the IBC

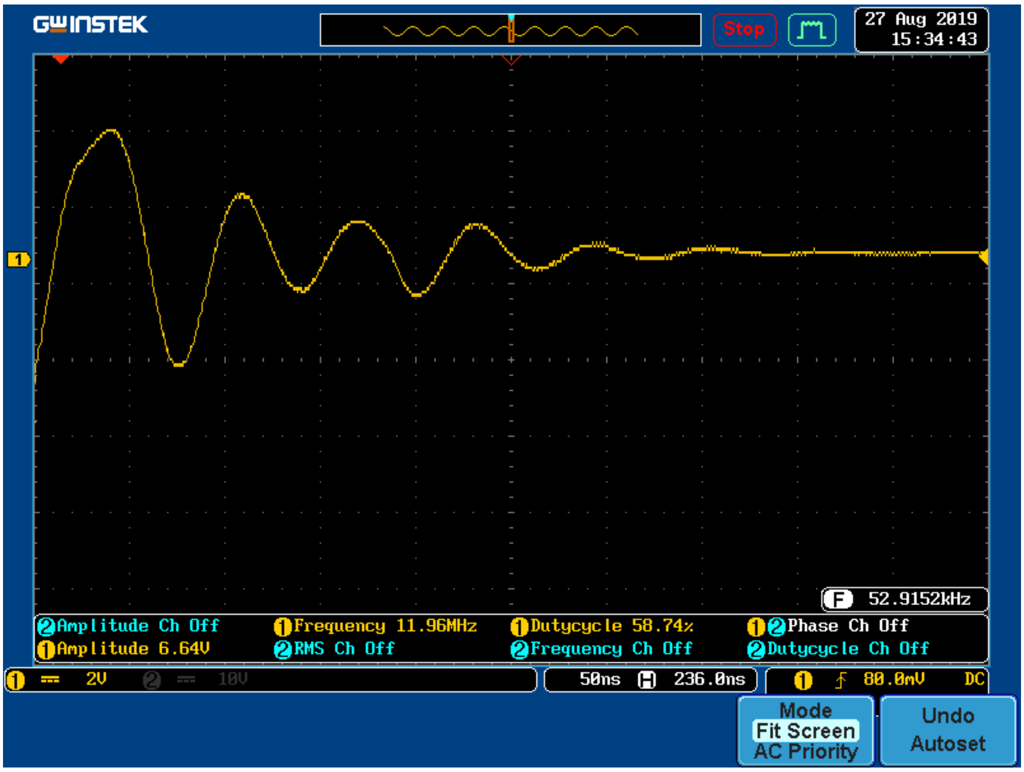


Figure 4.27 Transient response of output voltage

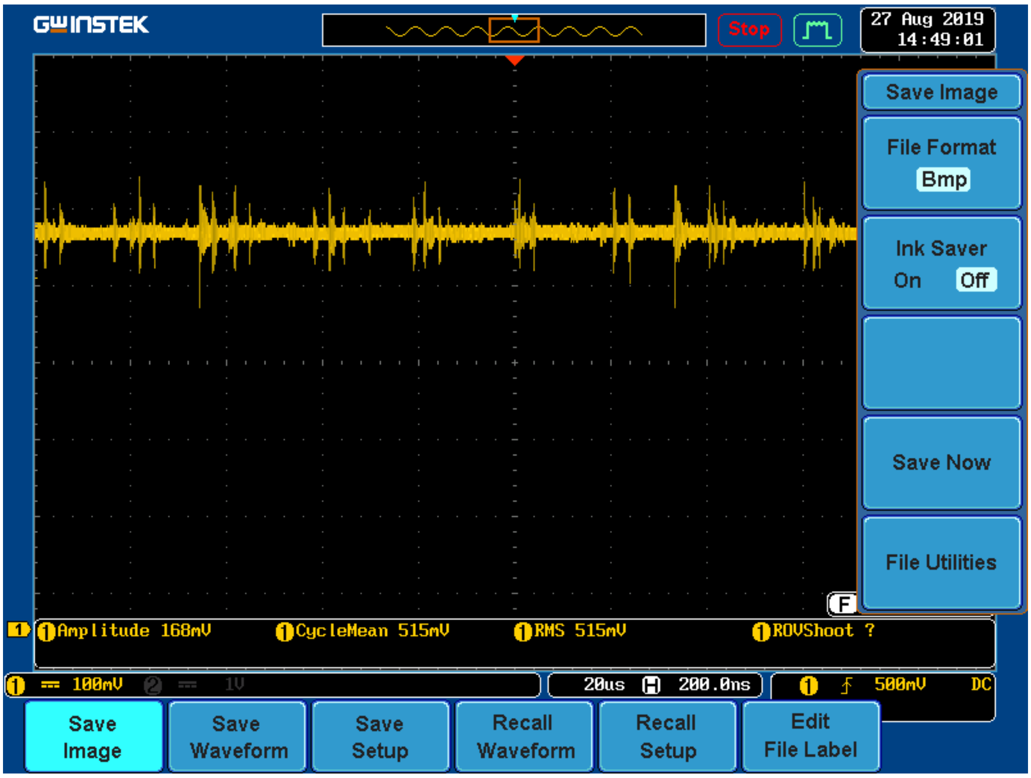


Figure 4.28 Ripple in input current

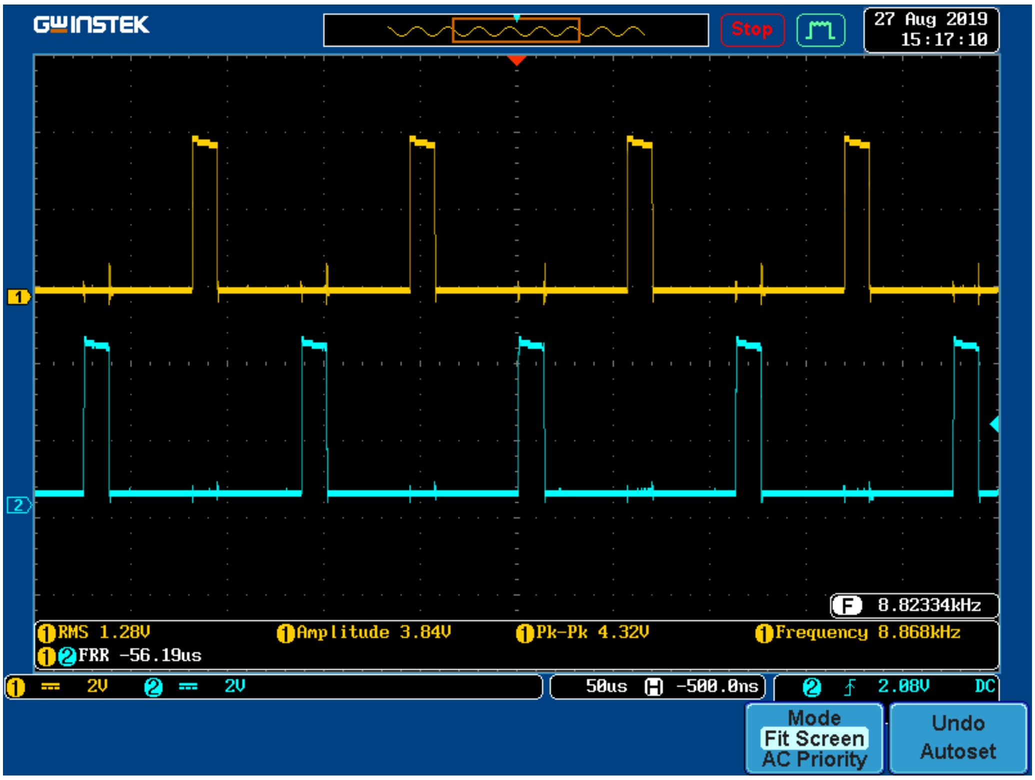


Figure 4.29 Switching pulse for two mosfet

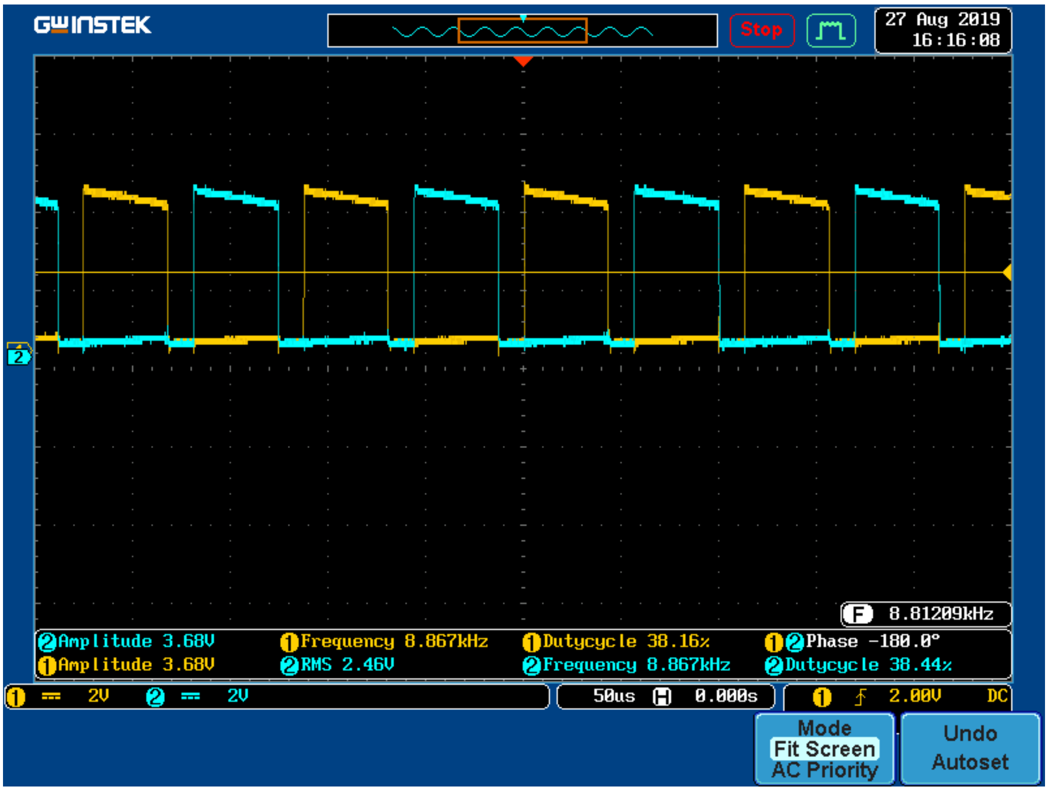


Figure 4.30 Switching pulse for mosfets

CHAPTER 5

CONCLUSION

5.1 Conclusion

The main object of this research was to identify most suitable dc-dc converter topology for solar photovoltaic system for high power as well as low power application. For some added advantages Interleaved Boost Converter was chosen for photovoltaic application and an improved interleaved boost converter with discrete inductors was proposed for better performance. Three different inductors for three consecutive range of input voltage/duty ratio were proposed instead of single optimum inductor in traditional interleaved boost converter. It was found that inductor value has a big impact on input current ripple, and minimum current ripple was found at different inductor value for different input voltage. After analyzing different aspect duty cycle was parted into three consecutive ranges and a separate and optimized inductor value was chosen for each range.

For controlling the switching and adjusting with the input a control algorithm was developed. Then a SIMULINK model was made for the proposed converter and simulated using MATLAB/SIMULINK. The simulation result was presented and compare with traditional interleaved boost converter.

From the simulation result it was found that using three different inductors for three duty ratio ranges both transient and steady state response can be improved. One single inductor for whole range of duty ratio generates more ripples in input current. From the analysis it was also found that by dividing whole duty cycle range (0 to 1) into three separate ranges better performance can be achieve.

The research also shows that inductor value has very nominal effect on output voltage. As the output of the solar varies widely depending on the environmental condition the proposed converter can be a good choice for solar photovoltaic application. It can also be used in other application where input variation of input voltage is huge. This converter is not economical for the application where input voltage variation is not remarkable.

The converter can give further better result if Silicon Carbide (SiC) diode and CoolMOS can be used instead of IGBTs and Si diodes.

The proposed converter has also some disadvantages. As the converter uses 6 inductors and 6 switches the size and cost of the converter will be increased. A sophisticated controller will be required to select right inductor regarding to the input voltage.

5.2 Future Scope

The analysis was done for two phase interleaved boost converter. It can be implemented and analyzed for three phase interleaved boost converter in future.

The proposed model can be implemented and analyzed for couple inductor and RCN based IBC.

In this paper efficiency and ripple amount was not calculated. In future work actual ripple amount can be calculated.

Only simulation work was performed in this research. In future a hardware model of the proposed converter can be developing and practical result can be compare with the simulation result.

The model can be analyzed for other DC-DC converter e.g. buck converter and result can be observed.

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