DESIGN OF A BI-DIRECTIONAL STEP-UP AND STEP-DOWN DC-DC CONVERTER

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

By

EGBUATU IFEANYI SAMUEL

In Partial Fulfilment of the Requirements for the Degree of Master of Science in Electrical and Electronic Engineering

NICOSIA, 2020

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Approval of Director of Graduate School of Applied Sciences

Prof. Dr. Nadire CAVUS

We certify this thesis is satisfactory for the award of Masters of Science in Electrical and Electronic Engineering

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To my parents…

ABSTRACT

As we know the demand of energy in the world right now grows on a daily basis. The international energy agency (IEA) have done their statistics and told us that the world is growing in to a global electrification. This brings about a study where power flow can be done in both forward and reverse direction this is called Bdc in power electronics. In this thesis, simple structure dc-dc Bdc have been presented. We make use of an inductor to wind both sides. In what's presented in this thesis we work on S-U and S-D converters. In both S-U and S-D modes, we analyse both CCM and DCM operation. In both S-U and S-D converter the CCM is divided to two parts while the DCM is divided into 3 parts. For us to achieve a high S-U and S-D gain we designed the circuit to be in series and parallel and also in charge and discharge modes. After the analyses have been done, we notice that the proposed topology has a higher S-U and S-D voltage gain when compared to the traditional BDC. Furthermore, after analysing we had a lower average value for switch current when compared to traditional topology. The configuration of the direct current BDC is designed to be very simple with suitable voltage rating of the components and low building cost. Finally, PSCAD/EMTDC software was used for the simulation of theoretical analysis and designed result to check the execution and general behaviour of the BDC.

Keywords: BDC; coupled inductor; high gain; S-U mode; S-D mode; CCM; DCM; PSCAD/EMTDC.

ÖZET

Bildiğimiz gibi dünyada şu anda enerji talebi günlük olarak artmaktadır. Uluslararası enerji ajansı (IEA) istatistiklerini yaptı ve dünyanın küresel bir elektrifikasyona doğru büyüdüğünü söyledi. Bu, güç akışının hem ileri hem de geri yönde yapılabileceği bir çalışmaya neden olur, buna güç elektroniğinde Bdc denir. Bu tezde basit yapı dc-dc Bdc sunulmuştur. Her iki tarafı sarmak için bir indüktör kullanıyoruz. Bu tezde sunulanlarda S-U ve S-D dönüştürücüler üzerinde çalışıyoruz. Hem S-U hem de S-D modlarında, hem CCM hem de DCM çalışmasını analiz ediyoruz. Hem S-U hem de S-D dönüştürücüsünde CCM iki kısma ayrılırken DCM 3 kısma ayrılır. Yüksek bir S-U ve S-D kazancı elde etmek için devreyi seri ve paralel ve ayrıca şarj ve deşarj modlarında olacak şekilde tasarladık. Analizler yapıldıktan sonra, önerilen topolojinin geleneksel BDC'ye kıyasla daha yüksek bir S-U ve S-D voltaj kazancı olduğunu fark ettik. Ayrıca, analizden sonra geleneksel topolojiye kıyasla anahtar akımı için daha düşük bir ortalama değere sahiptik. Doğru akım BDC'nin konfigürasyonu, bileşenlerin uygun voltaj değeri ve düşük bina maliyeti ile çok basit olacak şekilde tasarlanmıştır. Son olarak, teorik analizin simülasyonu için PSCAD / EMTDC yazılımı kullanıldı ve BDC'nin yürütülmesini ve genel davranışını kontrol etmek için sonuç tasarlandı.

Anahtar Kelimeler: BDC; bağlı indüktör; yüksek kazanç; S-U modu; S-D modu; CCM; DCM; PSCAD / EMTDC simülasyon.

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LIST OF ABBREVIATION

AC:	Alternating Current
BCM:	Boundary Conduction Mode
BDC:	Bidirectional Converter
C:	Capacitor Value
CCM:	Continuous Conduction Mode
D:	Duty cycle
DC:	Direct Current
DC/DC:	Direct Current to Direct Current
DCM:	Discontinuous Conduction Mode
ESR:	Equivalent Series Resistance
G:	Voltage Gain
IEA:	International Energy Agency
IGBT:	Insulated-Gate Bipolar Transistor
K:	Coupling Coefficient
LC:	Inductor and Capacitor
M:	Mutual Inductance
MOSFET:	Metallic Oxide Semiconductor Field Effect Transistor
PSCAD:	Power System Computer Aided Design
S:	Switch

C_H :	Capacitor at the load side
F_S :	Switching Frequency
I_{CH} :	Average Value of the Output Capacitor Current
i_L :	Inductor Current
i_{LL} :	Input Current Average Value
IL_{1P}:	Peak Current of Primary Coupled Inductor
IL_{2P}:	Peak Current of Secondary Coupled Inductor
P_i :	Input Power
P_O :	Output Power
R_{DS} (ON):	On State Resistance
R_H:	Resistance at Step-up Mode
R_L:	Resistance at Step-down Mode
S-U:	Step-up
S-D:	Step-down
S_1 :	Switch one
S_2 :	Switch two
S_3 :	Switch three
t1:	Time at the Point One
t2:	Time at Point Two
t_3:	Time at point Three
U_{C1} :	Voltage of the First Capacitor

$\boldsymbol{U_{C2}}$:	Voltage of the Second Capacitor
$\boldsymbol{V_H}$:	High Voltage Side
$\boldsymbol{V_{IN}}$:	Input Voltage
$\boldsymbol{V_L}$:	Low Voltage Side
$\boldsymbol{v_{l1}}$:	Inductor Voltage one
$\boldsymbol{v_{l2}}$:	Inductor Voltage two
$\boldsymbol{V_O}$:	Output Voltage
$\boldsymbol{\eta}$:	Efficiency
$\boldsymbol{\tau LH}$:	Normal Inductor Time Constant for Step-up Mode
$\boldsymbol{\tau LL}$:	Normal Inductor Time Constant for Step-down

CHAPTER 1

INTRODUCTION

Power converters are usually used in most applications to provide a desired power supply for many electronic equipment. Popular applications of converter include in servomotor drives, renewable power systems, home appliances, office equipment, telecommunication devices, electrochemical power suppliers and many more. Power converters give a regulated output higher than a given unregulated input for boost converters or lower output for buck inverters (Wen, Deng, Mao, & Batarseh, 2005). Power Electronic converter takes low level unregulated input-voltage and convert it to desired level of regulated output-voltage and vice-versa depending on the arrangement of the components (Win and Okamoto, 2012). These converters are of different types such as 3-level, switched capacitors, buck-boost converters, sepic-zeta, conventional boost-buck and many more. Despite the capabilities of this converters, the issues relating to global warming and economic challenges inherent to fossil fuels and introduction of renewable energy system exposed the limits of these converters and sparked the huge demand for converter that has the capabilities of producing high voltage gain and high efficiency.

Several researchers have contributed hugely by introducing different topologies of these type of converters. Most of these converters either have a certain benefit but also have their drawback as well. Recent research has examined combinations of these converter's configurations, for instance, the switched capacitor and coupled inductor can provide a high s-u and s-d voltage gain but its configuration is tasking. The 3-level type also have a low voltage gain. The sepic/zeta has to do with combining two power stages which makes the conversion efficiency decreased to mention but a few.

1.1 Traditional Dc-Dc Boost/Buck Bdc.

An illustration of this kind of converter is shown in our first figure. We use this kind of converter to inject power between 2 direct current sources in both forward and reverse direction. However, they incur large voltage stress due to porous l energy from its transformer. The bi dc-dc boost/buck converter steps up low level unregulated direct current(dc) to higher direct current voltage at the converter output and vice-versa. It can reach a high level of conversion gain to a certain point. These converters are widely for several applications that are beneficial globally such as in photovoltaic hybrid power systems, uninterrupted power supply(ups), fuel cells, other hybrid power products and also in battery chargers.

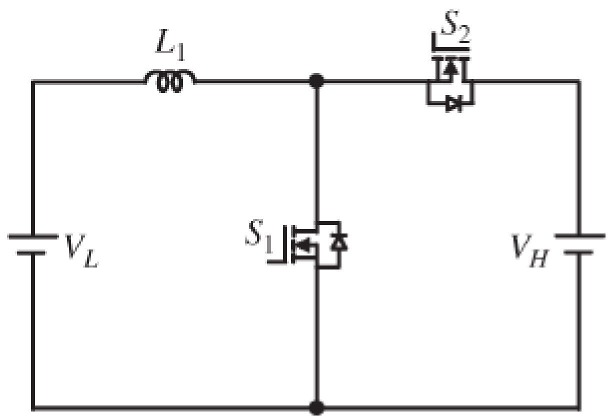


Figure 1.1: Conventional bi-directional boost/buck converter (Yang and Liang,2012).

1.2 Statement of Problem

With the mentioned advantages and applications, conventional dc-dc boost/buck bdc although make use of fly back converters which are attractive and easy to control but are not capable to gives a very high voltage conversion ratio and high voltage gain and also, they suffer experience the ill effects of high voltage weight on power gadgets because of spillage inductor vitality of the transformer. So as to reuse the spillage inductor vitality and to limit the voltage weight on the force gadgets a few scientists have given us the vitality recovery methods which can be utilized to brace the voltage weight on the force gadgets and to reuse the spillage inductor vitality. A few topologies have been introduced by various scientists to provide the solutions form the above-mentioned problems. (Papanikolaou and Tatakis, 2004) established the converter with structural simplicity and high voltage gain but switch mechanisms of this converter suffered from voltage stress. In the recent years (Berkovich and Ioinovici 2008), introduced modified dc-dc converter by using capacitor-Switch and inductor-switch for design transformer less converter. Another researcher also works on three switches high voltage converter (Pietkiewicz and Cuk, 1999). The recent modified high voltage gains transformer less dc-dc converter using capacitor-switch inductor-switch was found to be prominent among them, it is simple and relatively inexpensive but still suffered from switching problems, low voltage gains and voltage stress.

1.3 Aim of Study

1.3.1 General Aim

In this work our major aim is to design calculate and simulate the presented dc-dc s-u and s-d bdc and compare its voltage gain with the traditional converter.

1.3.2 Specific objective

- To analyse the overall circuit topology of the proposed converter
- Analyse both the CCM and DCM of the s-u and s-d converters
- Larger s-u and s-d gain compared to the traditional bi-directional boost/buck converter.
- Reduced voltage stress on the switches.
- We need to make sure our results give us switching current lower average value when compared with conventional bi dc-dc boost/buck converter.
- Higher efficiency in s-u and s-d modes when we compare to the traditional converter.
- To generate a higher calculated efficiency when changing the voltage at the low voltage side (VL) severally when comparing to the traditional bi-directional direct current to direct current increase/decrease converter.

1.4 Scope and Limitations

For us to know and access the eligibility of the presented converter, electric specification and circuit component is been selected. Simulation of the proposed converter will be done using PSCAD software throughout the research.

1.5 Thesis Outline

This thesis is divided into four (4) chapters

In the first chapter of the work I introduced the background, statement of problems and also outlines the challenges of previous converters and conventional bi-directional dc-dc boost/buck converters and proposed way to minimize them.

Chapter II discusses the fundamental background, investigates the relevant theories, characteristics, comprehensive literatures review and recent achievements on bi-directional direct current to direct current s-u and s-d converter.

Chapter III introduces different power circuit, circuits development and analysis; mathematical calculations, converter operation modes, design and multiple simulation of result using PSCAD software to prove the performances of the converter.

Chapter IV focuses on summary and conclusion of the thesis. General recommendations and areas to advance the work in the future will be presented in this part of the work.

1.6 Ethical Consideration

Considering the preparation of design requirements and standards ethical features of design procedures is implemented during the thesis work. Therefore, use of commonly recognized standards or customs, such as protection or confidentiality, are at pale; of trade-offs between different designs principles. The other ethical consideration is giving appropriate credits while using the ideas or words of other researchers by proper citing

CHAPTER 2

LITERATURE REVIEW

2.1 DC-DC Converter

Direct current to direct current converter is significantly used to proficiently create a directed voltage from a source that is either controlled or not or to a heap that is either steady or not consistent. DC-DC converters are high-recurrence power transformation circuits that utilization high-recurrence exchanging and inductors, transformers, and capacitors to smooth out exchanging clamour into controlled DC voltages. DC-DC converters can either be confined or non-disengaged, their detachment is controlled by when the information ground is associated with the ground of the yield There are various kinds of DC-DC converters which we notice here the buck converter, the lift converter, the buck-support converter, CUK converter, SEPIC converter. Some incorporate the mix of two converters as on account of buck-help converter, bi-directional boost/buck converter to get a specific function. As in the world just like technology advances so does topologies of DC-DC converters advance. New topologies are proposed to improve the efficiency and working conditions of previously made converter. We would highlight on some of these converters and briefly say few things about their topologies.

2.1.1 Buck converter

A buck converter can be said to be a converter that steps a voltage down (while stepping up current), producing a voltage lower than the input voltage at the output. They are used for various applications like in laptops, powerpacks, audio amplifiers, drones and many more. Let’s take a lithium battery for example, a buck converter can be utilized to charge a battery of that sort to 4.3v from a 5v USB port/source. Buck converters are utilized in rambles. Automatons regularly are fuelled from a multi-cell lithium battery pack. ordinary pack arrangements are 2-6 cells in arrangement. These battery packs produce a voltage in the scope of 6V-28V. A buck converter drops the battery voltage down to 5V or 3.4V for the flight controller (the cerebrum of the automaton) to utilize. The automaton business regularly calls buck converters BEC, which is short for battery disposal circuit. Below we can see diagrams showing a buck converter with associated signals.

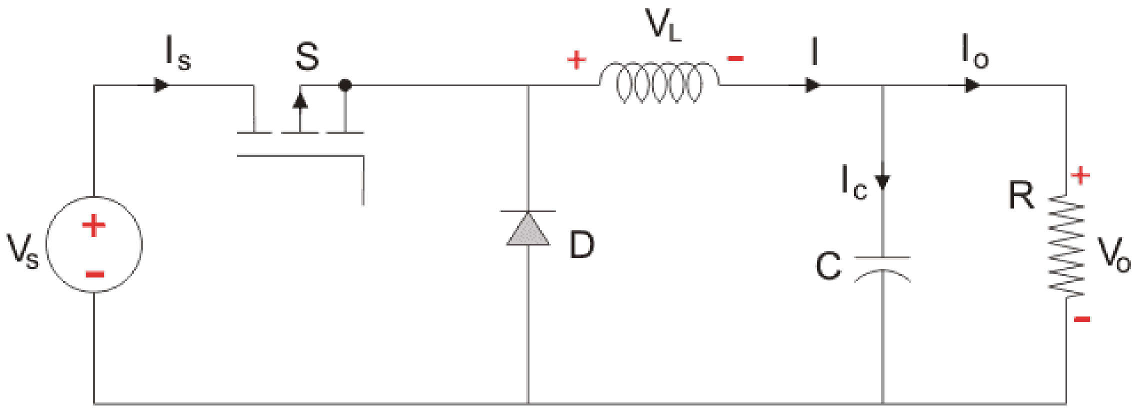


Figure 2.1: A conventional buck converter circuit.

As we can see in our diagram above, we have a voltage source, two switches (S, D), inductor and capacitor and our load. The switch which can be an IGBT or a MOSFET is connected directly to the input voltage, we also have the inductor and capacitor which forms the (LC) circuit. The LC circuit is a low pass filter that help us minimize the voltage and current ripples which makes us to have a pure resistive load at the output. Buck converters have two operating modes; the first mode is when the switch is on and the diode is off while the second mode is when the switch is off and the diode is on.

i. First Mode: Switch (IGBT or MOSFET) is on and diode is off.

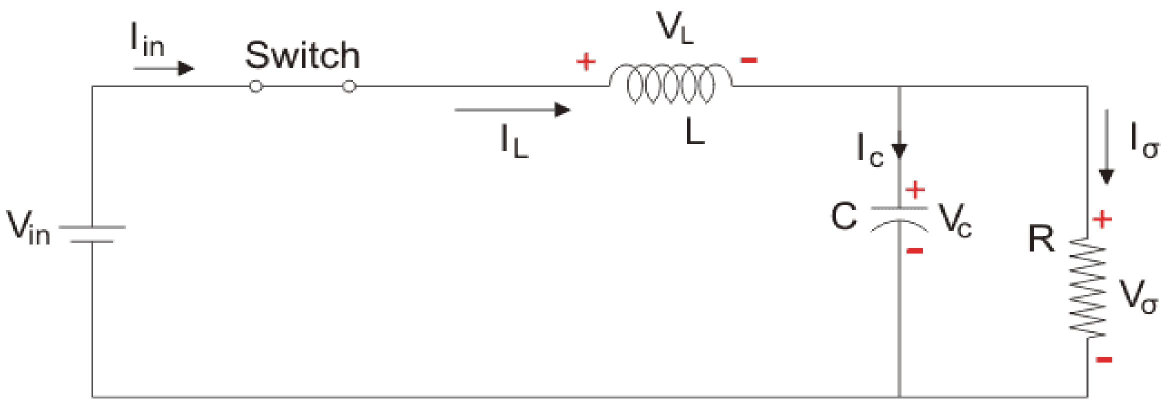


Figure 2.2: Circuit diagram of a buck converter when switch is on

The switch is on at T_{ON} and diode is off at T_{off}

$$T = T_{ON} + T_{OFF} \tag{2.1}$$

Switching frequency; F_S

$$F_S = \frac{1}{T} \tag{2.2}$$

$$\text{Duty cycle, } D = \frac{T_{ON}}{T} \tag{2.3}$$

Applying KVL to this buck converter we yield

$$V_{IN} = V_L + V_O \tag{2.4}$$

$$V_L = L\frac{di_l}{dt} = V_{IN} - V_O \tag{2.5}$$

$$\frac{di_l}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \left(\frac{V_{IN} - V_O}{L}\right) \tag{2.6}$$

When

$$T_{ON} = DT; \Delta t = DT \tag{2.7}$$

$$\Delta_{IL} switch\ on = \left(\frac{V_{IN} - V_O}{L}\right) DT. \tag{2.8}$$

ii. Second Mode: This is when the switch (*MOSFET or IGBT*) is off and the diode D is on.

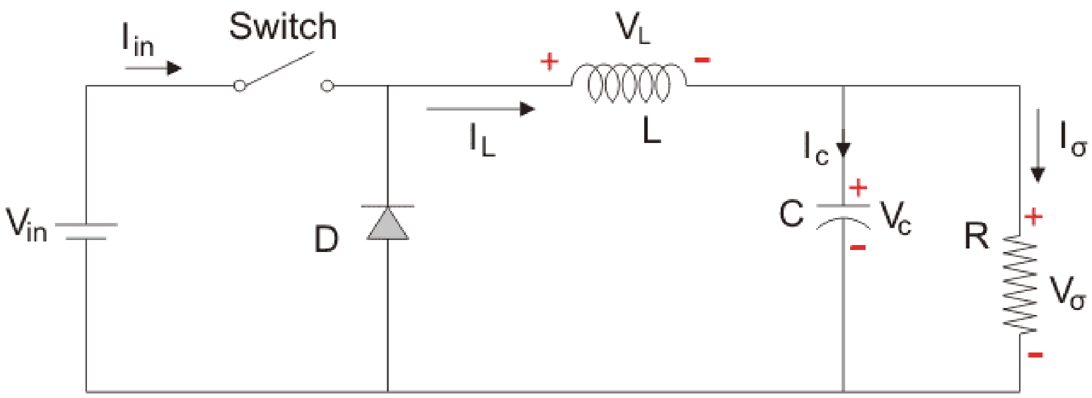


Figure 2.3: Circuit diagram of a buck converter when the switch is off and diode on.

In this mode the energy in the inductor is be en trasfered directly to the load.we would use kirchoff's voltage law to determine tssteady state operaton.

After the first mode is done,the second mode begins

$$0= V_L + V_O \tag{2.9}$$

$$V_L = \mathrm{L}\frac{di_l}{dt} = -V_O \tag{2.10}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)\,T} = \frac{-V_O}{L} \tag{2.11}$$

The switch is off, therefore

$$T_{OFF} = T - T_{ON} = T - DT = (1-D)T \tag{2.12}$$

Similarly,

$$\Delta T = (1-D)T \tag{2.13}$$

$$\Delta i_L switch\ off = \left(\frac{-V_O}{L}\right)\ (1-D)T \tag{2.14}$$

Adding up when the switch ison and when its off gives us zero;

$$\Delta_{IL} switch\ on\ +\ \Delta i_L switch\ off = 0 \tag{2.15}$$

$$\left(\frac{V_{IN}-V_O}{L}\right) \mathrm{DT+}\left(\frac{-V_O}{L}\right)\ (1-D)T = 0 \tag{2.16}$$

$$\frac{V_O}{V_{in}} = D \tag{2.17}$$

2.1.2 Boost converter

From the word 'boost' which means to increase or raise; we can say that the boost converter is simply a converter that steps up the voltage gotten from the input to give us a higher voltage at the output side. This converter is simply the opposite of the buck converter.

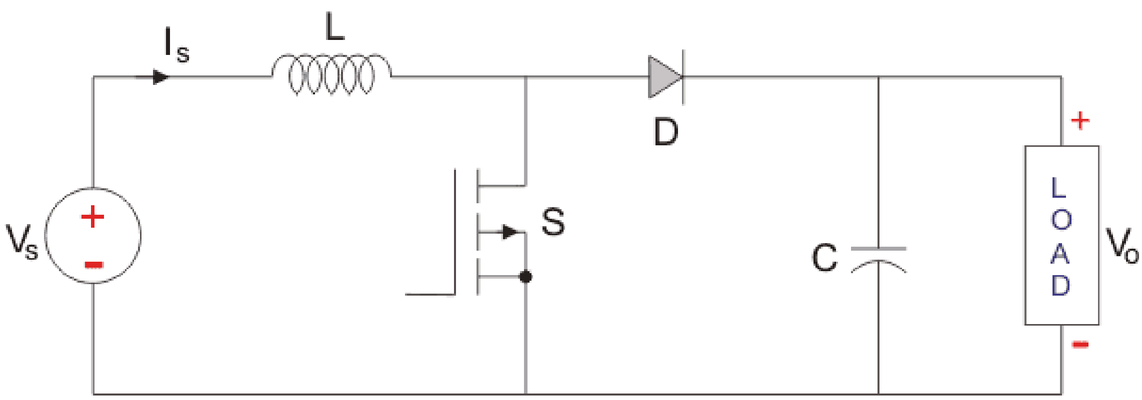


Figure 2.4: Circuit diagram of a conventional boost converter.

As we can see from the above circuit diagram, the source voltage is connected directly to the inductor which gives us a constant input current. The diode is in series with the inductor and also the switch is connected across the source. A capacitor is connected directly to d diode and also connected across the load. The boost converter has two mode just like the buck converter as well.

i. First Mode: When the switch (MOSFET and IGBT) is on and when the diode is off

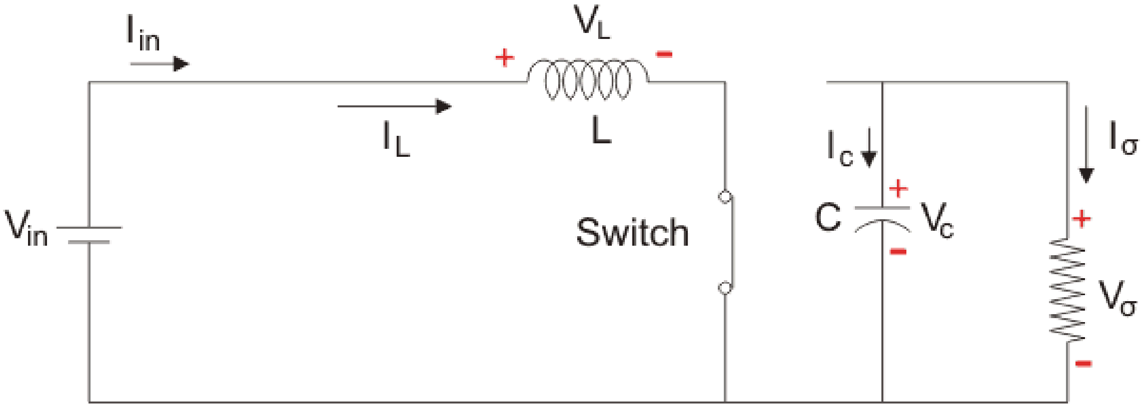


Figure 2.5: When the switch is on

The switch is on at T_{ON} and diode is off at T_{off}

$$T = T_{ON} + T_{OFF} \tag{2.18}$$

Switching frequency;F_S

$$F_S = \frac{1}{T} \tag{2.19}$$

Duty cycle,

$$D = \frac{T_{ON}}{T} \tag{2.20}$$

Applying KVL to this boost converter we yield

$$V_{IN} = V_L \tag{2.21}$$

$$V_L = L\frac{di_l}{dt} = V_{IN} \tag{2.22}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_{IN}}{L} \tag{2.23}$$

$$T_{ON} = DT; \Delta t = DT \tag{2.24}$$

$$\Delta_{IL} switch\ on = \left(\frac{V_{IN}}{L}\right) DT \tag{2.25}$$

ii. Second mode: when the switch is off and when the diode is on

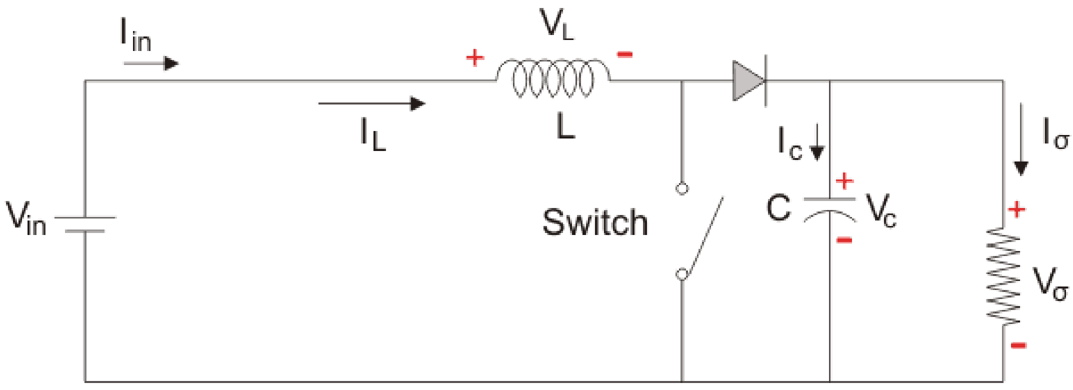


Figure 2.6: when the switch is off

Dealing with the second mode, power stored in the inductor is released to the load resistance and helps to keep the current direction in the same direction. This helps to increase or boost our load voltage.

When we apply Kirchhoff's voltage law, we can say

$$\mathrm{V_{IN}} = \mathrm{V_L} + \mathrm{V_O} \tag{2.26}$$

$$V_L = \mathrm{L}\frac{di_l}{dt} = \mathrm{V_{IN}} - \mathrm{V_O} \tag{2.27}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)\,T} = \left(\frac{V_{IN}-V_O}{L}\right) \tag{2.28}$$

The switch is off at

$$T_{OFF} = T - T_{ON} = T - DT = (1-D)T \tag{2.29}$$

$$\Delta T = (1-D)T \tag{2.30}$$

$$\Delta i_L switch\ off = \left(\frac{V_{IN}-V_O}{L}\right)\ (1-D)T \tag{2.31}$$

As we know

$$\Delta_{IL} switch\ on\ +\ \Delta i_L switch\ off = 0 \tag{2.32}$$

$$\left(\frac{-V_O}{L}\right)\ (DT)\ + \left(\frac{V_{IN}-V_O}{L}\right)\ (1-D)T \tag{2.33}$$

Therefore,

$$\frac{V_O}{V_{in}} = \frac{1}{1-D} \qquad (2.34)$$

As we can see from the above voltage gain , that if we make our duty cycle 1 it would lead to infinity which is not possible pactically. There fore the boost converter is a non-linerized circuit.we need to make the duty cycle to placed at a resonable range because any value higher than 0.8 would lead to the circuit not been stable.

2.1.3 Buck-boost converter

The combination of both buck and boost converter is called a buck-boost converter. A buck boost converter is a dc-dc converter that has the tendency to step-up or step down the voltage but that depends on the value of our duty cycle.

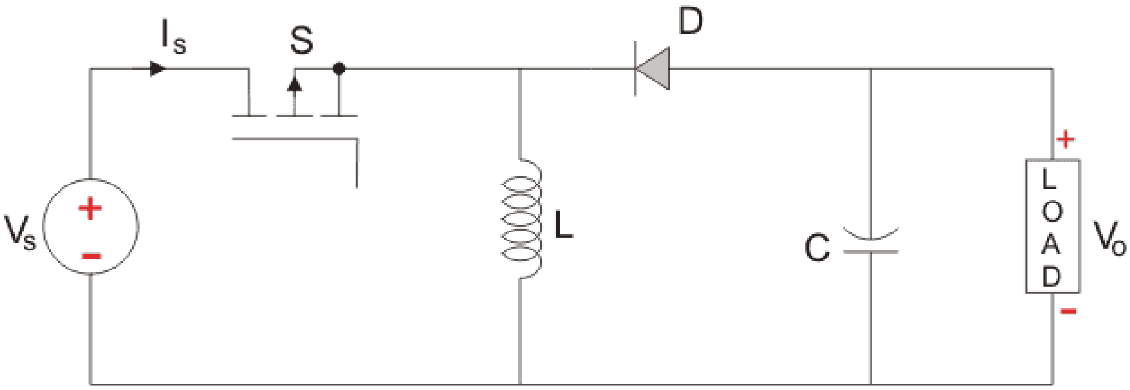


Figure 2.7: Buck-boost converter

From the diagram above we can see that the diode is connected to the direction facing the input voltage which makes the polarity of our load to be flipped in the right sense and the inductor is connected across the source voltage and the load.In this kind of circuit we use a pulsating method to either turn on or turn off the switch. This pulsating method can be done in either a time based manner or a frequency based manner. It is better to make use of the time based manner other than the frequency based because the frequency based have some few problems. We come across 2 modes in this kind of converter.

i. First Mode: When the switch (MOSFET and IGBT) is on and when the diode is off. When our active switch is on in the first mode current flows directly into the inductor and this is maintained throughout the on time.

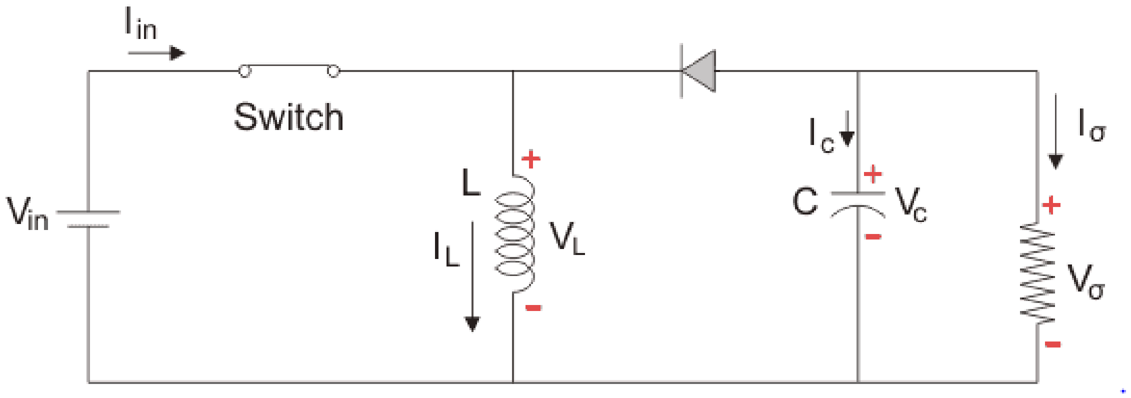


Figure 2.8: Active switch on in buck-boost

$$T = T_{ON} + T_{OFF} \tag{2.35}$$

Switching frequency; F_S

$$F_S = \frac{1}{T} \tag{2.36}$$

$$D = \frac{T_{ON}}{T} \tag{2.37}$$

Using Kirchhoff's voltage law to analyse this circuit

$$V_{IN} = V_L \tag{2.38}$$

$$V_L = L\frac{di_l}{dt} = V_{IN} \tag{2.39}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(DT)} = \frac{V_{IN}}{L} \tag{2.40}$$

When our active switch is on

$$T_{ON} = \mathrm{DT}; \Delta t = DT \quad (2.41)$$

$$\Delta_{IL} switch\ on = \left(\frac{V_{IN}}{L}\right) \mathrm{DT} \quad (2.42)$$

ii. Second Mode: We are dealing with when our active switch is off.

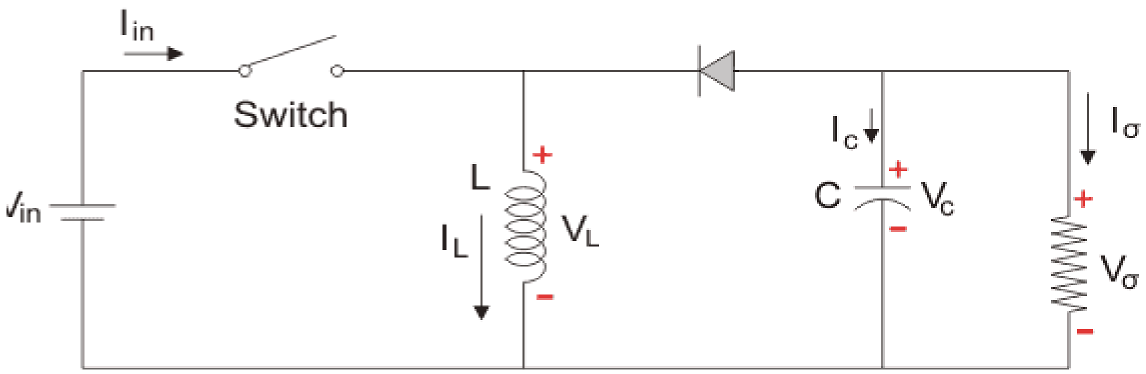


Figure 2.9: when the buck-boost active switch is off

In this part the sign of our inductor is changed and the power which is in the inductor is released to the output load

Analysing this circuit, we have

$$\mathrm{V_L} = \mathrm{V_O} \quad (2.43)$$

$$\mathrm{V_L} = \mathrm{L}\frac{\mathrm{di_l}}{\mathrm{dt}} = \mathrm{V_O} \quad (2.44)$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)\,T} = \frac{V_O}{L} \quad (2.45)$$

The switch is off at

$$T_{OFF} = T - T_{ON} = T - DT = (1 - D)T \quad (2.46)$$

$$\Delta T = (1 - D)T \quad (2.47)$$

$$\Delta i_L switch\ off = \left(\frac{V_o}{L}\right) (1 - D)T \quad (2.48)$$

As we know,

$$\Delta_{IL} switch\ on\ +\ \Delta i_L switch\ off = 0 \quad (2.49)$$

$$\left(\frac{V_O}{L}\right)(1-D)T\ +\left(\frac{V_{IN}}{L}\right)\ (D)T \quad (2.50)$$

Therefore, $\frac{V_O}{V_{in}} = \frac{-D}{1-D}$ (2.51)

From the voltage gain we can see that we can vary our out put voltage when we place our duty cycle to be less, greater or equal to 0.5.

2.2 Non Isolated Bi-directional Converters.

A non-isolated converter is a type of converter that has no isolation between the input and theoutput. This kind of converter is more efficient compared to the isolated ones. We have different kind of non-isolated converter which we would mention just a few, the boost/buck converter,the sepic converter, the cuk converter, the three level converter, the multilevel inverter and so on. The most widely used out of all this is the buck/boost converter because it s efficient and easy to derive.

2.2.1 The conventional bi-directional buck/boost converter.

When this converter is used for an energy storage system. The terminal of the high voltage side is connected to a busbar while the terminal of the low voltage side is connected tobatterystorage.

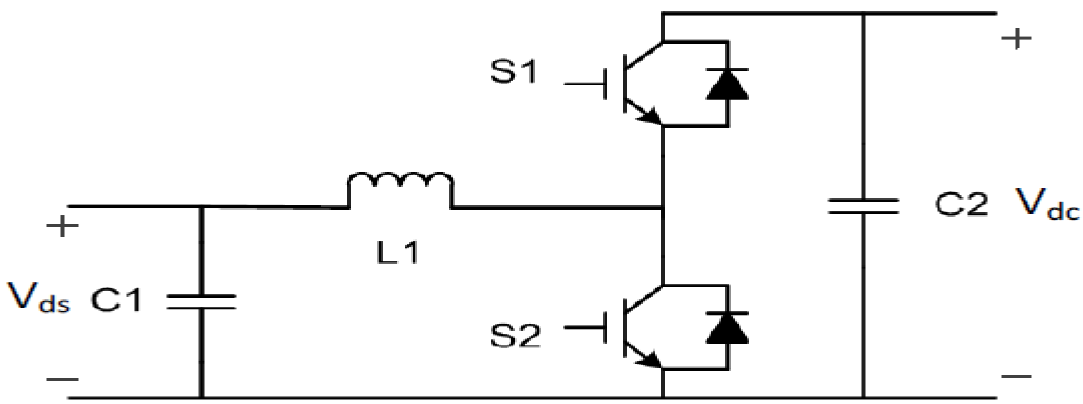


Figure 2.10: Conventional bi-directional dc-dc converter.

How this converter works is when we use a pulsating dc at the gate of the switches. When we fire a pulsating dc at the gate of switch *S1* and turn off switch *S2* this converter will operate in its charging mode but when we turn off the switch *SI* and fire a pulsating dc at switch *S1* this converter operates in its discharging mode. The draw back of this kind of converter is that its voltage gain for step-up and step down is on the low side.

2.2.2 The bi-directional cuk dc-dc converter

The difference between a uni-directional and a bi-directional cuk converter is that its diode is repleced with a switch particlarly a mosfet. Dealing with the forward direction S_1 is turned on while S_2 is turned off while body diode of S_2 acts as the main diode where direction of flow moves from V_{ds} to V_{dc} in the circuit below. In the reverse direction S_2 is turned on while S_1 is turned off while the body diode of S_1 acts as the main diode where the direction of flow is from V_{dc} to V_{ds}. This converter helps to lower the input and output current ripples and as well reduces the cost and size of high frequency operation. One of its drawback is that in converters where we have hard switching as the switching losses increases so is its interference for us to over come this we need to impose a zero swititching for both currrent and voltage which we call soft-switching.

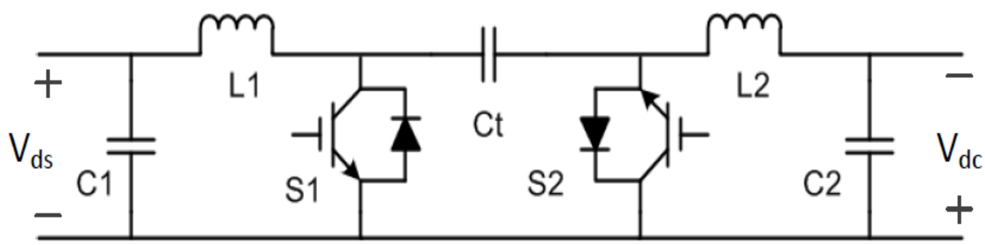


Figure 2.11: Bi-directional cuk dc-dc converter.

2.2.3 Bi-directional cuk converter with an active lamp.

What differentiates this converter with an active clamp with other cuk converters is that it has 2 clamped capacitor, a snubber capacitor C_{s1} *and* C_{s2} as well an auxilary switch and swo auxilary inductors l_{a1} and l_{a2}. The two inductors L_1 and L_2 are large enough to assume constant current. While the two capacitors C_1 and clamped capacitor C_C are large enough to assume constant voltage. Thi kind of converter is designed in a way that it has 9 operating modes in both its reverse and forward direction since both are identical.

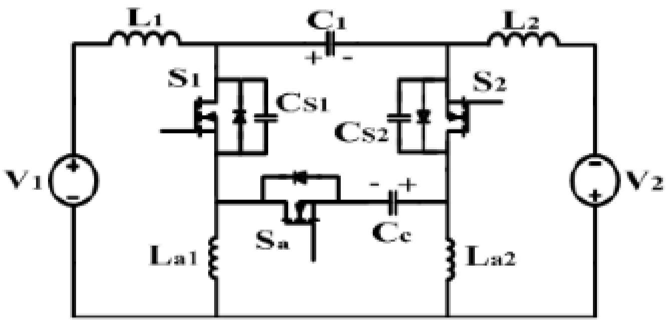


Figure 2.12: An active clamped bi-directional cuk converter.

2.2.4 Bi-directional sepic/zeta converter

This kind of converter has its advantage because it uses zvs and synchronous rectifier operation to reduce both switching and conduction losses.

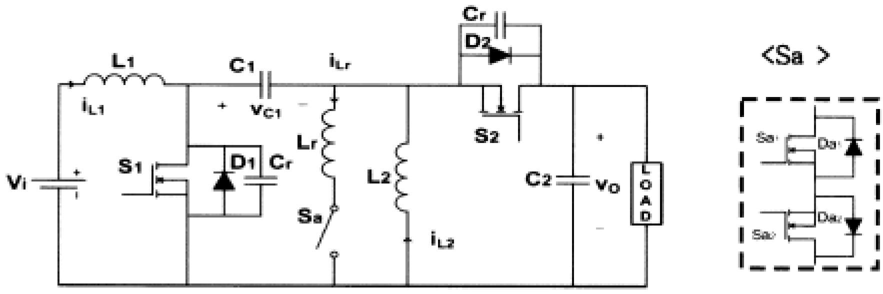


Figure 2.13: A sepic/zeta converter

The switch 1 and 2 are turned on and of with its anti-parallel diodes 1 and 2 respectively. The inductor l_1 and l_2 would be positive for the forward direction and negative for the reverse direction. This kind of converter behaves like a hard switching sepic converter in the forward direction and a zeta converter in the backward direction.We can say this converter is a sepic converter in the forward mode considering its mode of operation and in the reverse direction we can say its operation mode behave like the zeta converter. From the wave forms below we can see the waveform in both the forward and reverse direction.

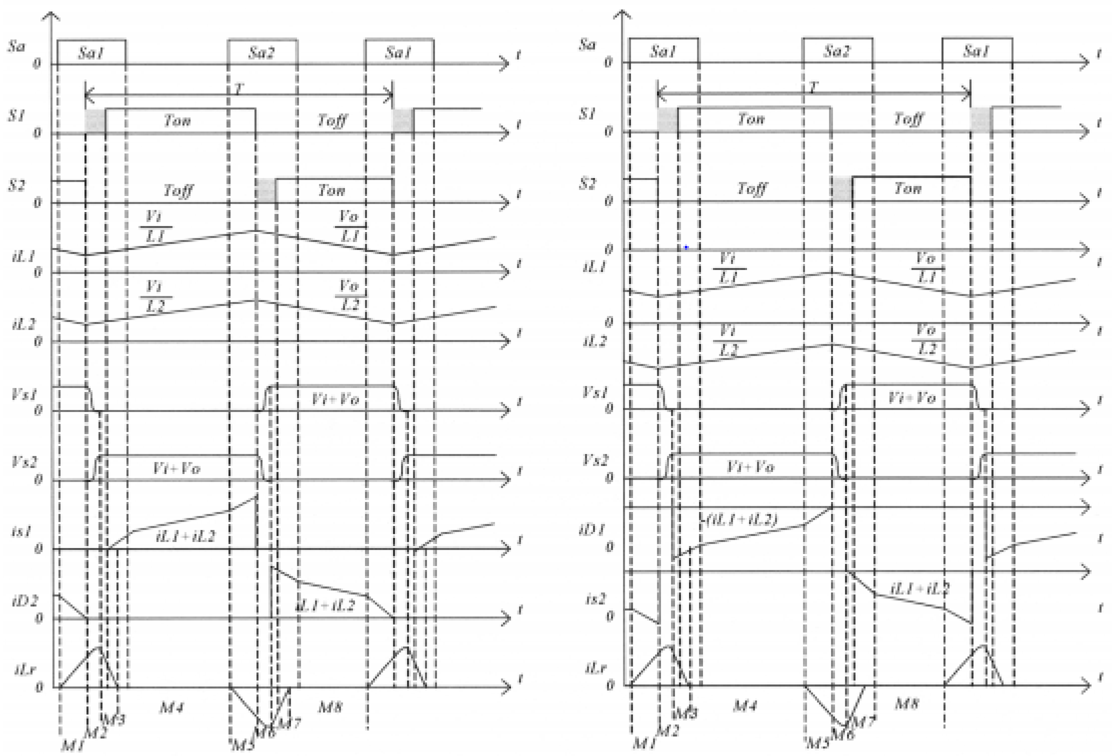


Figure 2.14: Forwad (sepic) mode and reverse mode(zeta) wave forms.

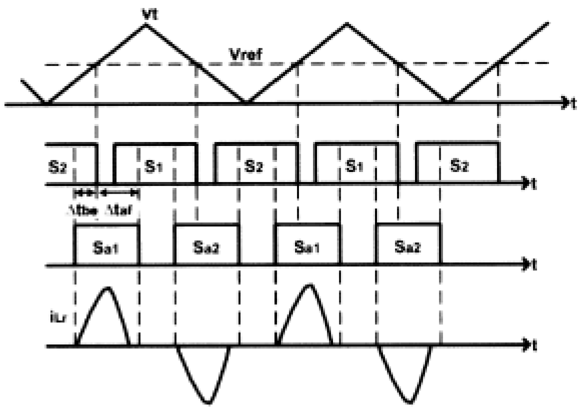


Figure 2.15: Timing diagram for the auxilary switches.

2.3 Derived Non-isolated Bi-diectional Dc-Dc Converters

We would discuss few topologies on non-isolated converters.

2.3.1 Added bi-directional dc-dc converter

This kind of converter was derived from the bi-directional boost/buck converter. This converter is a 2 phase added step up/step down converter althogh dis kind of converter is not limited to 2 phase alone we can have a number of N-phases. The switch s1 and s3 have a phase shift of 180 degrees while the switch s2 and s4 have a phase shift of 180 degrees as well. When we turn on switch s1 and s3 the switch would be in a positive or charging mode but when we turn on s2 and s4 at once the switch would be in a negative or discharging mode. This converter is very useful especially in high ripple current to be able to minimize them. The reduction of the curent ripples at the output is due to the addition of more switches or interleaved.

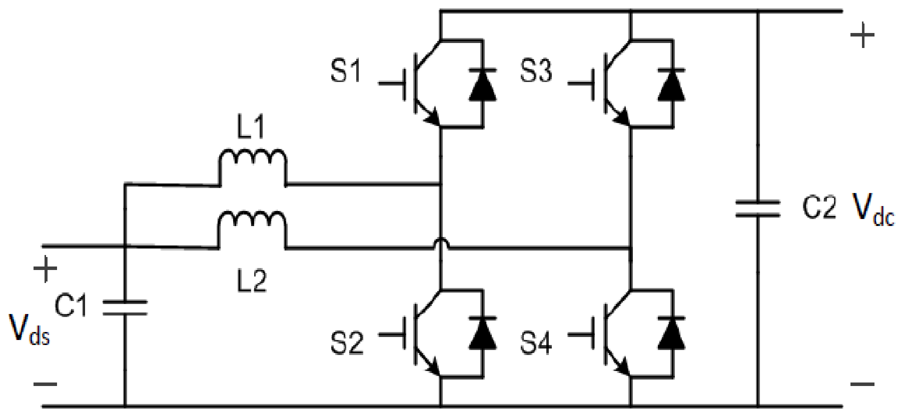


Figure 2.16: Additional bi-directional dc-dc buck/boost converter

2.3.2 Cascaded bi-directional dc-dc converter

A cascaded bidirectional converter doesn’t necessarily need to have a smaller voltage at V_{ds} compared to V_{dc}. This converter is used to step up or sted down the voltage of which everside needs it be it V_{ds} or V_{dc} .

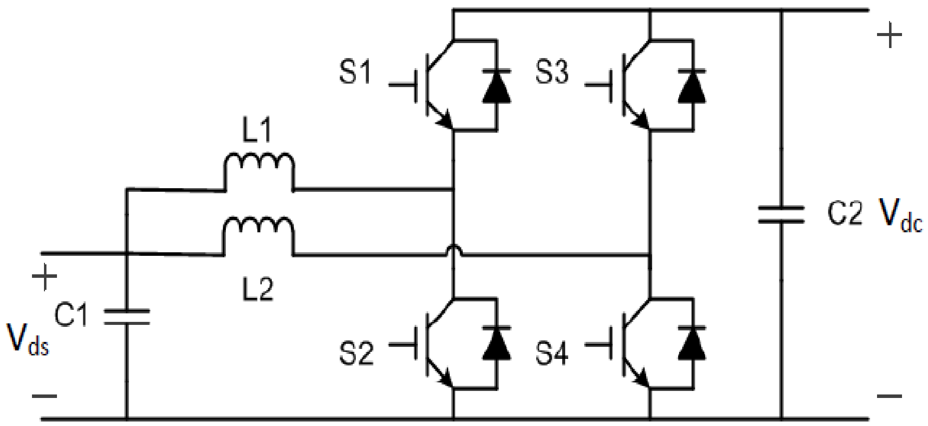


Figure 2.17: Cascaded bi-directional boost/buck converter

2.3.3 Multi-level(3-level) bi-directional dc-dc converter

This type of converter has a common ground for both the input and output terminal. This converter has reduced stress on the switches because of the reduced stress on this type of converter and also generates a higher efficiency but most atimes there might be hitches due to the fact that we have an unbalanced load when it comes to different levels of this type of converter be it a 3-level converter or 5-level or more. This problem of unbalanced load can be solved by using the capacitor charge control or the voltage clamping method. Most atimes in this converter we use a series method of configuration so we would be able to manage the system and also to balance the voltage. When we have the switches connected more in parrale than in serires we have lower voltage and higher current that's why its better we connect more of our switches in series to generate higher voltage. The 3-level converter can be used in photo-voltaic applications, electric vehicles and many more.

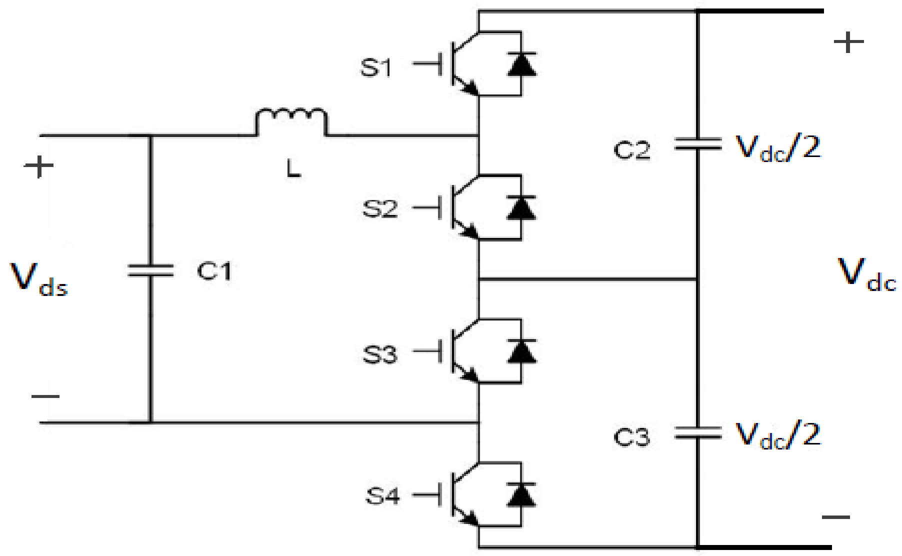


Figure 2.18: A basic bi-directional 3-level converter

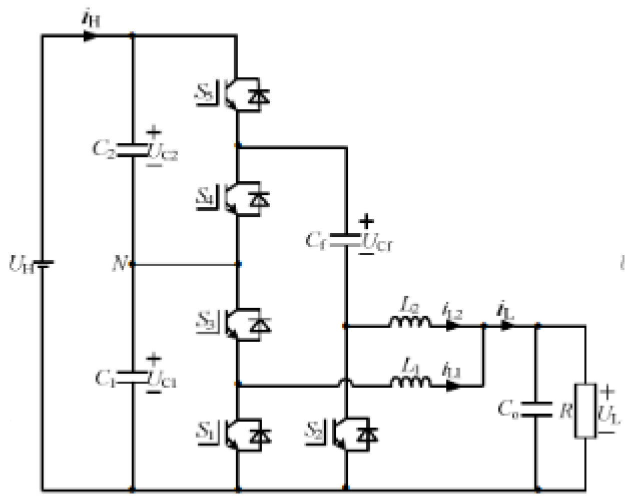


Figure 2.19: A more efficient 3-level bdc

From figure 2.19 we can see that this converter combines two different buck configuration and a switch capicitor topology which makes the buck converter possible to be an input series -output parallel type. In this more efficient 3-level bdc we have five switches, capacitors especially the fly back capacitors, inductors as well as the load. We can see that S_1 , S_3, C_1 and L_1 constructs a buck converter which we would call the first buck circuit while S_5 , S_2, C_2 and L_2 constructs the second buck citcuit . we shoukd note that S_5 and S_2 makes the buck converter and indirect buck circuit because the are not connected directly. The switches S_4 and S_2 and capacitors C_f and C_1 creates the capacitor voltage network. This converter has to be analyzed in both the step-up mode and the step down mode to gnerate our results.

2.3.4 Operation principle in step-down mode

In the step-down mode S_1 and S_2 are driven by same gate while also S_2 and S_4 are driven by another gate. The flyback capacitor is also clamped by the capacitor voltage of C_1 due to the relation of the switches S_4 and S_2 in the switched-capacitor network. This step-down voltage of the 3-level bdc has four circuit stages.

In the first stage switches S_3 and S_5 are turned on at the input side. The low voltage side is charged through the inductor L_1 by capacitor C_1 in the first buck circuit. As the capacitor voltage U_{cf} is clamped by capacitor voltage U_{c1} this makes both voltages to be equal which means $U_{cf} = U_{c1}$. This means that low voltage side can also be charged through L_2 by C_2 in the second buck circuit. In the second buck circuit the fly back capacitor voltage provides a voltage support for this circuit.

In the second stage switches S_2, S_3, S_4 are swiched on. The inductor L_1 charges the low voltage side. In this stage the two adjacent capacitors C_1 and C_f serves as the in put voltage of the first buck circuit. In this stage the flyback capacitor discharges due to the fact that the fly back capacitor is clamped by capacitor C_1 at the first buck circuit.

In the third stage we see some familiarity with the first stage because here $U_{cf} = U_{c1}$. . In this stage the switches $S_1$and S_5 are turned on. Only the inductor L_1 charges the low-voltage side. In the second buck circuit the ouput is charged bu the second inductor throught the second capacitor and also the flyback capacitor is charged with the current passing through second inductor .

In the fourth stage, the switches S_2, S_1, S_4 are turned on while the inductor L_1 and L_2 are used to charge the low voltage side. We should know that the flying capacitor C_f is also clamped by C_1 due to the conduction of switche four and two. In the second stage, C_f is discharges as it is clamped by C_1 in the first buck circuit. Lets make the duty cycle of $S_3 \ and \ S_5 \ to \ be \ d_1$.

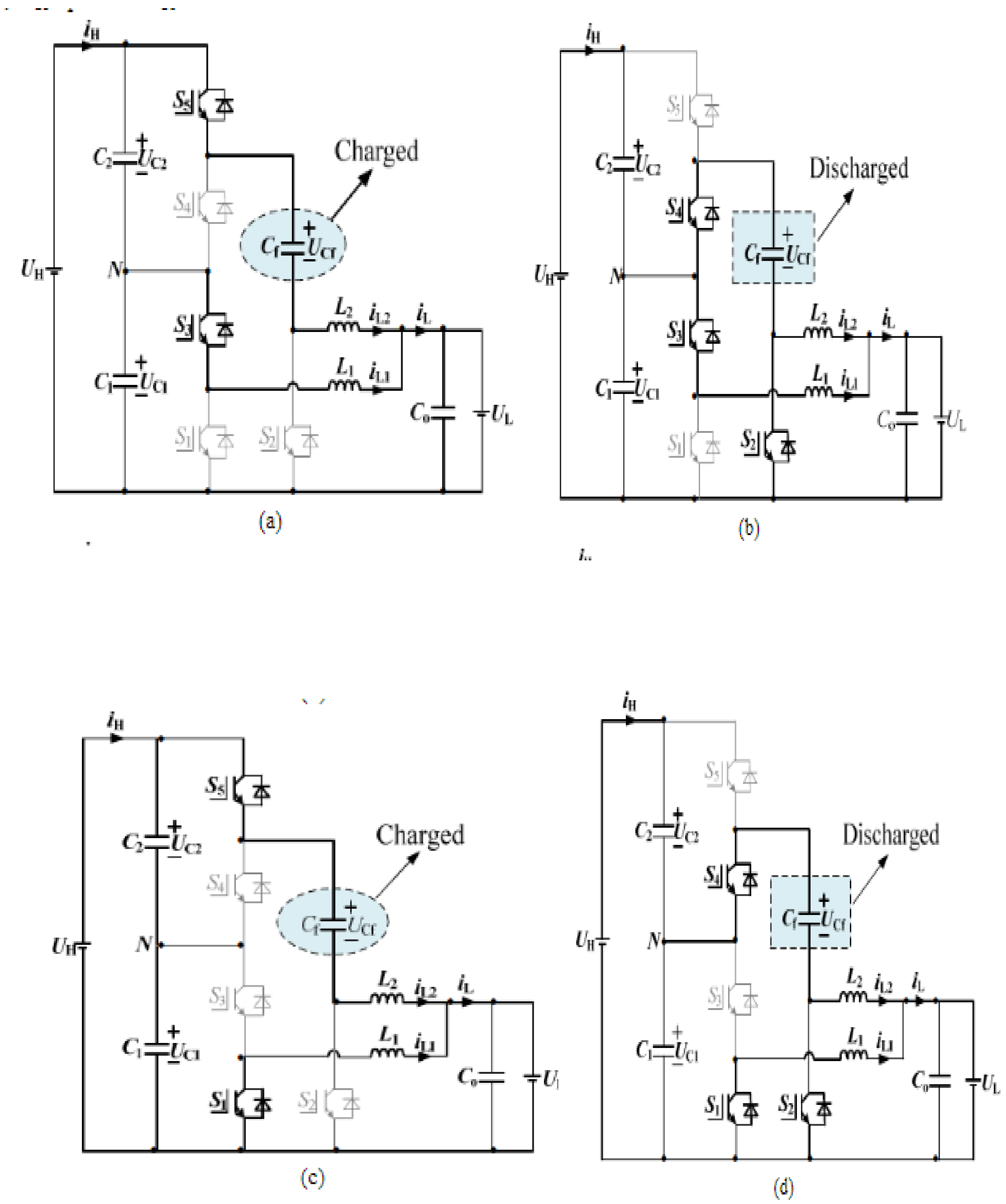


Figure 2.20: Four stages of a more efficient step-down 3-level bdc(a,b,c,d)

where d_1 is any value above 0.5, the bdc at the sted-down mode would work periodically as stages 1, 2, 1, and 3. If we have our duty cycle less than half then the converter would behave periodically like stage 4,2,4,3. The circuits below shows us the 4 stages of the step down 3-level bdc .

$$\frac{U_L}{U_H} = \frac{d_1}{2} \tag{2.52}$$

$$U_{C1} = U_{C2} = \frac{1}{2} U_H \tag{2.53}$$

$$\Delta i_{L1} = \Delta i_{L2} = \frac{U_L}{L} . \frac{1-d_1}{f_s} \tag{2.54}$$

Where U_{C1} , U_{C2} represents the voltage of capacitors one and two while $\Delta i_{L1}, \Delta i_{L2}$ represents the current ripples of both inductors. To calculate the output disturted wave or ripple we say;

$$\Delta i_L = \frac{U_L}{L} . \left(\frac{2d_1-1}{d_1}\right) \left(\frac{1-d_1}{f_s}\right) \text{where } d_1 \text{ greater than 0.5} \tag{2.55}$$

$$\frac{U_L}{L} . \left(\frac{1-d_1}{f_s}\right) \text{where } d_1 \text{ is less than or equal to 0.5} \tag{2.56}$$

2.3.5 Operation principle in the step-up mode.

The efficient 3-level bdc has a similar approach at the step up-mode when compared to the step down mode so it is not necessary re-peating the same circuit and stage topology. Once we are able to understand the step-down mode te same procedure applies to the step-up mode. In the step-up mode the switches S_1 and S_2 are represented by the duty cycle d_2.

$$\frac{U_H}{U_L} = \frac{2}{1- d_2} \tag{2.57}$$

$$\Delta i_{L1} = \Delta i_{L2} = \frac{U_L}{L} . d_2 T, = \frac{U_L}{L} . \frac{d_2}{f_s} \tag{2.58}$$

$$\Delta i_L = \begin{cases}\frac{U_L}{L} \left(\frac{2d_2-1}{f_s}\right) when\ d_2 \text{ is greater than 0.5}\end{cases} \tag{2.59}$$

$$\begin{cases}\frac{U_L}{L} . \frac{d_2(1-2d_2)}{(1- d_2) .f_s} \text{ when } d_2 \text{ is than or equal to 0.5}\end{cases} \tag{2.60}$$

CHAPTER 3

CIRCUIT DESIGN,MATHEMATICAL ANALYSIS AND SIMULATION RESULTS.

This part of the work tends to design the bi-directional step-up and step-down converter circuit,analyze them both in the step up part and step-down part and also make some calculative comparison between the conventional bi-directional buck boost converter and the proposed converter. The converter was also designed and simulated with the use of PSCAD/EMTDC software. This can also be done with the help of matlab but we chose pscad because most of the components on pscad are real components which we can actually see when we want to get them in the buzzer/store.

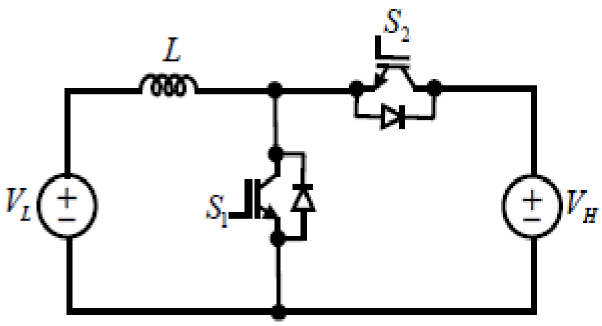


Figure 3.1: Conventional bi-directional dc/dc buck-boost converter

As we know dc-dc bdc are used to transfer energy between two dc sources. This converter consist of two switches S_1 and S_2 and one inductor L and two dc sources V_L and V_H .

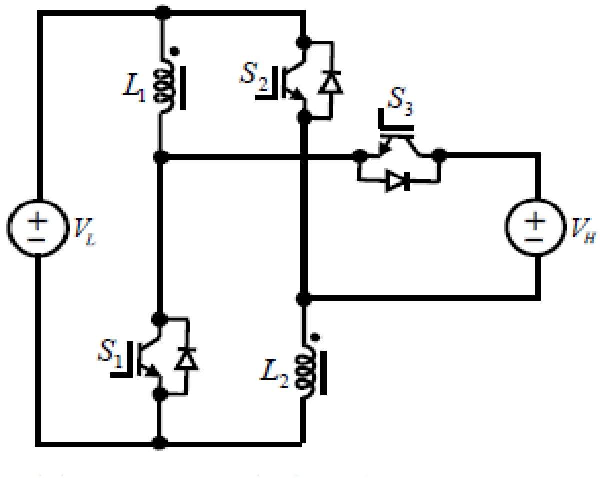


Figure 3.2 : Presented dc-dc bdc

This converter consist of three (3) switches S_1, S_2 and S_3 and two coupled inductors L_1 and L_2 and as well the two dc sources V_L and V_H which denotes the low-voltage side and the high voltage side. For us to analyze the circuit we need to address both the converter in its step-up and step down form and also for each of this forms (step-up and step-down), we need to analyse their continous conduction modes(CCM) and dis-continous conduction modes(DCM) of both converters. For us to analyze this converter we need to take some things into considerations like ignoring the on state resistance R_{DS} (on) of the switches and also ignoring the series resistance of bothe the capacitors and the coupled inductors. We ignore the capacitor because the capacitor is large enough and the voltage across this capacitors can be treated as constant.

3.1 Bi-directional Dc/Dc Step-Up Mode

This converter have the same winding on both the secondary and primary side of the coupled inductor. We also need to analyze the operating principles and steady state analysis of this converter and DCM and CCM modes.

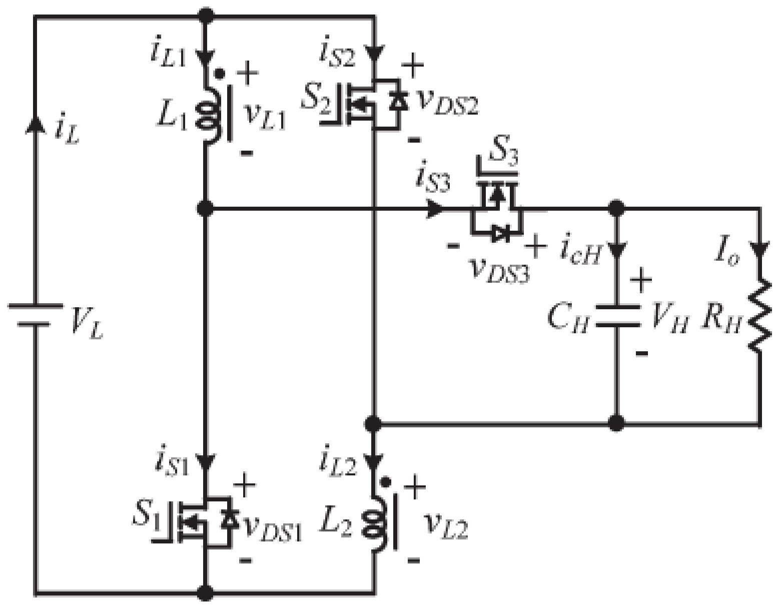


Figure 3.3: Step-up dc-dc bdc

In the step-up mode , we use the pwm technique to control the switches of the proposed converter . This is done by switching on switches S_1, S_2 and switching off S_3. When we switch on switches S_1, S_2 we generate a pulse. Since the coupled inductor have the same winding on both the primary and secondary side we therefor make both inductors to be the same which we can denote as;

$$L_1 = L_2 = L \tag{3.1}$$

This inductor have an inductance that's mutual and we denote as M, where

$$M = K\sqrt{L_1 L_2} = KL \tag{3.2}$$

Where K is the coupling co-efficient of the inductor

The voltage across the primary and secondary turns of the coupled inductor is given as follows

$$V_{L1} = L_1 \frac{di\,L_1}{d_t} + M \frac{di\,L_2}{d_t} = L \frac{di\,L_1}{d_t} + KL \frac{di\,L_2}{d_t} \tag{3.3}$$

$$V_{L2} = L_2 \frac{di\, L_2}{d_t} + M \frac{di\, L_1}{d_t} = L \frac{di\, L_2}{d_t} + KL \frac{di\, L_1}{d_t} \tag{3.4}$$

3.1.1 Step-up ccm operation

1. ***First Mode***: We use pwm method to control the operation of the switches. During the time (t_0, t_1), we switch on switches on switches S_1, S_2 and switch off S_3. Here what we notice is that energy is moved from the low voltage side through the assistance of the coupled inductor.The windings (essential and optional) of the coupled inductor are intended to be in corresponding with one another. The vitality that is put away in capacitor C_H is discharged to the load. Therefore we obtain the voltage across coupled inductor L_1 and L_2 to be

$$VL_1 = VL_2 = V_L \tag{3.5}$$

When we substitute equation 3.3,3.4 and 3.5 to get

$$\frac{di\, L_1(t)}{d_t} + M \frac{di\, L_2(t)}{d_t} = \frac{V_L}{(1+K)L}, \; t_0 \le t \le t_1 \tag{3.6}$$

2. ***Second Mode***: In the second mode we switch off switch S_1 and S_2 and switch on S_3. In this mode for us to transfer energy to C_H and then to the load, we need to connect our coupled inductor in series with the low voltage side V_L. Since the primary and secondary turns of the coupled inductor are in series with each other, then we come across this equation

$$iL_1 = iL_2 \tag{3.7}$$

$$VL_1 + VL_2 = V_L - V_H \tag{3.8}$$

$$\frac{di\, L_1(t)}{d_t} + \frac{di\, L_2(t)}{d_t} = \frac{V_L - V_H}{2(1+K)L}, \; t_1 \le t \le t_2 \tag{3.9}$$

Using state space method to analyze we get

$$\frac{DV_L}{(1+K)L} = \frac{(1-D)(V_L - V_H)}{2(1+K)L} = 0 \tag{3.10}$$

Simplifying equation 3.10 we yield our voltage gain to be

$$G_{CCM}(step-up) = \frac{V_H}{V_L} = \frac{(1+D)}{(1-D)} \quad (3.11)$$

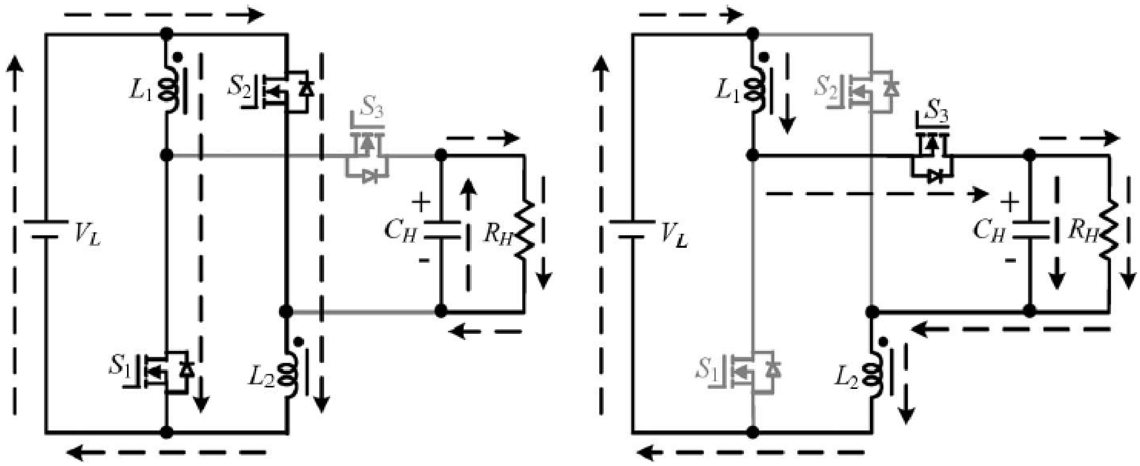


Figure 3.4: Flow path of current in ccm mode(1,2) in step-up converter

3.1.2 Step-up dcm operation

1. ***First Mode***: In this mode also we use the pwm method to control the switches to know where we would generate pulses or not. . During the time (t_0, t_1), we switch on switches on switches S_1, S_2 and switch off S_3. This operation is really similar to the operation of the continuous conduction mode. We need to determine the peak current that went through the primary and secondary winding and we can get this from equation 3.6 and this is given by

$$IL_{1P} = IL_{2P} = \frac{V_L D T_S}{(1+K)L} \quad (3.12)$$

2. ***Second Mode***: During the time (t_1, t_2), we switches off switches S_1, S_2 and switch on S_3. The low voltage side is in series with the coupled inductor so as to transfer energy to the capacitor C_H and the load. The windings of the inductor are in serires and also the current iL_1 and iL_2 through the primary and secondary winding of the coupled inductors are decreased to zero at $t = t_2$. From this we have another equation for current iL_{1p} and iL_{2p}.

$$IL_{1P} = IL_{2P} = \frac{(V_H - V_L)D_2 T_S}{2(1+K)L} \tag{3.13}$$

3. ***Third Mode***: During the time (t_2, t_3), we still switch off switches S_1, S_2 and switch on S_3. At this point we don't have energy stored in the coupled inductor. All the energy have been transferred,therefore the energy in the coupled inductor equals zero. The energy stored in C_H is also transferred to the load.

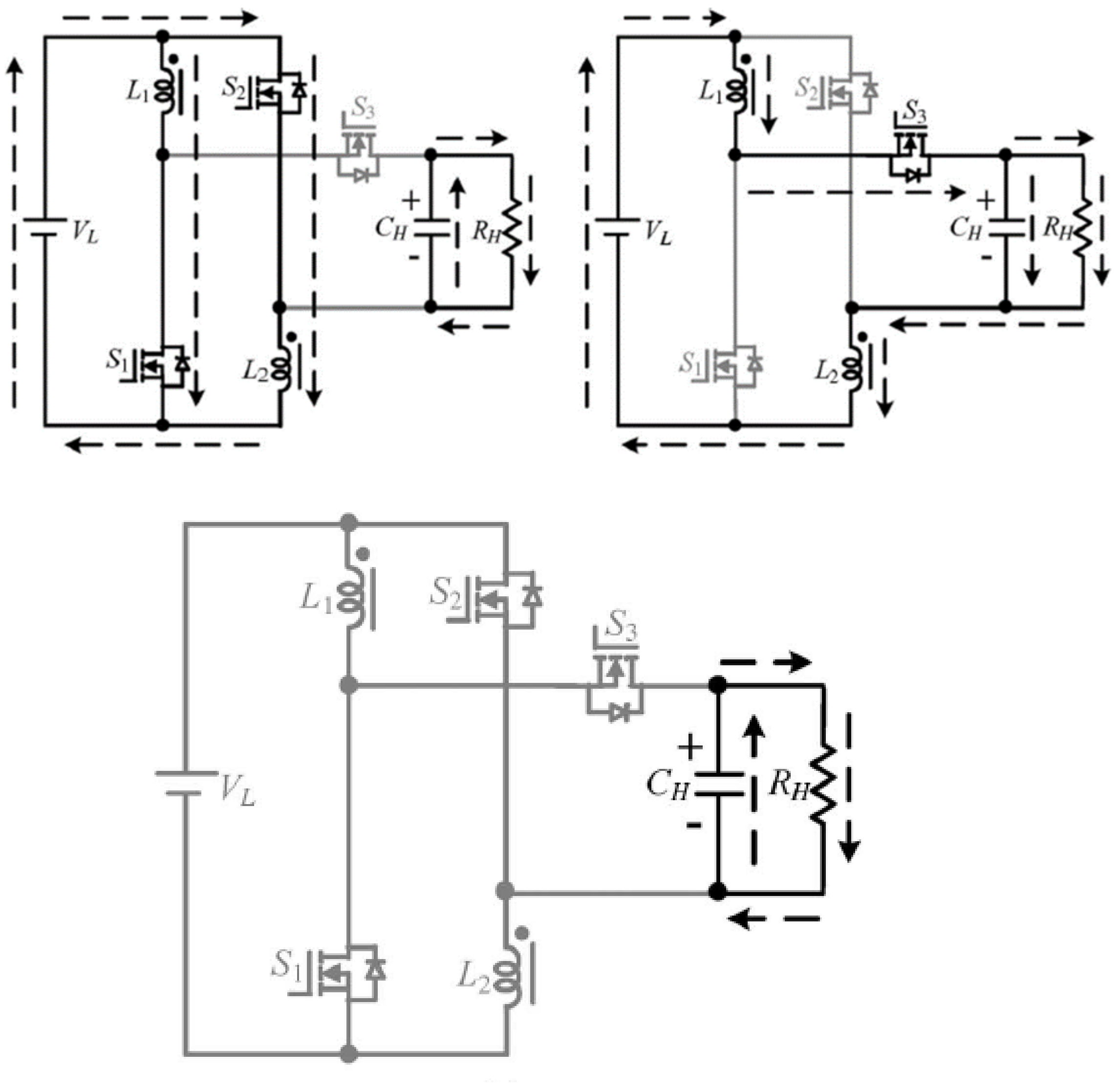


Figure 3.5: Current flow path of dcm mode(1,2,3) in step-up converter

From equations 3.12 and 3.13 we get

$$D_2 = \frac{2DV_L}{V_H - V_L} \tag{3.14}$$

The average value of the output at the capacitor current is given by

$$Ic_H = \frac{\frac{1}{2}D_2T_S\, IL_{1P} - I_O\, T_S}{T_S} = \frac{1}{2}\, D_2\, IL_{1P} - I_O \qquad (3.15)$$

When we add equation 3.12, 3.14, 3.15, Ic_H will be

$$Ic_H = \frac{D^2\, V^2 LT_S}{(1+K)L(V_H - V_L)} - \frac{V_H}{R_H} \qquad (3.16)$$

We can re-write Ic_H under steady state condition when its equat to zero to be

$$Ic_H = \frac{D^2\, V^2 LT_S}{(1+K)L(V_H - V_L)} = \frac{V_H}{R_H} \qquad (3.17)$$

Then we have the normal inductor time constant to be

$$\tau LH \equiv \frac{L}{R_H T_S} = \frac{Lf_S}{R_H} \qquad (3.18)$$

Where f_s is our switching frequency.

When we add eqution 3.17 and 3.18 we get our voltage gain for discontinuus mode which is

$$G_{DCM}(Step - up) = \frac{V_H}{V_L} = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{D^2}{(1+K)\tau LH}} \qquad (3.19)$$

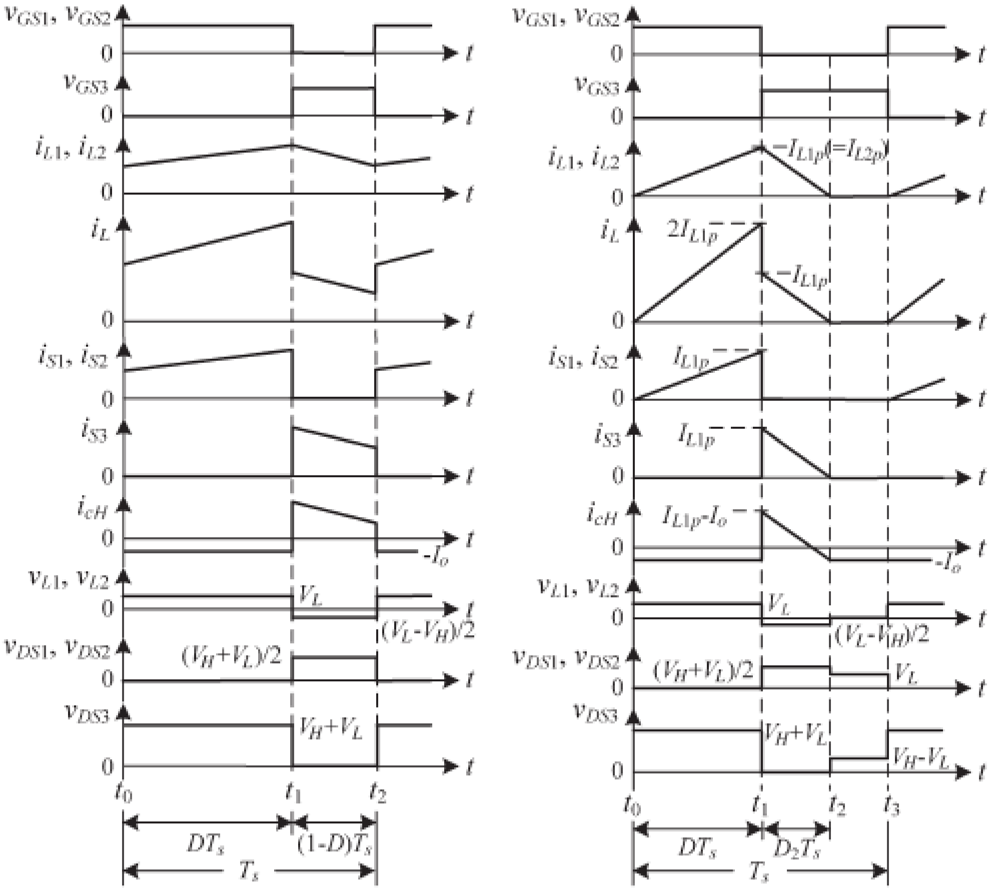


Figure 3.6 : Waveform of ccm and dcm in the step-up mode.

3.1.3: Step-up mode operating boundary conditions for ccm and dcm

When we talk about boundary conditions we mean that the voltage gain of the DCM must be equal to CCM this is what we call boundary conduction mode (BCM). So now we say the normalized induction time can be re-written as

$$\tau LH, B = \frac{D(1-D)^2}{2(1+K)(1+D)} \tag{3.20}$$

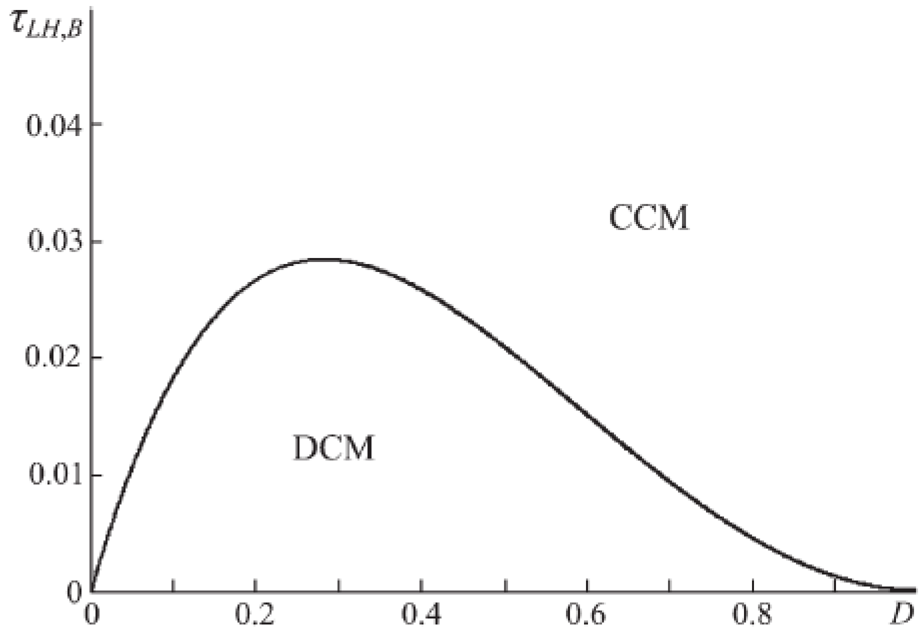


Figure 3.7: Boundary conditions in step-up mode (making k=1)

From the figure above if τLH is greater than τLH,B the proposed converter in the step-up mode is operated in the continuous conduction mode (CCM).

3.2 Bi-directional Dc-Dc Step-down Mode

In the step down mode we use the pulse width modulation method to control the switches of the step down converter. We use the act of synchronous rectification in our switches S_1 and S_2. Which simply means making use of switches like power mosfets while the pulsating method is used for our switch S_3. We also need to describe this converter in both the CCM and DCM operation and analyze the modes in each operation. This is analyzed in a steady state form.

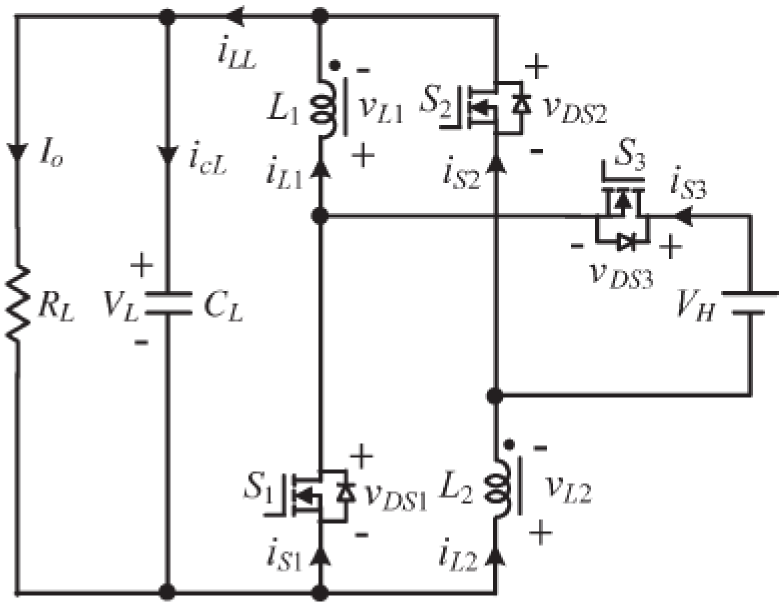


Figure 3.8: Step-down dc-dc bdc

3.2.1 Step-down ccm operation

First mode: In the first mode, at time (t_0 , t_1) the switches S_1 and S_2 are turned off while S_3 is turned on. Here how the power flow works is that the energy of the high voltage side which is V_H is transferred to the coupled inductor and the capacitor C_L and the load but we should note that the primary and secondary windings of the coupled inductors are in series. From herewe would say;

$$i_{L1} = i_{L2} \tag{3.21}$$

$$v_{L1} + v_{L2} = V_H - V_L \tag{3.22}$$

When we substitute both equations we get

$$\frac{di\, L_1(t)}{d_t} = \frac{di\, L_2(t)}{d_t} = \frac{V_H - V_L}{2(1+K)L}\ ,\ t_0 \leq t \leq t_1 \tag{3.23}$$

Second mode: In the second mode, at time (t_1 , t_2), S_3 is turned off while we turn on switches S_1 and S_2. The energy which is stored in the coupled inductor is released to our capacitor C_L and also to the load. We should note that in the second mode the primary and secondary winding of the coupled inductor are in parallel so we can now determine the voltages across the two inductors which would give us the equation below.

$$VL_1 = VL_2 = -V_L \tag{3.24}$$

When we substitute equation 3.3 and 3.4 to 3.24 we get

$$\frac{di\, L_1(t)}{d_t} = \frac{di\, L_2(t)}{d_t} = \frac{V_L}{(1+K)L}\,,\ t_1 \le t \le t_2 \tag{3.25}$$

When we apply state space method we get

$$\frac{D(V_H - V_L)}{2(1+K)L} = \frac{(1-D)V_L}{(1+K)L} = 0 \tag{3.26}$$

When we simplify the eqution 3.26 we get our step-down voltage gain to be

$$G_{CCM}(step - down) = \frac{V_L}{V_H} = \frac{(D)}{(2-D)} \tag{3.27}$$

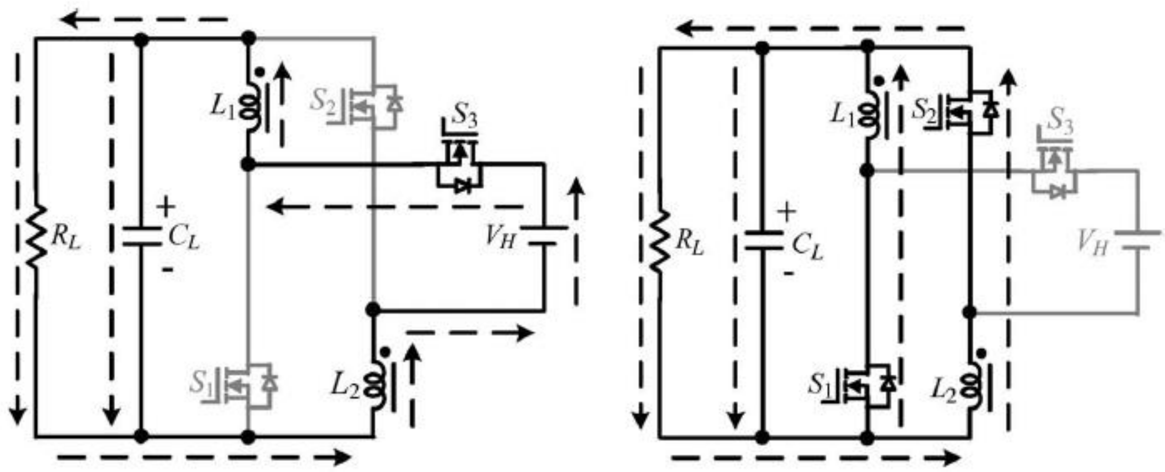


Figure 3.9: Flow path of current in ccm mode(1,2) in step-downconverter

3.2.2 Step-down dcm operation

In the step-down DCM operation we encounter three modes which we would use to analayze the discontinuous part of the step-down converter.

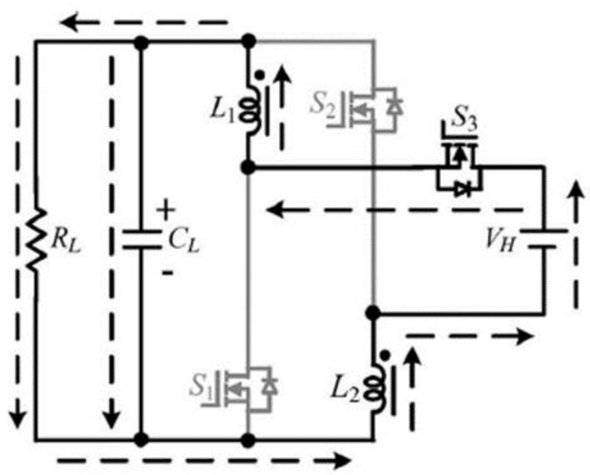
1. ***First Mode:*** In the first mode of the dis-continuous conduction mode operation at time (t_0 , t_1) the switches S_1 and S_2 are turned off while S_3 is turned on. This first mode has the same similarity with that of the first mode of the continuous conduction mode when it comes to operarion principles. We denote the two peak current of the primary and secondary coupled inductor to be

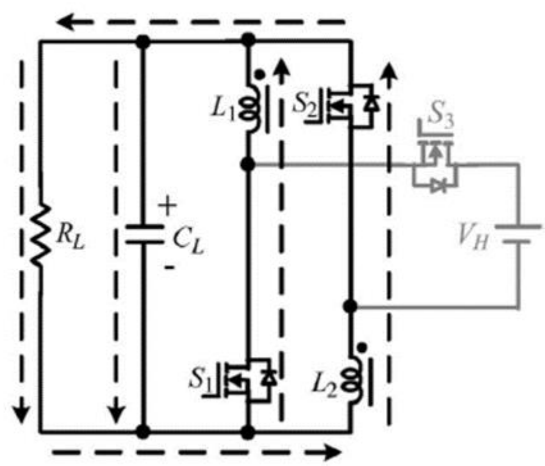
$$IL_{1P} = IL_{2P} = \frac{(V_H - V_L)DT_S}{2(1+K)L} \tag{3.28}$$

2. ***Second mode***: At the second mode at at time (t_1 , t_2) the switches S_1 and S_2 are turned on while S_3 is turned off. In this part the primary and secondary winding of the coupled inductors are in parallel while the energy stord in the inductor is released to the capacitor C_L and also to the load. We should also note that the current of the primary and seconday part of the coupled inductor $IL_1 = IL_2$ is decreased to zero at $t = t_2$. We can also say that our two peak current can be written like this below

$$IL_{1P} = IL_{2P} = \frac{(V_L)D_2 T_S}{(1+K)L} \tag{3.29}$$

3. ***Third mode***: In the third mode t at time (t_2, t_3) the switche S_3 is still turned off while switches S_1 and S_2 are still on .At this point since we have already released the energy in the coupled inductor to the capacitor in mode two, therefore the energy now in the coupled inductor would be zero in the third mode meaning IL_1 and $IL_2 = 0$. The energy stored in the capacitor is noe released to the load.





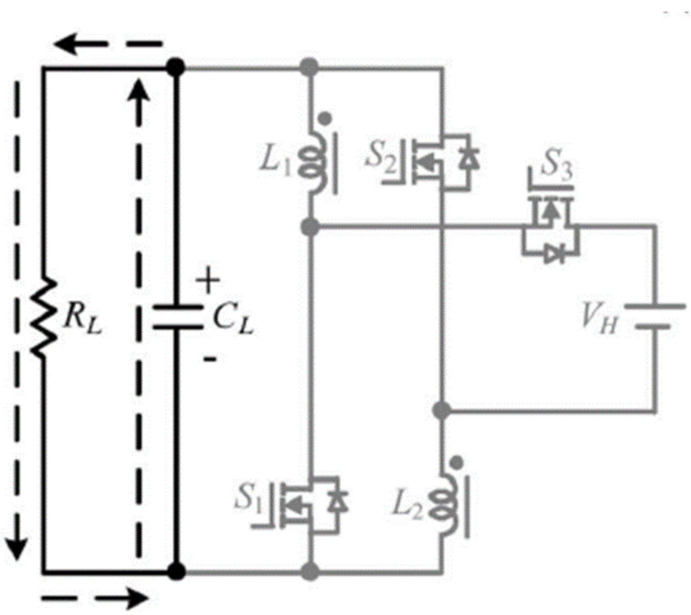


Figure 3.10: Current flow path of dcm mode(1,2,3) in step-down converter

We can say that from equation 3.28 and 3.29 we yield our D_2 to be

$$D_2 = \frac{D(V_H - V_L)}{2\,V_L} \tag{3.30}$$

For each switching period we get our average value of our out put capacitor to be

$$Ic_L = \frac{\frac{1}{2} DT_S\, IL_{1P} + \frac{1}{2} D_2\, T_S(2I_{L1P}) - I_0 T_S}{T_S} = \frac{1}{2}\, DI_{LIP} + D_2\, I_{LIP} - I_0 \tag{3.31}$$

Adding equation 3.28 and 3.30 into 3.31 we get

$$I_{CL} = \frac{D^2 T_S (V_H - V_L)V_L + (V_H - V_L)^2}{4(1+K)LV_L} - \frac{V_L}{R_L} \tag{3.32}$$

Under steady state our capacitor current Ic_L is zero, so we can rewrite the equation as

$$I_{CL} = \frac{D^2 T_S (V_H - V_L)V_L + (V_H - V_L)^2}{4(1+K)LV_L} = \frac{V_L}{R_L} \tag{3.33}$$

The normal inductor time constant yields

$$\tau LL \equiv \frac{L}{R_L T_S} = \frac{Lf_S}{R_L} \tag{3.34}$$

Adding 3.33 to 3.34 we yield out voltage gain for DCM fot step -dowmode to be

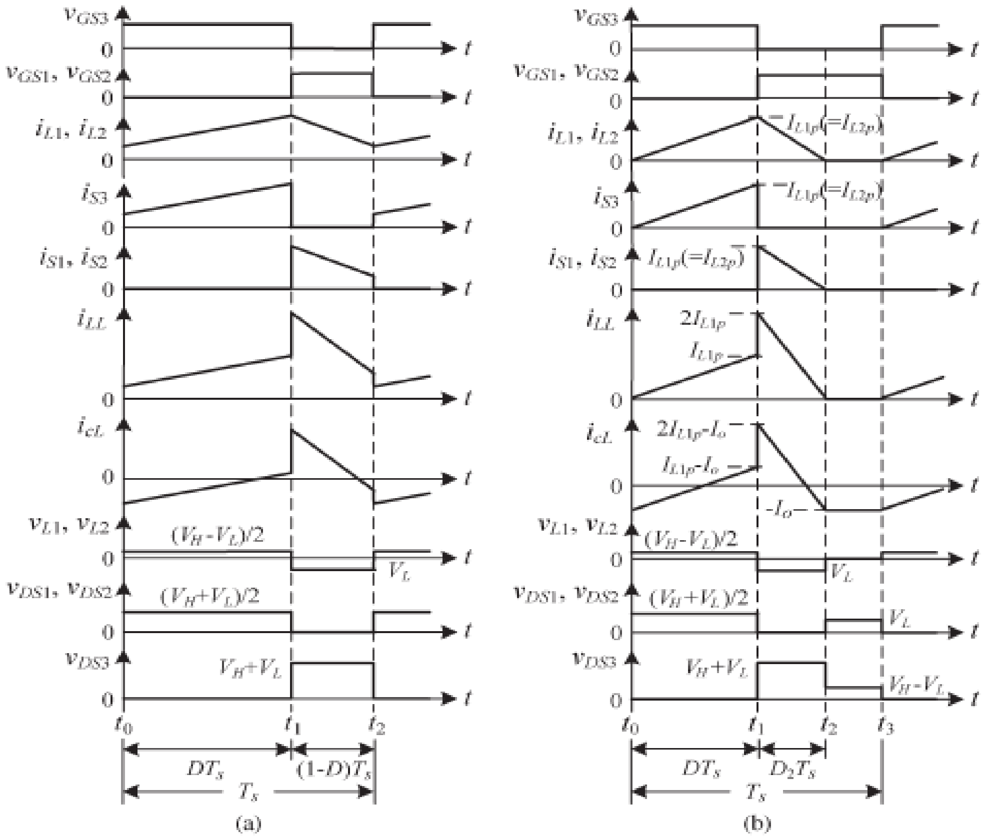


Figure 3.11: Waveforms of ccm and dcm in the step-down mode

$$G_{DCM}(Step - down) = \frac{V_L}{V_H} = \sqrt{\frac{2}{1+\sqrt{1+\frac{16(1+K)\tau LL}{D^2}}}} \tag{3.35}$$

3.2.3 Step-down mode operating boundary conditions for ccm and dcm

When our analylized converter in the step-down mode operates in the boundary condition mode we mean that the voltage gain at the CCM mode is equal to the voltage gain at the DCM mode .Therefore our normalized inductor time constant τLL can be written as

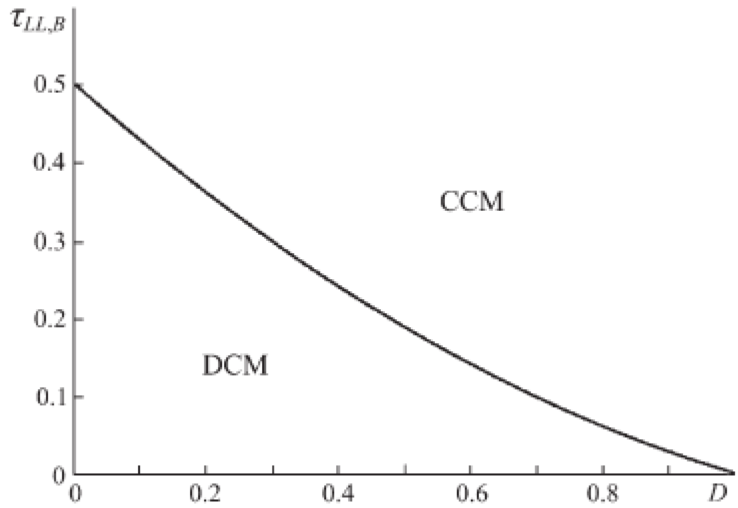


Figure 3.12: Boundary conditions in step-down mode (making k=1)

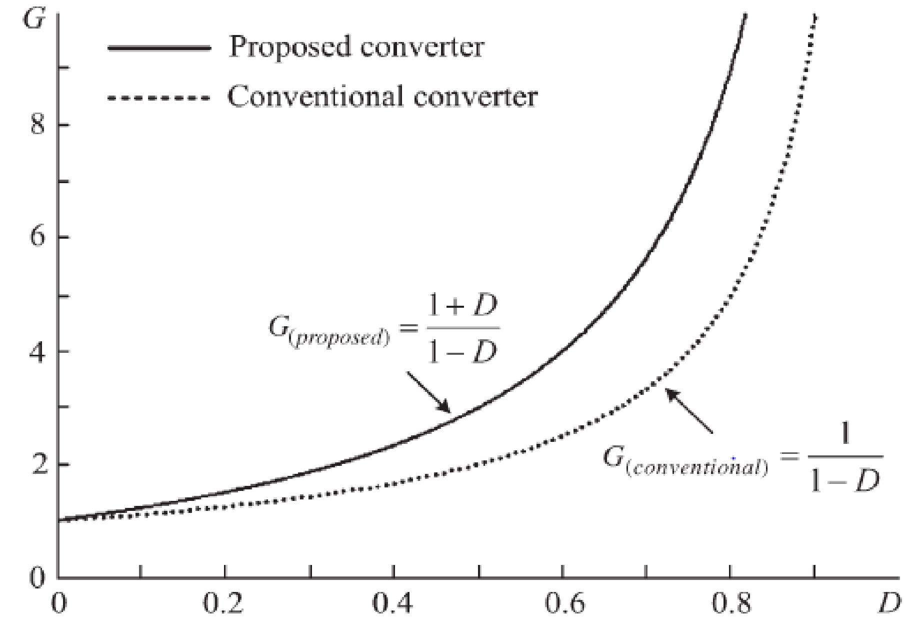
$$\tau LL, B = \frac{(1-D)(2-D)}{2(1+K)} \quad (3.36)$$

From the figure above if τLL is greater than τLL,B the proposed converter in the step-down mode is operated in the continuous conduction mode (CCM).

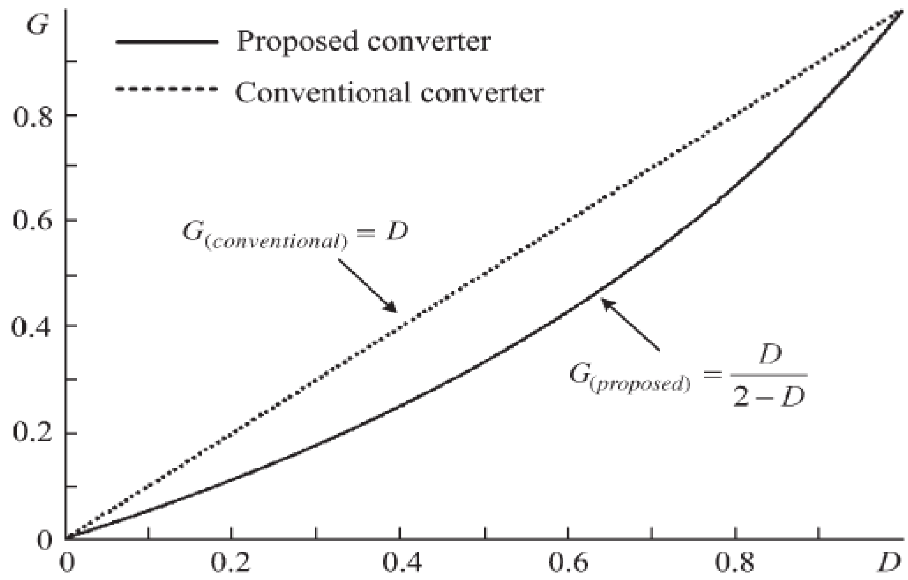
3.3 Comparing the Proposed Converter with Conventional Boost/buck Bdc.

3.3.1 Voltage gain

In this section we would look at the voltage gain curve for the proposed converter and compare it with the traditional converter for step-up and step-down modes in the CCM operation. As we can see from the curve below the proposed converter has a clear improvement in its voltage gain when compared to the conventional converter.



(a)



(b)

Figure 3.13: Voltage again comparison in ccm operation (a) step-up (b) step-down

3.3.2 Switches voltage stress

We derive the stresses on the three switches of the proposed converter as

$$\left\{ VD_{S1} = VD_{S2} = \frac{V_H + V_L}{2} \right. \tag{3.37}$$

$$\{VD_{S3} = V_H + V_L \tag{3.37}$$

The stress on the switches S_1 and S_2 of our conventional converter is given as

$$VD_{S1} = VD_{S2} = V_H \tag{3.38}$$

From here we can say if we want to use our proposed converter for a high step up and step down voltage gain application we need select our switches S_1 and S_2 to have a lower voltage value comarpared to the conventional converter but keeping our switch S_3 to be of the same value with the conventional converter.

3.3.3 Swiching current average value

If we operate our proposed converter in a continous conduction mode operation for step up mode, we can say that our input current average value i_L can be written as

$$I_L(Proposed) = \frac{2I_{L1}(proposed)DT_S+I_{L1}(proposed)(1-D)T_S}{T_S}$$

$$= (1 - D)\, I_{L1}(proposed) \tag{3.39}$$

Where I_{L1} is the average value of i_{LI}

The average value of i_L when operated in the continuous conduction mode in the conventional converter would be written as

$$ILconventional= IL1I_L(conventional)$$

$$= i_{LI}(conventional) \tag{3.40}$$

Using the same electric specification for both conventional and proposed converter our input power can be written as

$$P_{in} = V_L I_L(conventional) = V_L I_L(presented) \tag{3.41}$$

Substituting equation 3.39 and 3.40 to 3.41 we yield

$$I_{L1}(presented) = \frac{I_{LI}(conventional)}{1+D} \tag{3.42}$$

If we operate our proposed converter in a continous conduction mode operation for step up mode, we can say that our input current average value i_{LL} can be written as

$$I_{LL}(proposed) = \frac{I_{L1}(presented)DT_S + 2I_{L1}(presented)(1-D)T_S}{T_S}$$

$$= (2 - D)\, I_{L1}(presented) \qquad (3.43)$$

Using the same electric specification for both conventional and presented converter our output power can be written as

$$P_o = V_L I_L(conventional) = V_L I_L(presented) \qquad (3.44)$$

We derive this equation below from 3.43 and 3.44 to yield

$$I_{L1}(presented) = \frac{I_{LI}(conventional)}{2-D} \qquad (3.45)$$

So far from equation 3.42 and 3.45 we can see that the switching current in the presented converter is less than that of the conventional boost/buck bdc.

3.3.4: Analyzing the converter efficiency

For us to analyze the converter efficiency we need to bring into consideration the equivalent series resistor(ESR). In the step-up mode of the proposed converter r_{L1} and r_{L2} represents the equivalent series resistance of the primary and secondary winding of the coupled inductors. We also use r_{S1}, r_{s2} and r_{s3} to represent the on state resistance of the switches S_1, S_2 and S_3 accordingly. switches S_1, S_2 and turn of S_3 as shown in the circuit below.

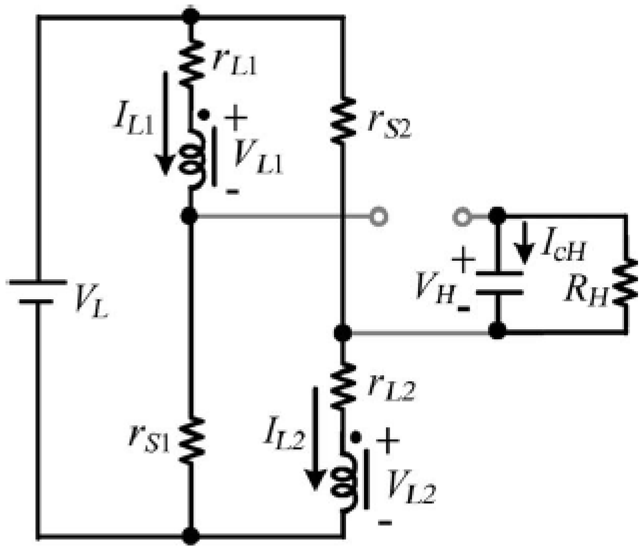


Figure 3.14: Presented Step-up mode circuit equivalent when S_1, S_2 is turned on and S_3 off

To get the average value of i_{CH} and v_{L1} we do this

$$I_{cH}^{I} = -\frac{V_H}{R_H} \tag{3.46}$$

$$V_{L1}^{I} = V_L - I_{L1}(r_{L1} + r_{S1}) \tag{3.47}$$

When the switches S_1, S_2 are turned off and S_3 is turned on as shown in the equvalent circuit shown in fig 3.15 below.

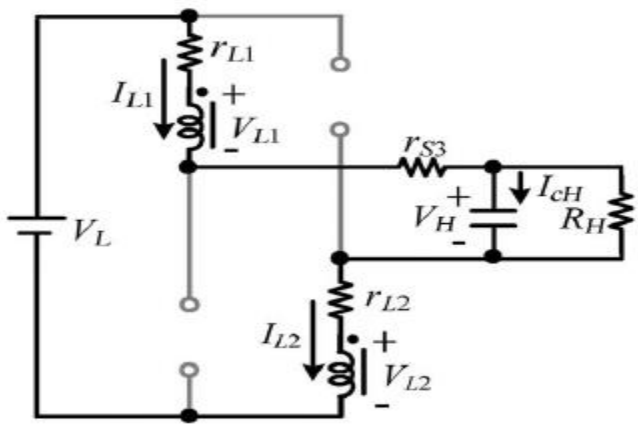


Figure 3.15: Presented Step-up mode circuit equivalent when S_1, S_2 is turned off and S_3 on

$$I_{cH}^{II} = I_{L1} - \frac{V_H}{R_H} \tag{3.48}$$

$$V_{L1}^{II} = \frac{V_L - V_H - I_{L1}(r_{L1} + r_{S3} + r_{L2})}{2} \tag{3.49}$$

When we use amp-sec balance on C_H we yield

$$\int_0^{DT_S} I_{cH}^{I}\, dt \; + \; \int_0^{(1-D)T_S} I_{cH}^{II}\, dt \; = 0 \tag{3.50}$$

When we add 3.46 and 3.48 to 3.50 then I_{L1} yields

$$I_{L1} = \frac{V_H}{(1-D)R_H} \tag{3.51}$$

When we use v-sec balance on L_1 we get

$$\int_0^{DT_S} V_{L1}^{I}\, dt \; + \; \int_0^{(1-D)T_S} V_{L1}^{II}\, dt \; = 0 \tag{3.52}$$

Our voltage gain would be gotten when we substitute 3.47 and 3.49 into 3.52 to yield

$$\frac{V_H}{V_L} = \frac{(1+D)(1-D)R_H}{(1-D)^2 R_H + 2D(r_{L1} + r_{S1}) + (1-D)(r_{L1} + r_{L2} + r_{S3})} \tag{3.53}$$

$$\frac{V_H}{V_L} = \frac{(1+D)}{(1-D)} \times \frac{(1-D)^2 R_H}{(1-D)^2 R_H + 2D(r_{L1} + r_{S1}) + (1-D)(r_{L1} + r_{L2} + r_{S3})} \tag{3.54}$$

To get the input power

$$P_i = V_L \times I_i \tag{3.55}$$

$$P_i = V_L \times I_{L1}(1 + D) \tag{3.56}$$

$$P_i = \frac{(1+D)V_L V_H}{(1-D)R_H} \tag{3.57}$$

$$P_O = V_H I_O \tag{3.58}$$

$$P_0 = \frac{V_H^2}{R_H} \tag{3.59}$$

$$\eta = \frac{P_O}{P_i} \tag{3.60}$$

$$\eta(presented) = \frac{(1-D)}{(1+D)} \times \frac{V_H}{V_L} \quad (3.61)$$

$$\eta(presented) = \frac{(1-D)^2 R_H}{(1-D)^2 R_H + 2D(r_{L1} + r_{S1}) + (1-D)(r_{L1} + r_{L2} + r_{S3})} \quad (3.62)$$

Dealing with the step-down mode when the switches S_1, S_2 are turned off and S_3 is turned on as shown in the equvalent circuit shown in fig 3.16 below.

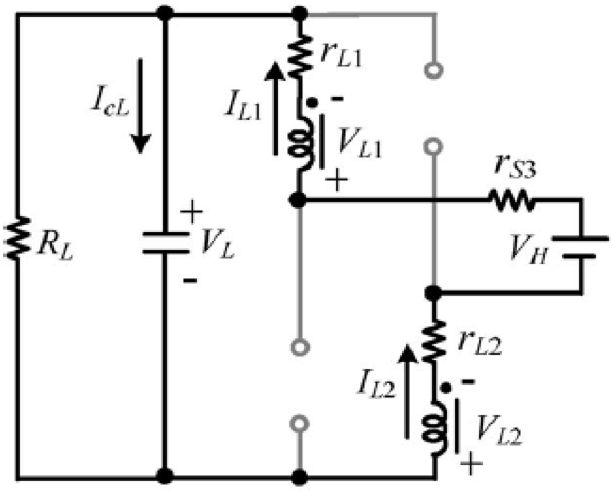


Figure 3.16: Presented Step-down mode circuit equivalent when S_1, S_2 is off and S_3 on

To get the average value of i_{CL} and v_{L1} we do this

$$I^{I}_{cL} = I_{L1} - \frac{V_L}{R_L} \quad (3.63)$$

$$V^{I}_{L1} = \frac{V_H - V_L - I_{L1}(r_{L1} + r_{S3} + r_{L2})}{2} \quad (3.64)$$

When the switches S_1, S_2 are turned on and S_3 is turned off as shown in the equvalent circuit shown in fig 3.17below.

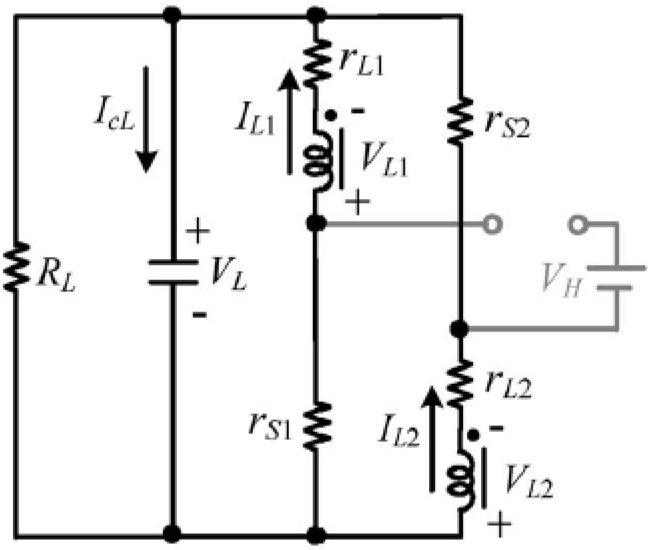


Figure 3.17: Presented Step-down mode circuit equivalent when S_1, S_2 is on and S_3 off

To get the average value of i_{CL} and v_{L1} we do this

$$I_{cL}^{II} = 2I_{L1} - \frac{V_L}{R_L} \tag{3.65}$$

$$V_{L1}^{II} = -V_L - I_{L1}(r_{L1} + r_{S1}) \tag{3.66}$$

When we use amp-sec balance on C_L we yield

$$\int_0^{DT_S} I_{cL}^{I}\, dt \; + \; \int_0^{(1-D)T_S} I_{cL}^{II}\, dt \; = 0 \tag{3.67}$$

When we substitute we find out that I_{L1} yields

$$I_{L1} = \frac{V_L}{(2-D)R_L} \tag{3.68}$$

When we use v-sec balance on L_1 we get

$$\int_0^{DT_S} V_{L1}^{I}\, dt \; + \; \int_0^{(1-D)T_S} V_{L1}^{II}\, dt \; = 0 \tag{3.69}$$

After substituting equation 3.58 and 3.60 into 3.63 we get or voltage gain to be

$$\frac{V_L}{V_H} = \frac{D}{(2-D)} \times \frac{(2-D)^2 R_L}{(2-D)^2 R_L + 2(1-D)(r_{L1}+r_{S1}) + D(r_{L1}+r_{L2}+r_{S3})} \tag{3.70}$$

We obtain our P_i and P_o to be

$$P_{in} = V_H I_{L1} D = \frac{D V_L V_H}{(2-D) R_L} \tag{3.71}$$

$$P_0 = \frac{V_L^2}{R_L} \tag{3.72}$$

The efficiency now can be written as

$$\eta = \frac{P_O}{P_{in}} \tag{3.73}$$

$$= \frac{(2-D)^2 R_L}{(2-D)^2 R_L + 2(1-D)(r_{L1} + r_{S1}) + D(r_{L1} + r_{L2} + r_{S3})} \tag{3.74}$$

For us to compare we just need to consider the equations for the conventional converter and also its equivalent circuit but the calculation wont be expantiated because it also follows the same procedure as the presented converter. For clarity sake we would show the equivalent circuit of the conventional step-up and step-down converterin its switches on and off state mode below.

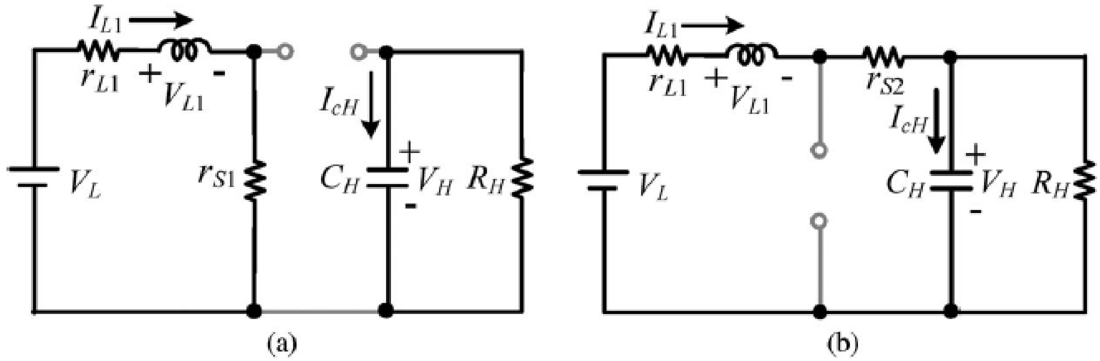


Figure 3.18: Conventional Step-up circuit equivalent (a) S_1on, S_2 off(b)) S_1off, S_2 on

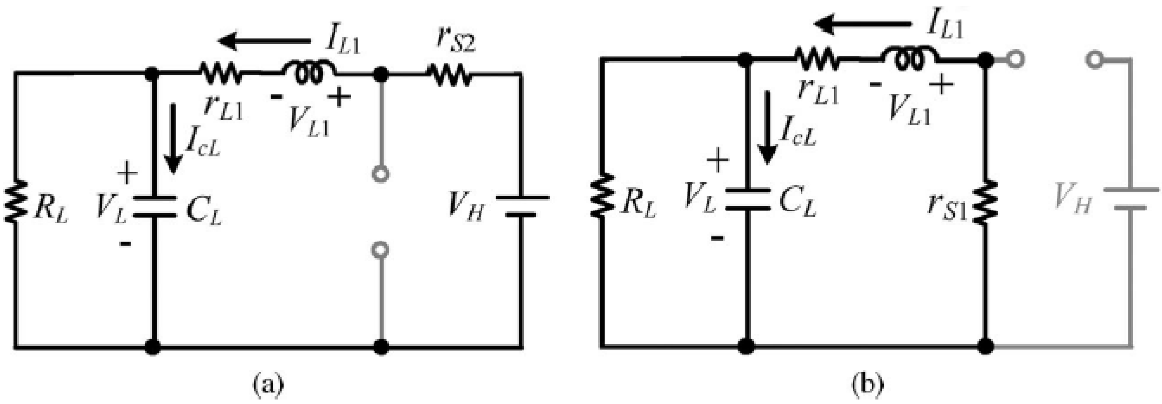


Figure 3.19: Conventional Step-down circuit equivalent (a) S_1off, S_2 on (b) S_1on, S_2 off

For the step-up mode of the equivalent conventional converter that we can see in Fig 3.18, r_{L1} represents the equivalent series resistance of the inductor. We also denote the on state resistance of the two switches to be written as r_{S1} and r_{S2} . we write the efficiency as

$$\eta = \frac{P_O}{P_{in}} \tag{3.75}$$

$$= \frac{(1-D)^2 R_H}{(1-D)^2 R_H + D(r_{L1}+r_{S1}) + (1-D)(r_{L1}+r_{S2})} \tag{3.76}$$

For the step- down of the equivalent conventional converter that we can see in Fig 3.19. we can write the efficiency using the same method in the step -up mode to yield

$$\eta = \frac{P_O}{P_{in}} = \frac{R_L}{(1-D)^2 R_L + D(r_{S2}+r_{L1}) + (1-D)(r_{L1}+r_{S1})} \tag{3.77}$$

3.3.5: Calculated efficiency comparison

Lets compare the efficiency of both the proposed converter and the conventional converter using mathematical method. Using this format we need to put few parameters into consideration. Considerng voltage values for low voltage side and high voltage side.We would have the same inductor resistactancw for both r_{L1} and r_{L2}. The reisstance of the three switches r_{S1}, r_{S2} and r_{S3} have to be same.For clarity sake we would consider three scenerios.

- ***For the first scenerio*:**

$$r_{L1} = r_{L2} = 11m\Omega$$

$$r_{S1} = r_{S2} = r_{S3} = 23m\Omega$$

$$V_H = 42v\ , V_L = 21V$$

- ***For second scenerio*:**

$$r_{L1} = r_{L2} = 11m\Omega$$

$$r_{S1} = r_{S2} = r_{S3} = 23m\Omega$$

$$V_H = 42v, V_L = 14V$$

- ***For third scenerio*:**

$$r_{L1} = r_{L2} = 11m\Omega$$

$$r_{S1} = r_{S2} = r_{S3} = 23m\Omega$$

$$V_H = 42v, V_L = 10.5V$$

Substituting this values above into the equations for proposed step-up and step-down converter and also the conventional step-up and stepp-down converter we get our calculated efficiency. This calculated efficiency results would be shown in figures as we can see below for the three scenerios.

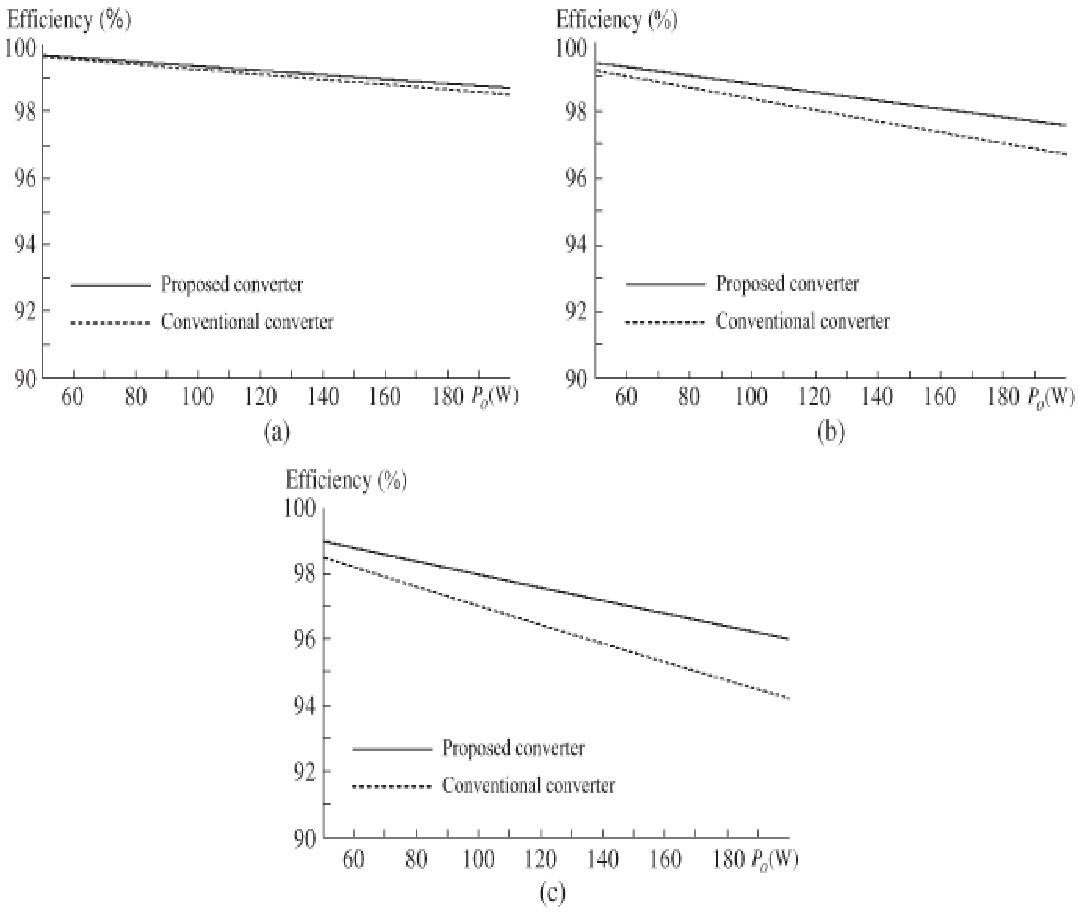


Figure 3.20: Comparing step-up mode calculated efficiency for scenerio 1,2,3

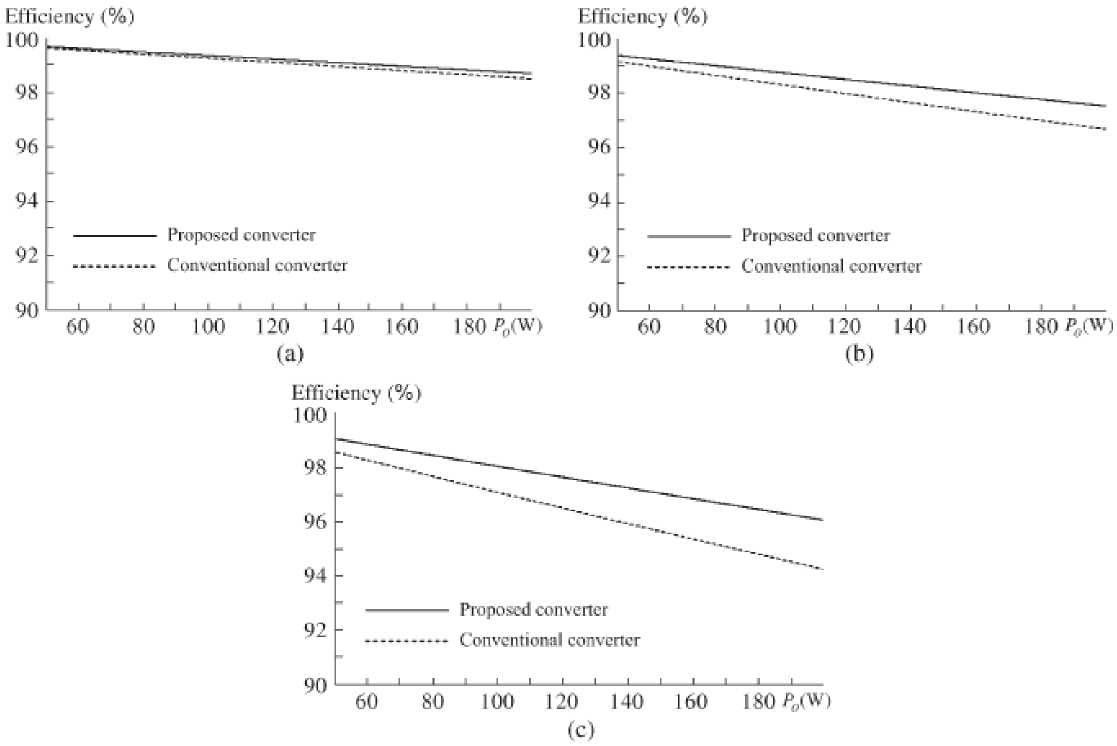


Figure 3.21: Comparing step-down mode calculated efficiency for scenerio 1,2,3

From here we can see that for us to achieve a higher efficiency we need to use the proposed converter but if we are considering to work to achieve alower voltage then we can go with the conventional converter due to lower cost. Since high efficiency is paramount to us its best to go with the proposed converter.

3.4 Simulation Results of the Presented Converter

This part of the work tends to show us the values which we used in getting our desired results, the circuit diagram in step-up and step-down modes which was drawn using the simulation software and also our different waveforms gotten when simulated. The simulation was done using pscad/emtdc software which is a power system software that gives us accurate results and also the actual components in this software are exactly what we can get in the buzzer. We would have to summarize our design in Table 3.1 for simulation purpose.

Table 3.1: Simulation Parameters

Component(s)	**Quantity**	**Values**
Low Voltage (V_L)	1	10 Volts
High Voltage (V_H)	1	45 Volts
Inductor (L_1 and L_2)	2	0.000055H
Switching Frequency (F_s)		50KHZ
Duty Cycle		0.8
IGBT	4	
Resistor(R_H)	1	50Ω
Resistor (R_L)	1	1Ω
Capacitor (C_L)	1	200μF
Capacitor (C_H)	1	50 μF

3.4.1 Simulation results

The simulated results are as follows.

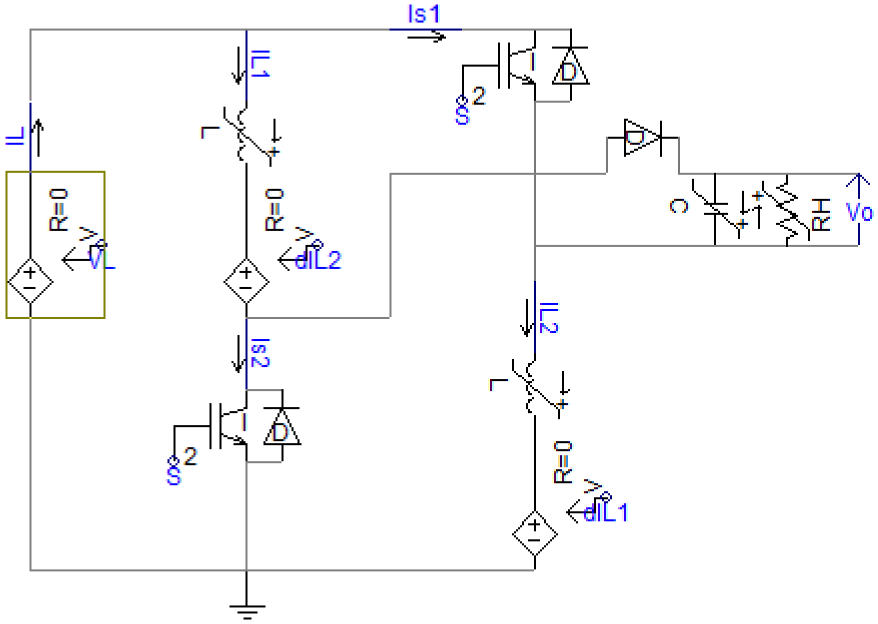


Figure 3.22: PSCAD Designed Circuit Diagram for Step-Up Mode

3.4.2 Step-up dc-dc bdc simulation results

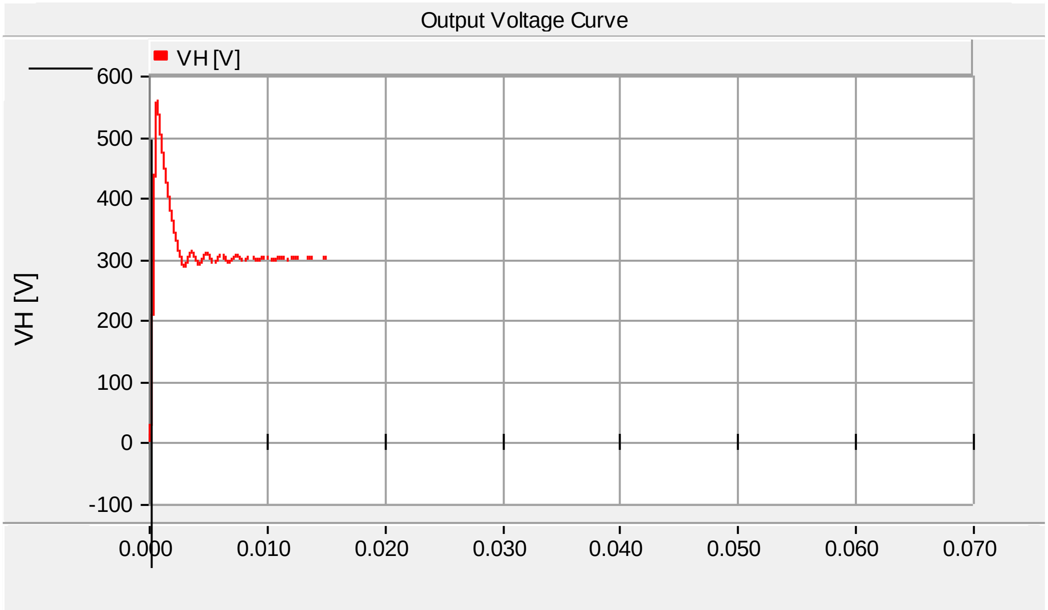


Figure 3.23: Output voltage curve (V_H)

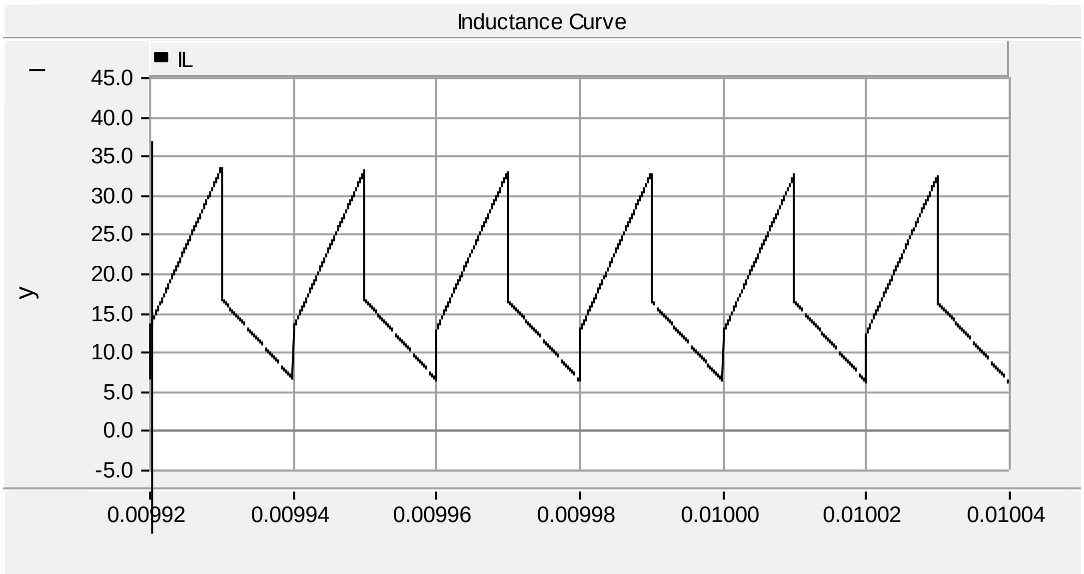


Figure 3.24: Step-up inductance current curve (I_L)

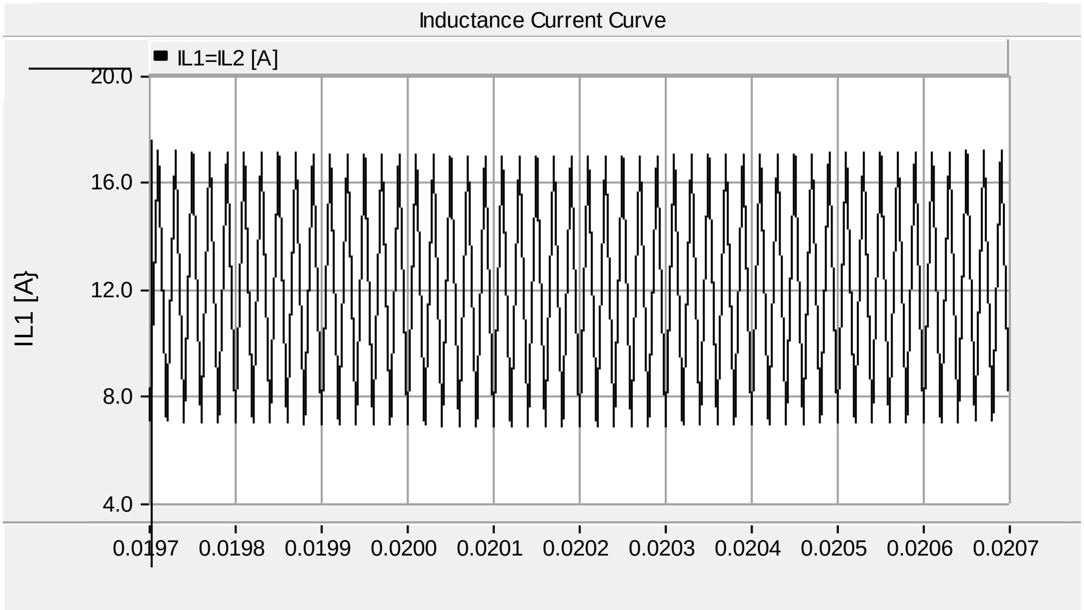


Figure 3.25: Inductance current curve for $IL_1 = IL_2$

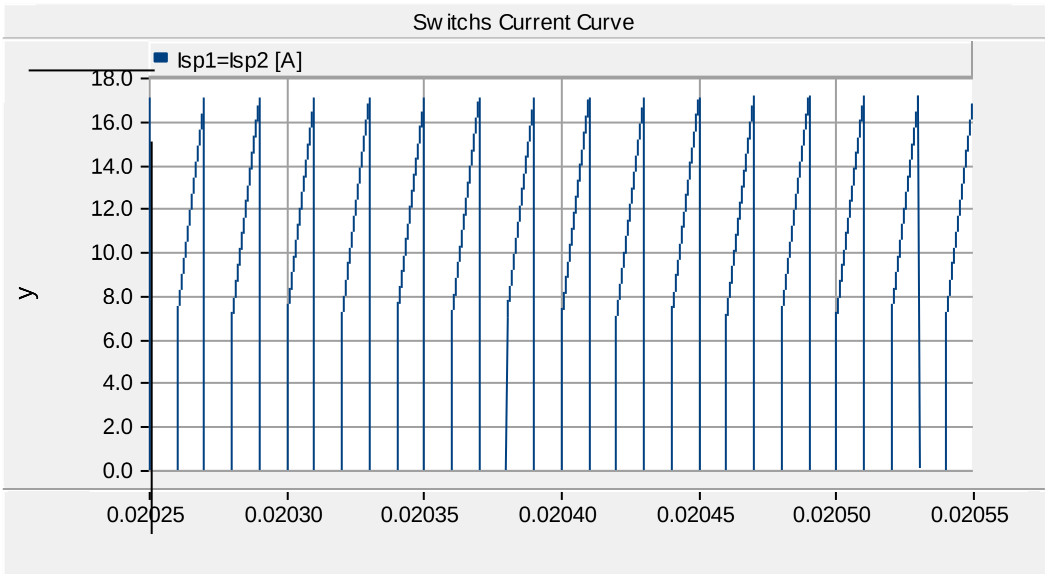


Figure 3.26: Switching current curve for S_1 and S_2

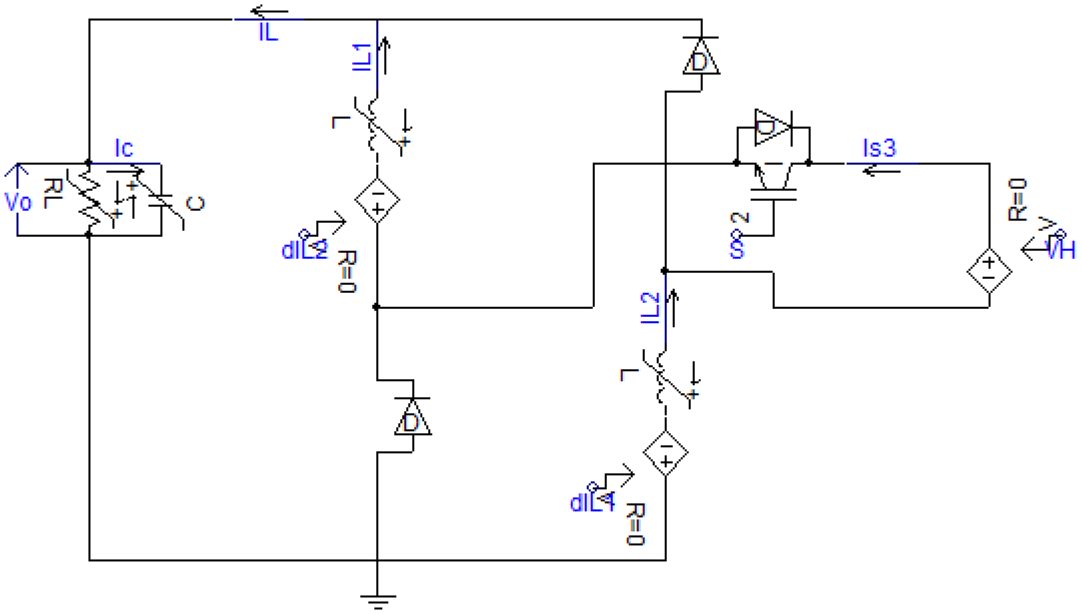


Figure 3.27: PSCAD Designed Circuit Diagram for Step-Down Mode

3.4.3 Step-down dc-dc bdc simulation results

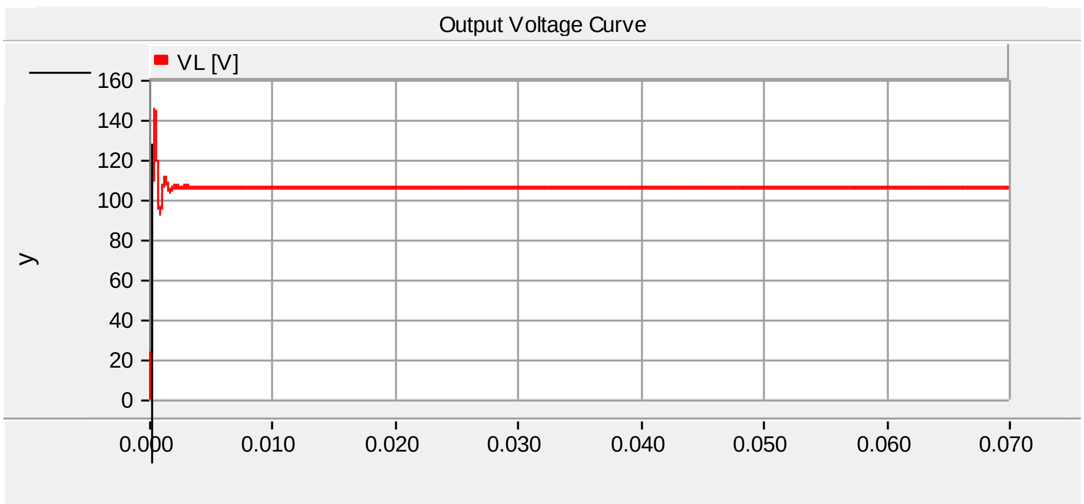


Figure 3.28: Output voltage curve (V_L)

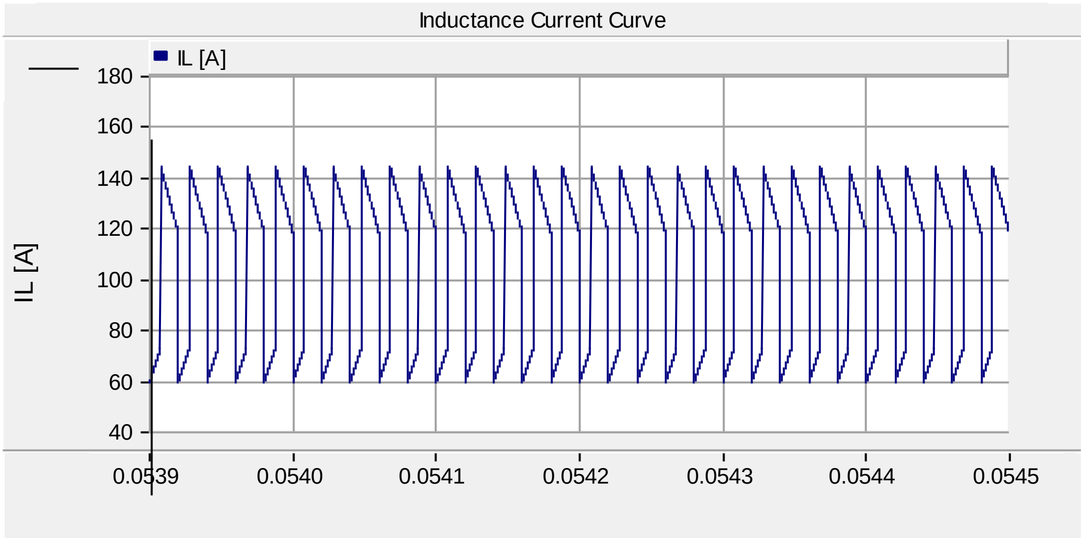


Figure 3.29: Step-down inductance current curve (I_L)

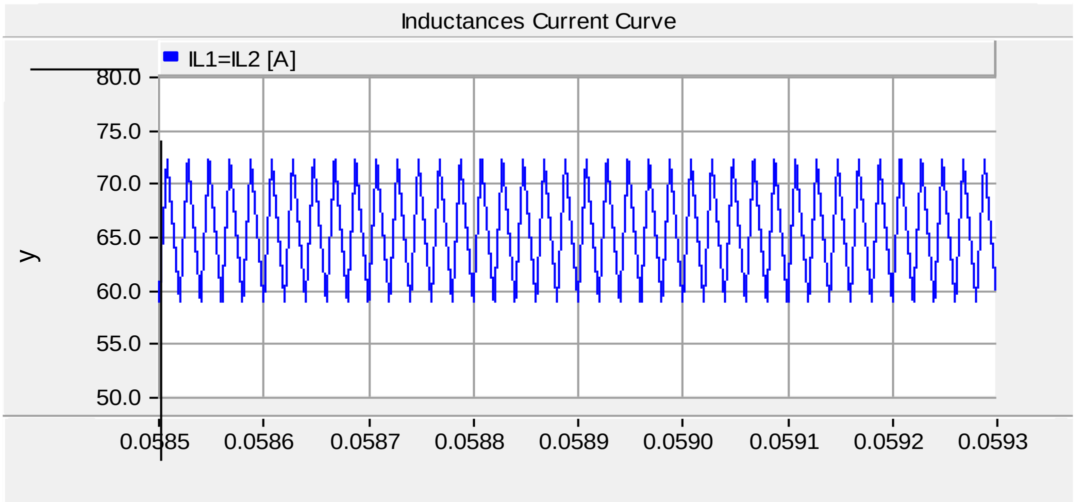


Figure 3.30: Inductance current curve $IL_1 = IL_2$ for step-down

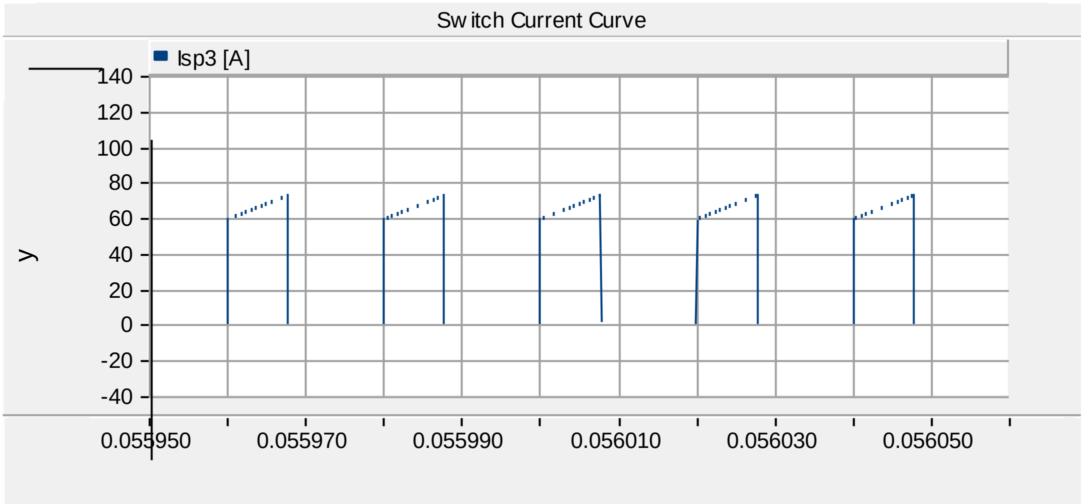


Figure 3.31: Step-down switching current curve for S_1 and S_2

3.5: Simulation Results Conclusion For Both Step-up and Step- down Converter

From the simulation above we noticed a higher voltage value at the Output voltage curve (V_H) for the step up mode which started at its initial point zero but when the switches where turned on as configured in the step-up mode we notice a transient state and the voltge rose to 565V at 0.001sec and dropped to 300Vand became stable at 0.016sec in its steady state.The Step-up inductance current curve (I_L) maintaned a 34A at steady state automatically we know that the value for I_{L1} and I_{L2} would be 17A each but from the simulation graph we can also see that the value we got was also 17A as seen in Figure 3.25 and also the switching current for switches S_1 andS_2 was gotten to be 17A as seen in Figure 3.26.

In the step down converter the output voltage curve (V_L) started at its initial point zero but when the switches were turned on the voltage rose from 20v to 146v then we noticed a transient state for some few mili seconds then the voltage became stable at 106v in its steady state.The Step-down inductance current curve (I_L) maintaned a 144A at steady state automatically we know that the value for I_{L1} and I_{L2} would be 72A each but from the simulation graph we can also see that the value we got was also 72A as seen in Figure 3.30 and also the average switching current for switches S_1 andS_2 was gotten to be 72A as seen in Figure 3.31. From both converters we noticed a higher step-up voltage gain for both s-u and s-d modes and also lower average switching current for the two modes.

CHAPTER 4

CONCLUSION AND RECOMMENDATION

4.1: Conclusion

So from our results we can see that the dc-dc bdc s-u and s-d circuit is an intresting type of converter not just because it gives us a higher efficiency than the previous conventional converters but it's whole topology is very understandable. In the thesis work we used the pscad/emtdc software to generate our results. From the simulation above we noticed a higher voltage value at the Output voltage curve (V_H) for the step up mode which started at its initial point zero but when the switches where turned on as configured in the step-up mode we notice a transient state and the voltge rose to 565V at 0.001sec and dropped to 300Vand became stable at 0.016sec in its steady state.The Step-up inductance current curve (I_L) maintaned a 34A at steady state automatically we know that the value for I_{L1} and I_{L2} would be 17A each but from the simulation graph we can also see that the value we got was also 17A as seen in Figure 3.25 and also the switching current for switches S_1 andS_2 was gotten to be 17A as seen in Figure 3.26. In the step down converter the output voltage curve (V_L) started at its initial point zero but when the switches were turned on the voltage rose from 20v to 146v then we noticed a transient state for some few mili seconds then the voltage became stable at 106v in its steady state.The Step-down inductance current curve (I_L) maintaned a 144A at steady state automatically we know that the value for I_{L1} and I_{L2} would be 72A each but from the simulation graph we can also see that the value we got was also 72A as seen in Figure 3.30 and also the average switching current for switches S_1 andS_2 was gotten to be 72A as seen in Figure 3.31. From both converters we noticed a higher step-up voltage gain for both s-u and s-d modes.We where able to see that the proposed converter gave us a lower average value of the switching current and a higher voltage gain than the conventional converter. Also the waveforms we got attest to the steady state analysis and operating principle. At full load condition the presented direct current to direct current bdc gives us a higher efficiency for both the step-up and step-down mode which are higher than the traditional converter.

4.2: Recommendation

The mode of operation of this thesis is covered on the steady state analysis of the dc-dc bi-directional s-u and s-d mode. This circuits were designed in a way that we had to use the same value for our inductors L_1 =$L_2 = L$ which made our inductor current $i_{L1} = i_{L2} = i_L$ to be the same and also the same value for the 3 switches at steady state condition. A future research work for this converter is to use a more efficient mosfet or igbt switch and also have different inductor values for the number of inductors which would give us a different inductor current value.Also anlyzing the future work and see what the new results entails and comparing it to this work which was analyzed in this thesis.

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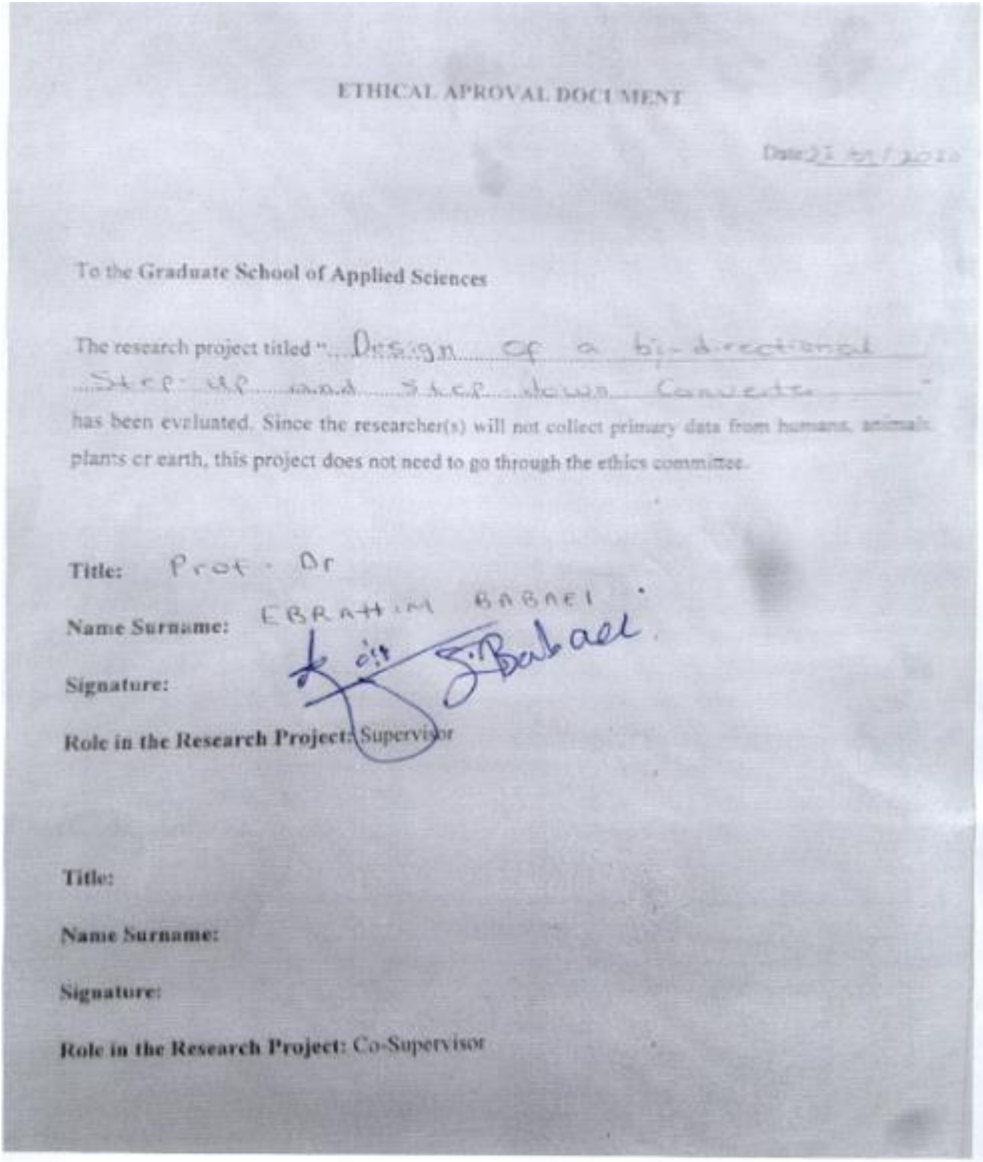
APPENDICES

APPENDIX 1

ETHICAL CONTRACT FORM



ETHICAL APROVAL DOCUMENT

Date: [illegible]

To the Graduate School of Applied Sciences

The research project titled "Design of a bi-directional Step-up and Step-down Converter"

has been evaluated. Since the researcher(s) will not collect primary data from humans, animals, plants or earth, this project does not need to go through the ethics committee.

Title: Prof. Dr

Name Surname: EBRAHIM BABAEI

Signature:

Role in the Research Project: Supervisor

Title:

Name Surname:

Signature:

Role in the Research Project: Co-Supervisor

APPENDIX 2

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