GORKEM SAY

Z-SOURCE DC TO DC CONVERTER

NEU 2017

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

By
GÖRKEM SAY

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

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Approval of Director of Graduate School of Applied Sciences

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I declare that there isn’t any replacement from other published works. This thesis contains my original studies. I also declare that all outcomes, and all obtained graphics have been reached by myself. Different studies have been used for illuminate the way of the understanding logic.

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Signature:

Date:

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ABSTRACT

The world has become critical point in terms of energy. The oil, coal or gasoline age will be over soon. Because, mankind has figured out the energy demand increases day by day. If all the demand is tried to supply from oil, coal or gasoline, the atmospheric pollution reaches critical point or limited mines over in 100 years. Fortunately, mankind has started to turn towards renewable energy. But the renewable energy sources have caused new problems. Such as photovoltaic arrays, the production of arrays have high cost. Besides, the efficiency of arrays changes between 19%-24%. But solar panels can supply energy over the years. This is unique specifications.

The use of dc to dc converters can intervene in this point. This low efficiency can be increased by using dc to dc converter to obtain high voltages or higher power. Not only for this purpose but the dc to dc converters have wide application area.

To achieve high efficiency, high gain need to be obtained. As a result, the low input can be reached high voltage or high power to supply the demand of application.

Z-source dc to dc converter is a converter that can boost the input voltage to higher voltages by using unique structure to achieve high efficiency and high gain. This unique structure exceeds the limitations and boundaries of classical converters.

This thesis explains Z-source dc to dc converter. Besides, circuit structure has been analyzed and designed. Also, high gain converter has been analyzed. Calculation of components have been achieved. Besides, simulation of Z-source dc to dc converter has been achieved in MATLAB Simulink.

Keywords: Photovoltaic (PV); Renewable energy; DC to DC converter; Z-source; MATBLAB Simulink

ÖZET

Dünya, enerji açısından cok kritik bir noktaya geldi. Petrol, kömür, ve benzin gibi yakıtların çağı yakında sona erecek. Çünkü insanlık, enerji ihtiyacının günden güne arttığnın farkına vardı. Eğer bütün talep petrol veya kömürden karşılanmaya çalışılırsa, atmosferik kirlilik kritik düzeye ulaşacak veya sınırlı olan madenler yüzyıl içinde bitecek. Neyse ki, insanlık yenilenebilir enerjiye doğru yönelmeye başladı. Fakat, yenilenebilir enerji, solar panellerin üretiminin yüksek maliyeti veya solar panellerin büyüklüğü gibi yeni problemlere neden olmaya başladı. Bunun yanında, panellerin verimi yüzde 19 ve 24 gibi düşük verimler arasında değişmekte. Fakat, solar paneller yıllarca enerji sağlayabilir. Bu eşsiz bir özellik.

DC DC ceviriciler tamda bu noktada müdahalede bulunuyor. Bu düşük verim dc dc ceviricileri kullanarak yüksek gerilimlere ve yüksek güçlere artırılmasını sağlamakta. Sadece bu amaç için değil fakat dc dc ceviricilerin cok geniş uygulama alanları mevcut.

Yüksek verimi gerçekleştirebilmek için, aynı zamanda yüksek kazanc elde edilmesi gerek. Sonuç olarak düşük gerilime sahip kaynak, uygulamanın talebine göre yüksek gerilime ve yüksek güce ulaşabilir.

Z kaynaklı (empedans kaynaklı) cevirici, yüksek kazanç ve yüksek verim gerçekleştirken eşsiz yapısını kullanarak, daha yüksek gerilimler elde edebilir. Bu eşsiz yapı klasik ceviricilerin limitasyon ve sınırlarnı aşar.

Bu tez Z kaynak dc dc ceviriciyi açıklamaktadır. Bunun yanında, devre yapısı analiz edilmiş ve dizayn edilmiştir. Ayrıca yüksek kazanç cevrim analiz edilmiştir. Kullanılan elemanların hesaplamaları yapılmıştır. Bununla birlikte, Z kaynaklı dc dc çeviricinin simulasyonları MATLAB Simulink’te yapılmıştır.

Anahtar kelimeler: yenilenebilir enerji; dc dc cevirici; Z kaynaklı dc dc cevirici; yüksek kazanç; MATLAB Simulink

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LIST OF ABBREVIATIONS

D:	Duty cycle
f:	Switching frequency
T:	Period of switch
Vin, Vs:	Input voltage
Vo:	Output voltage
Vc:	Capacitor voltage of z-source network
V_L:	Inductor voltage of z-source network
C:	Capacitor value of z-source network
L:	Inductor value of z-source network
I_L:	Inductor current of z-source network
Ic:	Capacitor current of z-source network
Co:	Output capacitor
Lo:	Output inductor
V_{Lo}:	Voltage of output inductor
V_{Co}:	Voltage of output capacitor
I_{Lo}:	Current of output inductor
Ico:	Current of output capacitor
Δi_{LO}:	Current ripple of output inductor
Δi_{CO}:	Ccurrent ripple of output capacitor
AC:	Alternating Current
DC:	Direct Current
CCM:	Continuous Conduction Mode
MPPT:	Maximum Power Point Tracker

CHAPTER 1
INTRODUCTION

In the developing world, the efficiency, stability and cost have came to an important point, especially in technology section. Because of the limited energy sources, people have headed to invent new sources or improve the exist sources. But the invented methods have caused new problems. Researchers have been focused on to improve, develop and solve efficiency problems for many years. To reach the best efficiency and high gain, different methods have been achieved.

1.1 Subject: What is the Subject of the Thesis?

Sun is the limitless sources that people can profit by it. But the solar panel process has taken some money. To obtain electricity, this method is very expensive and the efficiency is very low such as 19 % - 24 %. But by using some devices that has called MPPT (maximum power point tracking), the efficiency and the gain can be increased in voltage level. Maximum power point tracker is the booster that boost the output of photovoltaic array under the control strategies. Mppt can increase the solar panel dc voltage using dc to dc converter topologies. Using this way, lower voltage value can be increased to desired voltage level and can be converted to AC (Seyedmahmoudian et al., 2016).

In terms of structures of the ordinary or common dc to dc topologies have boundaries to handle perfect efficiency and high gain in renewable energy sources or other any systems. Fang Zheng Peng was offering a novel unique topology that has an original empedance link to combine the source and main circuit. This was a z source dc to dc converter. First z-source topology has presented by him in 2003 and some papers have been published by researchers since 2003. Z-source converter has explained in (Peng, 2003).

This thesis will explain the z-source dc to dc converter topology that has a unique efficiency, minimal cost and perfect stability. With unique structure, inrush currents and harmonic distortion have been taken down to minimal value. Also, 300 Watt system will be designed and simulated in following sections. Also filter inductor design will be explained in following sections. Not only in mppt but the z-source topology can be used in all converter applications (ac-ac, dc-ac, ac-dc, dc-dc). Z-source dc to dc topology shown in Figure 1.1.

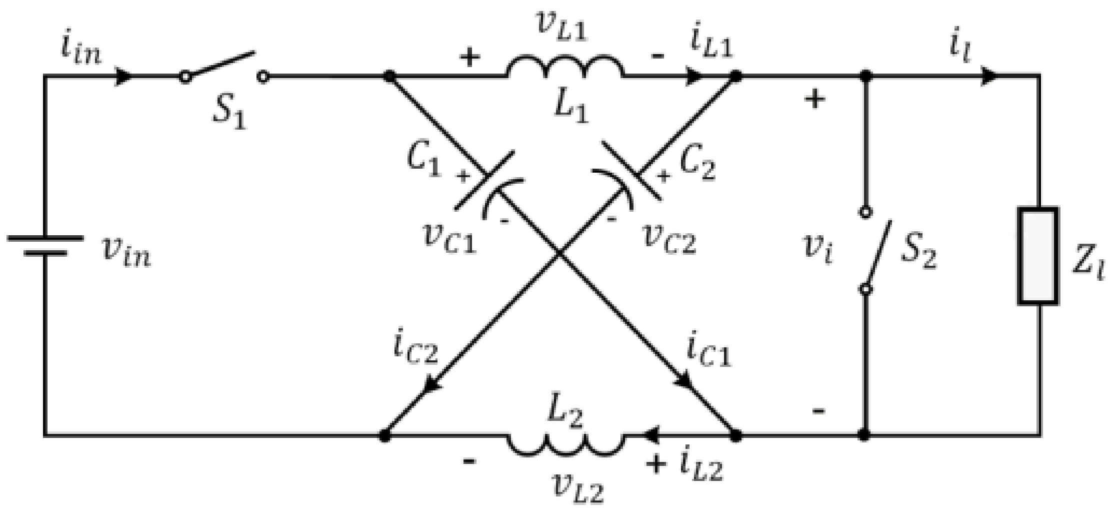

Figure 1.1: Z-source dc to dc converter circuit

It has z shaped two inductors and two capacitors that couple the system to the load and source. The value of capacitors and the value of inductances are equal. Pulse with modulation (PWM) technique will be used to switch the switches. The output voltage can be set to any higher value depend to the duty cycle of the switch. Also depend to the duty cycle, output can be adapted to buck or boost. This feature makes the z-source topology takes one step ahead of traditional topologies (Peng, 2003).

Every chosen parameter is very important for the efficiency, stability and cost. Therefore, the system design and calculations must be done very carefully and simulation tests are necessary. The detailed explanations will be presented following chapters. Every step will be described one by one and also simulation test will be explained using MATLAB Simulink. Moreover, advantages will be explained following chapters. All operations have been operated and explained with CCM (continuous conduction mode).

1.2 Objective

To design high gain dc to dc converters, efficiency should be conserved and kept high. Traditional and classical dc to dc converters cannot achieve this conserved because of their limitations. New topologies have been introduced many times to exceed these limitations.

- Z-source is the one of the topologies with high gain and high efficiency. Therefore, the one of the main objective of thesis is the proof of high gain. Thesis will be supported with examples, calculations and simulations to understanding of z-source.

- Second objective of the thesis is the comparion of the z-source dc to dc converter with other topologies. With explanations, waveforms graphics, comparisons will be clearly understandable.

- Exceeding of classical dc-dc converter limitations.

- Also, illumination of the way to design and understand the z-source for users and learners is the other objective of the thesis. Thus, people who read this thesis will be able to learn and design z-source dc to dc converter.

- Calculations will be achieved to chose of component.

1.3 Importance: Why is it Important?

Z-source has key advantages to become important topology. Cost, efficiency and size are the most demanded parameters by users.

In terms of cost, z-source topology has used minimal component for operation. Also component numbers affect the size of circuit. Minimal component means that the size of circuit will be smaller. In terms of structure of z source converter has taken important role of power electronic world. Because of structure z source has offered high gain, wide range capability and high efficiency. The boundaries of classical dc-dc boost circuit is the barrier to reach high gain and desired efficiency. z-source is the circuit that has a structure to reach the objective. Also with the unique structure, z-source can achieve the buck and boost operations. This specification take the z source one step ahead from other topologies. It can be achievable wide range applications.

Capability of circuit will be shown in following chapters.

1.4 Literature Review

In literature, there are some papers have been published about z-source converter (or inverter). But the most of them are about z-source inverter. First z-source idea has been explained by Fang Zheng Peng. In Fang Zheng paper, new topology was about the traditional converters boundaries could be exceed with unique impedance network of the z-source. It could be used boost and buck operation with same circuit and it could be applied all dc to ac, ac to dc, ac to ac and dc to dc conversions. This thesis's main starting point is this paper. This thesis inspires same topology and same principle but different power conversion (Peng, 2003).

The other reference was dynamic modeling and analysis of z-source converter. It was about AC signal model and design. The simulation result and experimental results were illuminating. Choice of capacitors and inductors have been evaluated and some considerations have been published (Liu, Hu, & Xu, 2007).

Shen has helped understanding of z-source operation modes and characteristics of the z-source inverter (Shen & Peng, 2008).

Other inspired paper was Fang Zheng Peng. Same topology has been used in this thesis. Similar operating principle has been used. It has helped to understanding of dc to dc conversion of z-source (Fang, 2008).

Sarode has helped to understand mathematical operations during operation of modes (Sarode & Kadwane).

Galigekere has evaluated the continuous conduction mode of PWM z-source converter. Besides, mathematical approaches has illuminated the current and voltages on components. Besides, waveforms were critical point (Galigekere & Kazimierczuk, 2012).

Comparison between other topologies and z-source topology have been evaluated. Shen has compared the z-source inverter with traditional inverter. The importance of z-source has emphasized. Switching device power, passive components, CPSR and efficiency comparisons have been achieved. The z source have passed all tests and comparisons in several papers were about z-source topology surveys and comparison with other topologies

(Shen, Joseph, Wang, Peng, & Adams, 2007), (Sreeprathab & Joseph, 2014), (Husev, et al., 2016), (Mahale & Patil, 2016).

Not only z-source but the other topologies surveys and comparisons have been evaluated In Forouhzesh and Tofoli papers, nonisolated high voltage, high gain topologies have been presented (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017), (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016), (Tofoli, de Castro pereira, de Paula, & Junior, 2015).

1.5 Explanation: What have been Done in Each Chapter

To achieve best performance and intelligibility of thesis, all chapters have been categorizied simply. Chapters can response all question just by reading. This is very important for intelligibility of thesis. As a result, audiences can design z-source dc to dc converter by reading all thesis.

In chapter 2, high gain converters have been described. In 2.1, the importance of the high gain has been explained. Some examples have been given about it. Next topic was topologies that provide high gain. In 2.3, description of high gain topologies have been explained and have been given some details about these topologies. Other topic was comparison about these topologies. Last part of this chapter was advantage of the z-source converter. What doesmakes z-source one step ahead from other topologies? It has been answered this question by explaining advantages of z-source dc to dc converter.

In chapter 3, z-source dc to dc converter has been elaborated. Detailed explanation of z-source has been given. In subsection 3.1 of chapter 3, detailed description of converter and operation have been given to understand it. In 3.2, description of application has been presented. Next section was about design of converter. In this section, 300 W system has been designed. The converter has designed to convert 12 V to 240 V. In 3.4, inductor design has been explained to bring ability of design coupled inductor and filter inductor to audiences.

In chapter 4, simulation results has been shared. 300 W converter has been simulated. Then, their results have been shared. Besides, efficiency calculation has been achieved and comments have been shared.

Last chapter was about conclusion. Outcome of thesis has been shared.

CHAPTER 2
HIGH-GAIN DC-DC CONVERTERS

High gain dc to dc converters will be described in this chapter. Importance of the high gain, topologies or techniques that provide high gain, descriptions of each topology and techniques and advantage of the z-source converter have been included.

2.1 Why is it Important to Have High Gain?

Such as motor drivers, renewable energy applications, robotic applications, military applications, space applications or other special applications have needed to consume high voltage or high power from limited energy sources. Therefore, Wide power range is important and necessary for some areas.

Batteries, photovoltaic arrays and wind turbines are the some of the limited sources or low voltage suppliers. They all need to booster circuit that has high gain to obtain higher voltages. Especially nowadays, electrical vehicles need high power such as tesla's 2017 P100D version has a 451 kw motor power or sun powered homes, UPSs, different robotic projects need to consume demanded power. Also in space applications, the power is always limited because of the size of spacecraft. The size has cost millions of dollars.

To obtain high voltage range from limited sources, high gain must be provided (Tofoli, de Castro pereira, de Paula, & Junior, 2015). A lot of reasons effects the high gain such as efficiency, losses, right topology, right control strategy, right material, right component. One of the key point is the achievement of high efficiency with right topology. Because, if losses is reduced, high efficiency will be provided. Thus, one more step will be taken to reach the high gain. Ofcourse, the correct topology has to be chosen and besides the cost should be keep low.

Structure of z-source has offered to high gain. Voltage gain-duty cycle waveform shown in Figure 2.1.

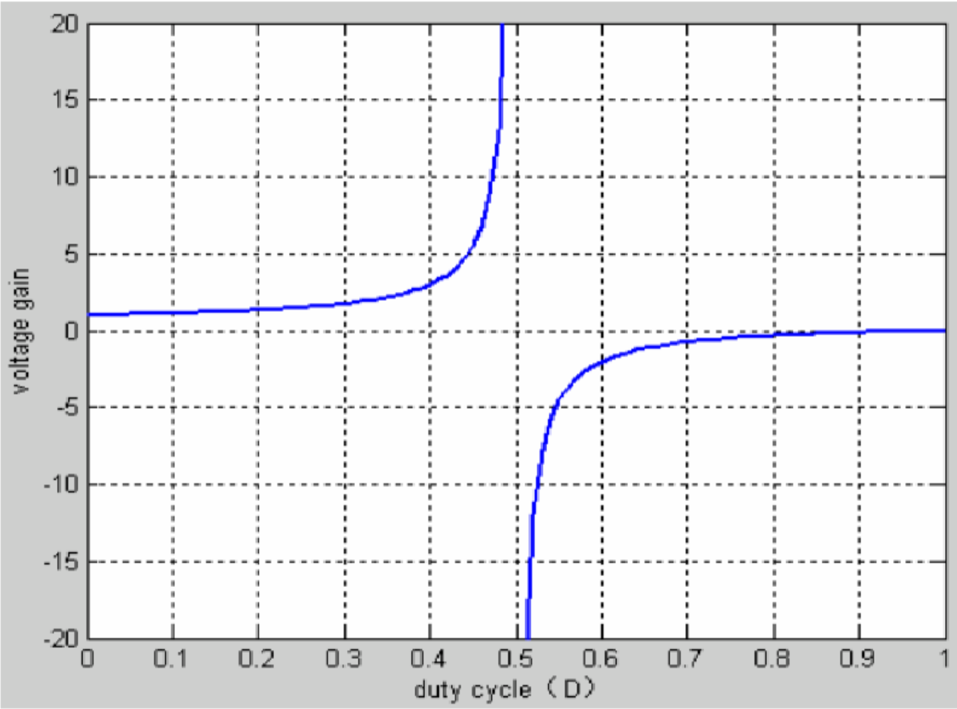

Figure 2.1: Duty cycle waveform of z-source dc to dc converter

Figure shows that when duty cycle approach to 0.5 from 0, voltage gain increase dramatically. Between 0 and 0.5, the topology is in positive region and it means that it is in boost mode. On the other hand, when the duty cycle approach to 0.5 from 1, voltage gain is in negative region. It means that the converter is in buck mode (Fang, 2008). This feature brings that the desired voltage can be any value between 0 and infinity. Detailed explanations of waveform and provements will be included in following chapters.

2.2 Which Topologies can Provide High Gain?

Nowadays, dc-dc converters have a wide research area. Topologies are being developed and improved day by day by researchers. According to demand of application, topologies varies. Some of applications demand high voltage or high gain. To apply correct strategy, categorization should be achieved. High gain topologies can be analyzed in groups. Categorization of topologies shown in Figure 2.2.

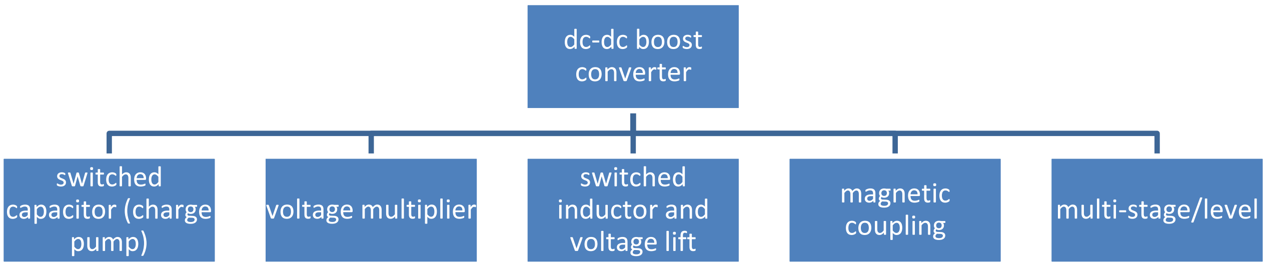

Figure 2.2: Dc to Dc boost converter topologies (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017)

- switched capacitor (charge pump)
- voltage multiplier
- switched inductor and voltage lift
- magnetic coupling
- multi-stage/level

In survey of step up dc dc converters, authors have grouped the z-source converter under a magnetic coupling in some papers. Subgroups of topologies can be shown in following figures.

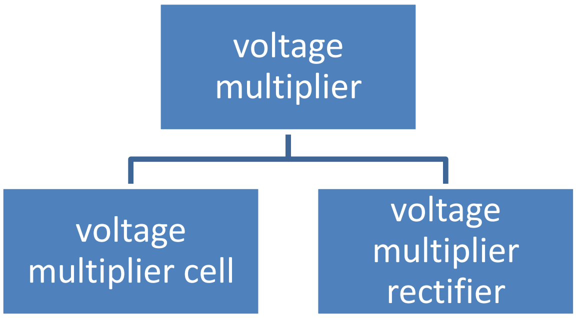

Figure 2.3: Voltage multiplier

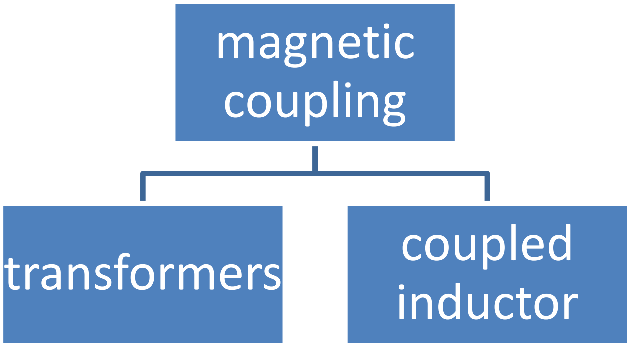

Figure 2.4: Magnetic coupling

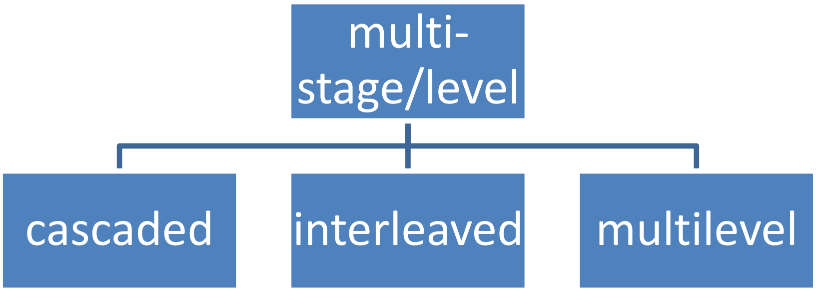

Figure 2.5: Multi-stage/level

Before the high gain converter introduces, the conventional dc to dc step up converter will be explained.

2.2.1 Conventional dc to dc step up converter

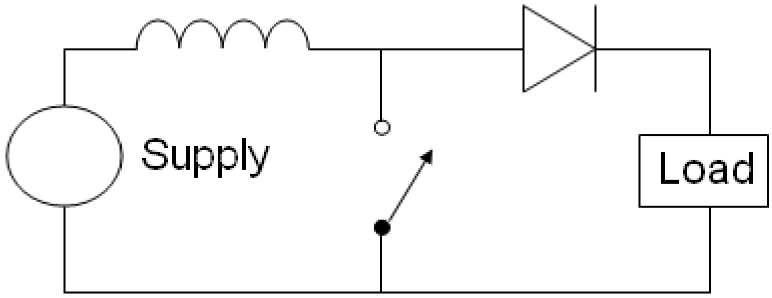

Figure 2.6: Convetional dc to dc step up converter circuit

The dc to dc boost converter is the converter that converts lower voltage to upper voltage levels. In boost converter, the input voltage always lower than the output. The boost converter consists from inductor, switch element (transistor, mosfet, igbt), diode, capacitor and filter elements (depend to design). Capacitor filter or capacitor-inductor filter have added to circuit for eliminates or reduce the voltage ripple or noises. The step up traditional converter is the most used converter. Also, the easiest topology to operate it.

The main working principle is the switching the switch.

1- When the switch is OFF, the inductor starts to store energy because of the current behavior.
2- When the switch is ON, while empedance increase, the current will be decreased. The magnetic field will be demolished. Thus, the current will be maintained towards to the load.

When the switch is operated enough frequency, the inductor will not reduce to zero and the voltage of load will higher than input voltage. The pulse has used to switch the switch element. ON and OFF states can be shown in Figure 2.7 and Figure 2.8 (de Paula, de Castro Pereira, de Paula, & Tofoli, 2014), (Tofoli, de Castro pereira, de Paula, & Junior, 2015).

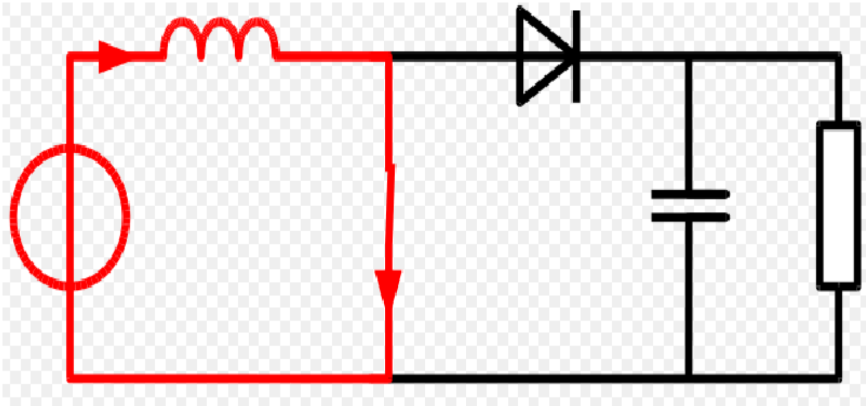

Figure 2.7: Conventional step up converter switch ON state

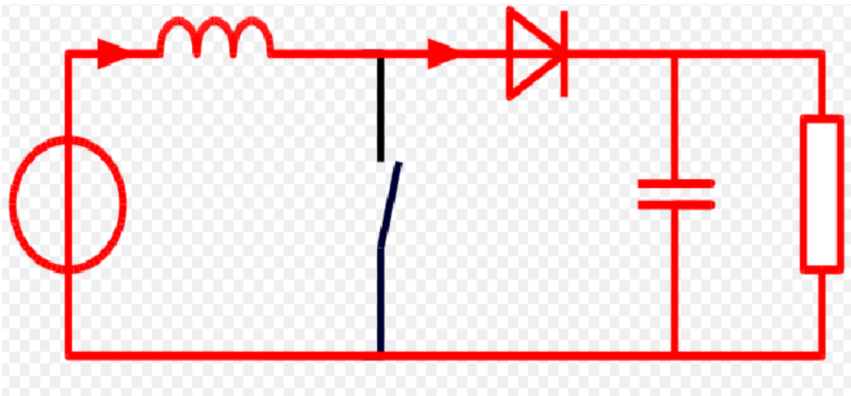

Figure 2.8: Conventional step up converter switch OFF state

Advantages;

- Simple to operate.
- Simple to understand.
- Low cost.

Disadvantages;

- Non isolated.
- Low efficiency.
- Not for high voltage conversion.
- Noises.
- Ripples (Tofoli, de Castro pereira, de Paula, & Junior, 2015).

2.2.2 Switched Capacitor

Switched capacitor in other words, charge pump technique is popular between boost converters. Because, switched capacitor structure has an ability of integration and modularity. The charge pump converter transfers capacitive energy only. it is not boost the voltage via magnetic energy transfer. In literature, there are several switched capacitor topologies. One of the topologies is basic charge pump (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017). CP is shown in Figure 2.9a.

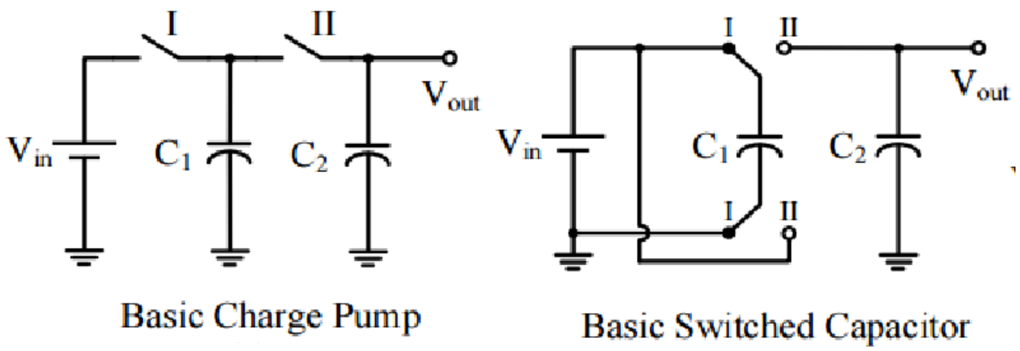

Figure 2.9: Charge pump circuits (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017)

The working princible of the basic charge pump is switching the switches. When switch 1 is turned ON, the energy is charged to capacitor 1. When the switch 2 is turned ON, energy of first capacitor is transferred to second capacitor. Thus, the energy has been pumped by first capacitor to second capacitor.

Second switched capacitor is two-phase switched capacitor voltage double (TPVD). TPVD can be shown in Figure 2.9. For higher gains, Capacitor 1 is connected series to the source and this connection can double the output voltage (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017).

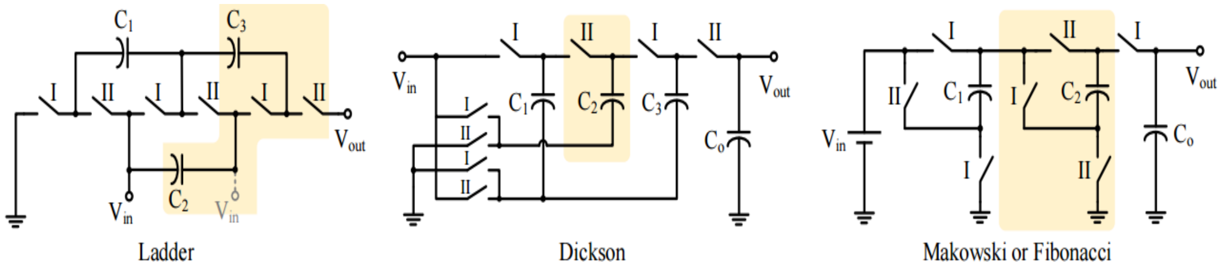

Figure 2.10: Improved switched capacitor examples (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016)

The ladder switched capacitor can be shown in Figure 2.10. It consists of two ladder capacitors. Different gains can be obtained by changing nodes. On the other hand, the Dickson doesn't use active switch, it uses diodes. By driving each stage with clock cycle, charge is transferred between stages from input to output (Doutreloigne, 2010).
Another charge pumb circuit is the Makowski switched capacitor. Number of components less than the other topologies. It can be achieved high voltage. Makowski SC also known as a Fibonacci.

Makowski voltage gain depends to Fibonacci number sequence {1, 1, 2, 3, 5…}. It can be increased by setting the sequence. Besides, the voltage gain of Dickson CP changes linearly depend to stages. N*Vin is the output voltage. N is the number of charge pump stages. Besides, the makowski's voltage gain increase exponentially. Hence, Makowski has a high-step up ability. But it has capacitor voltage stress and switch voltage stress depends to wide range (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016).

Switched capacitor circuits have some problems. One of these problems is transient of high current. It effects directly efficiency and power density. The solution is the adding of inductor. By adding the inductor, the circuit gains 2 advantages, efficient regulation and clear off current transient.

The last charge pump circuit is the Multilevel Modular Capacitor clamped converter. This converter can be achieved any demanded voltage gain in terms of structure. Power losses has decreased and higher efficiency than the other charge pump circuits (Tofoli, de Castro pereira, de Paula, & Junior, 2015).

2.2.4 Voltage Multiplier

Voltage multiplier circuits consist of diodes and capacitors. Voltage multipliers are efficient, simple and low cost. It can be obtained high voltage. There are 2 voltage multiplier circuit group.

2.2.4.1Voltage Multiplier Cell

Voltage multiplier circuit is simple to adapt any circuits. VMC circuits can be operated in high gain applications (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017). Some of voltage multiplier circuits can be shown in Figure 2.11.

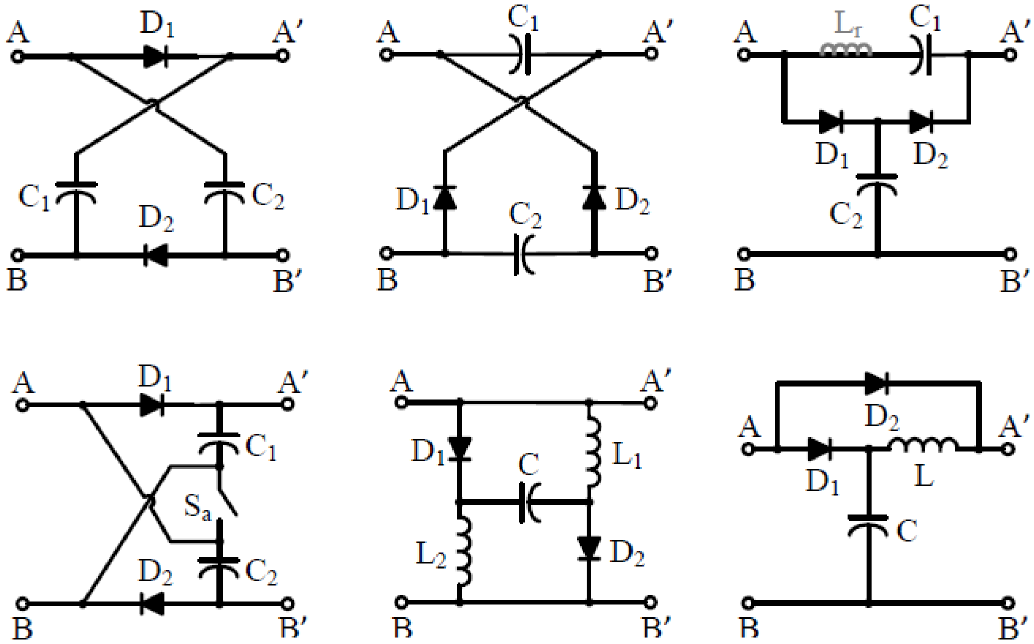

Figure 2.11: Voltage multiplier examples (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016)

Some of the voltage multiplier cell circuits have only capacitors and diodes. Besides, others have inductors to increase gain and switches is needed to drive inductors. The voltage gain of the figured circuits are equal. Hence, the voltage gain is (1+D)/(1-D). To decrease the power loss and increase the efficiency, small inductor can be added where the zero current switching is achieved as shown in Figure 2.11. By adding inductor, circuit becomes more efficient. by compromising inductors and capacitors, voltage gain can be increased. Also by compromising the circuits, high voltage gain can be obtained (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017), (Tofoli, de Castro pereira, de Paula, & Junior, 2015), (de Paula, de Castro Pereira, de Paula, & Tofoli, 2014).

2.2.5 Switched inductor and voltage lift

Next topology is the switched inductor and voltage lift that is widely popular in dc-dc converters. In this method, capacitor is charged to one level. Then the output voltage increased by the capacitor that charged before. This process is achieved over and over with including of extra capacitor to increase the voltage level much more. Some of the converters using this technique such as SEPIC, cuk converters and zeta converters. To achieve higher output gain, multistage (n) can be added (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016), (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017).

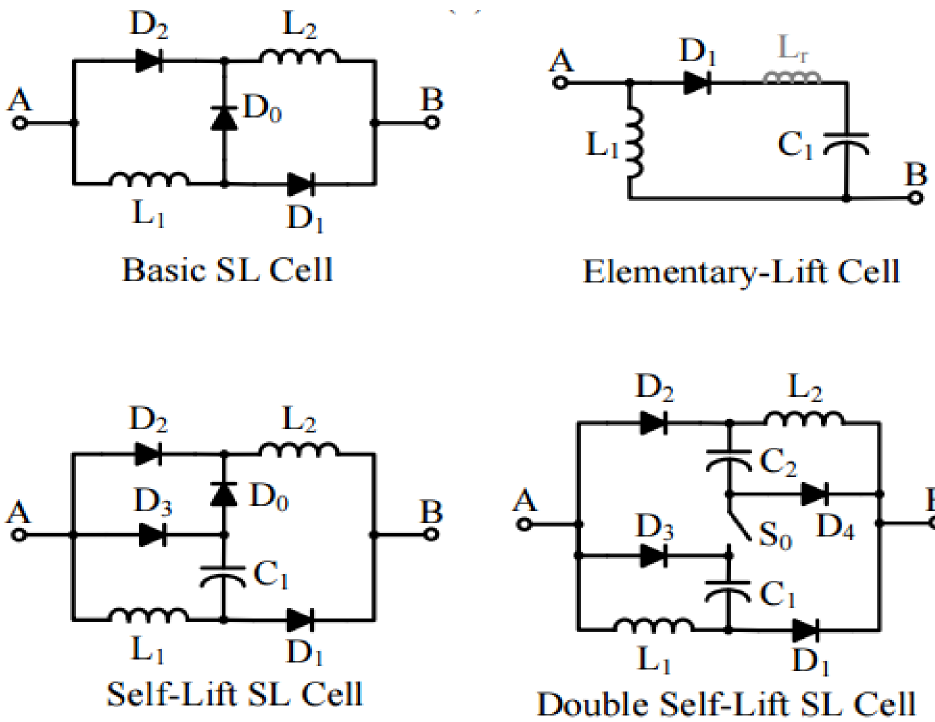

Figure 2.12: Switched inductor types (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016)

Different switched inductor and voltage lift boost topologies can be seen in Figure 2.12. Elementary-Lift Cell is the basic switched inductor converter. The size of the converter can be decreased, because of the same inductance of inductors, the inductors can be placed in same core. Double Self-Lift SL cell is the compromise of elementary VL cell and SL cell can be shown. This new technique is the so called self lift SL cell. Also, in literature there are more versions such as an active switched inductor, improved active switched inductor, hybrid active switched inductor, quasi active switched inductor. All versions have different advantages and disadvantages. Also, sepic converter will be examined under the switched inductor section (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016), (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017).

2.2.5.1 SEPIC (single-ended primary-inductor converter)

Single-ended primary-inductor converter have abilities to convert input voltage to higher than, lower than and equal to output voltage. The switch has been controlled by square wave pwm signal. It operated buck-boost converter.

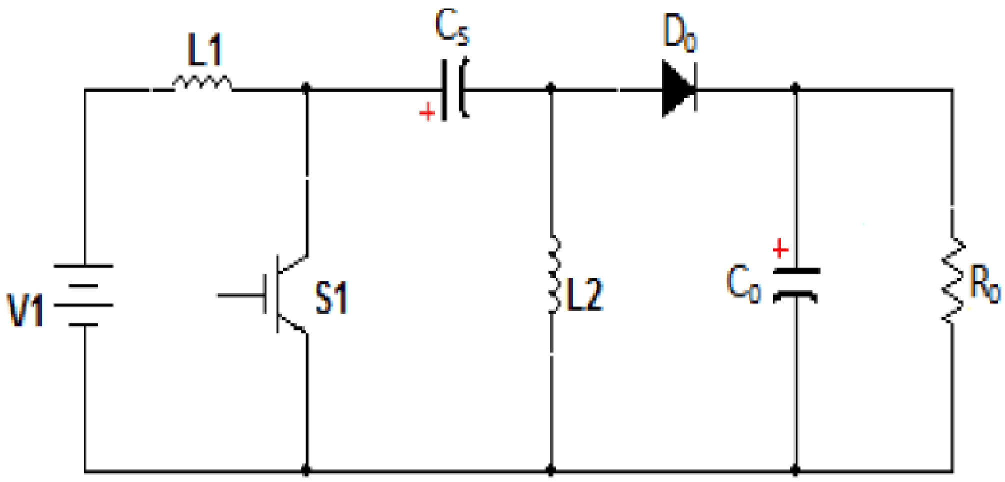

Figure 2.13: Single ended primary inductor circuit

When the switch is ON state, current on L1 inductor will increase and current on L2 will become negative. The switch will be short circuit. The voltage on Cs will nearly equal to the V1 and voltage on L2 will nearly equal to –V1. Thus, magnitude of current on L2 will increase depend to C1 energy supply and L2 will be stored energy (Zhang, 2013), (Erikson, 2001).

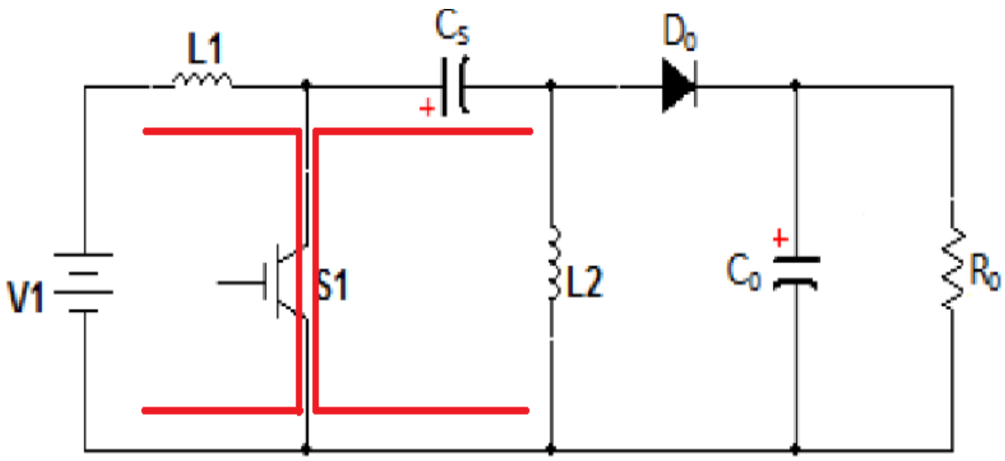

Figure 2.14: SEPIC switch turn ON state

When the switch is OFF state, current on Cs will be equalizied to current on L1, because inductors can not change instantaneous. Finally, L2 and L1 have delivered the power to the load.

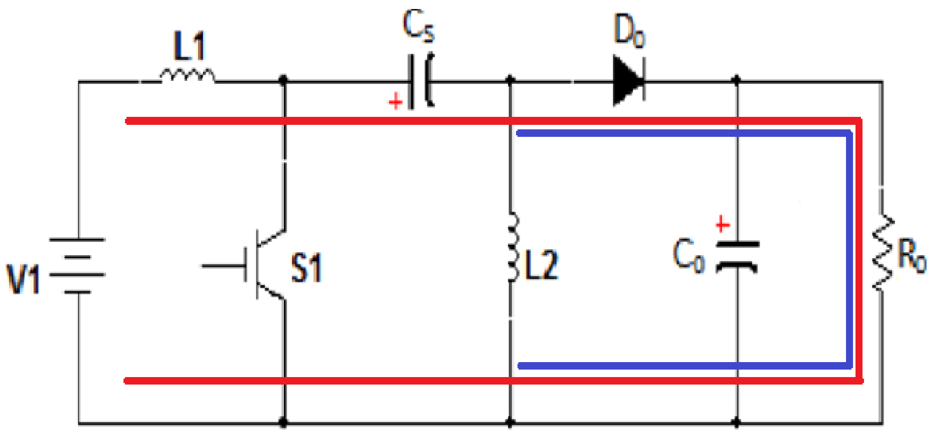

Figure 2.15: SEPIC switch turn OFF state

Fast, ultrafast diodes should be used. Because of voltage spikes of inductors, switching time of diodes should be fast.

Advantages;

- Having non-inverted output.
- True shutdown.

Disadvantages;

- Pulsating output current.
- It transfers energy through Cs, and required current handling ability.
- Difficult to operate (Zhang, 2013), (Erikson, 2001).

2.2.6 Magnetic Coupling

The magnetic coupling topology is the widely used converter technique. Magnetic coupling is included both nonisolated and isolated converters. One of the benefit is the size of circuit can be decreased by using coupled inductor which decreases the number of core. Another benefit is the boost capability. However, the leakage inductance can be occured. Magnetic coupling can be divided in 2 sections (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017).

a- Transformer.
b- Coupled inductor.

2.2.6.1 Transformer

Transformers based converters are very popular in power electronics. It has high gain ability and there are 2 types of transformer isolated and non-isolated.

In isolated transformer technique, there are transformer, diodes, switches. It can meet high gain demand (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016). In Figure 2.16, it can be seen the structure of isolated transformer.

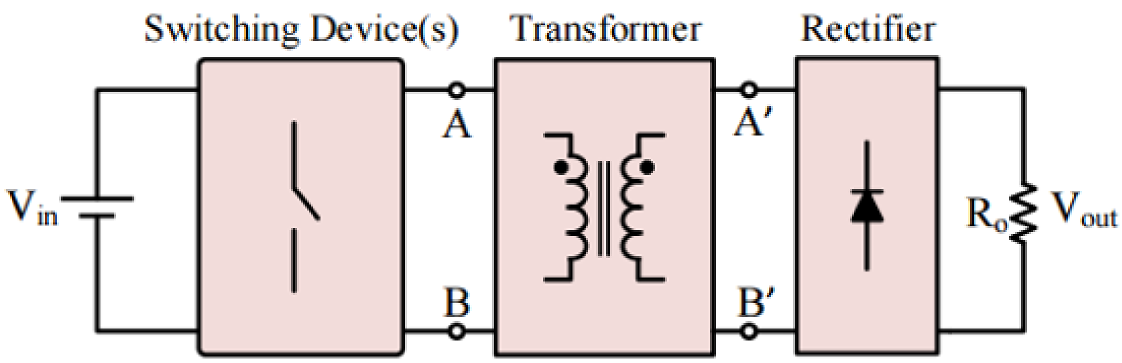

Figure 2.16: Transformer based topologies (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017)

In Figure 2.17, half bridge and full bridge transformers can be shown.

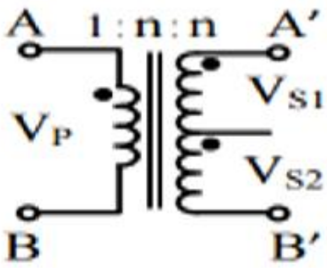

Figure 2.17: Half bridge and Full bridge transformers (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016)

To purpose of increase the gain or boost factor, many researches has been published which include z-source dc to dc converters, dual half bridge, dual active bridge. It is important to consider the take account magnetizing inductance and leakage inductance. Switching losses can be occurred because of leakage inductance. but it can be suit for soft switching.

Other kind of transformer is the built-in transformer. The difference between isolated and built in transformer is that the built-in transformer uses direct energy transfer to derive non isolated transformer. it has shown difference in Figure 2.18 (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017)

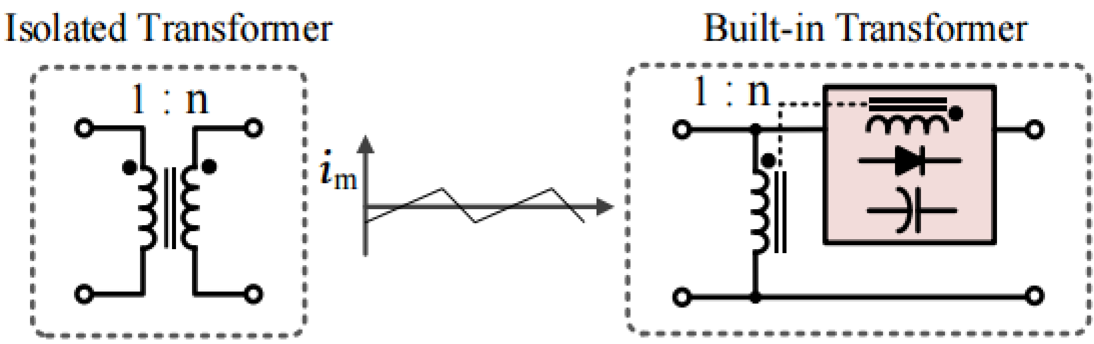

Figure 2.18: Isolated and non ısolated transformers (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017)

Input directly supply one part of energy and rest of it transfer energy using voltage multiplier to increase gain and efficiency. In Figure 2.18, it has shown several built-in transformers. In primary side, there are switching links. In secondary side, there are charge pump switched capacitors. To obtain high gain and decrease the transformers turn ratio, voltage multipliers have added (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016).

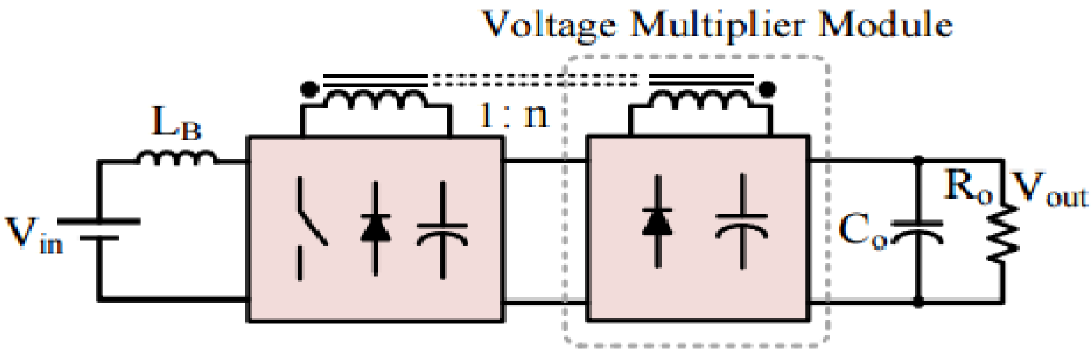

Figure 2.19: Combine of transformers and voltage multipliers (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017)

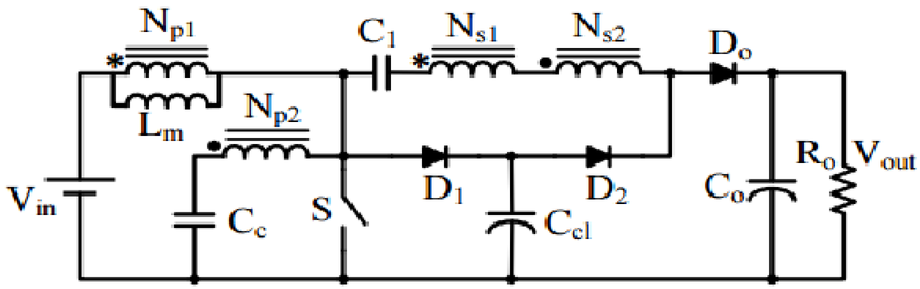

Figure 2.20: Combine of transformers and coupled inductors (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017)

To increase gain factor, efficiency and performance, there are two control variant which include coupled inductor and transformer turn ratio. It has shown in Figure 2.20.

2.2.6.2 Z-source dc-dc converter

Z-source dc to dc converter can be reviewable under both transformers and coupled inductor topologies. Z-source uses empedance network to obtain high gain boost ability. Inrush currents and harmonics have been taken down to minimal value via unique structure. Also z-source circuit is a simple, cheaper and modular. This spec effects size of the circuit (Peng, 2003).

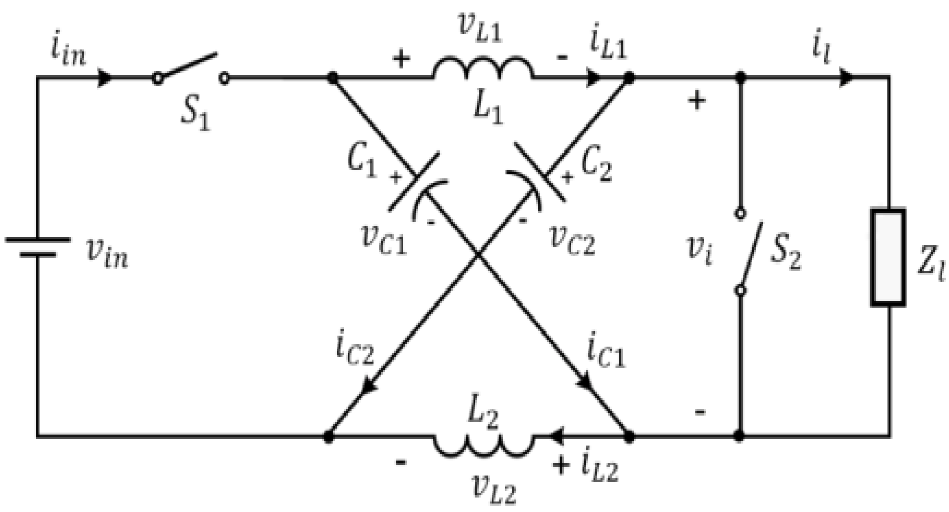

Figure 2.21: General z-source dc to dc converter circuit

S1 is in conduction and S2 is turned off state. Supply voltage (Vs), (cells or battery) supply energy to the z-source capacitors. Simultaneously, z-source inductors transfer their energy to the load.

S1 is in nonconduction mode and S2 is ON. Inductor starts to store energy for release it towards to the load (Fang, 2008).

2.2.7 Coupled inductor

Coupled inductors remind the transformers in terms of structures. It has a high gain capability. It can be used to obstruct falling of diode current. This ability can be achieved by using leakage inductance. Also coupled inductors can be used to decrease the current ripple for high gain applications (Tofoli, de Castro pereira, de Paula, & Junior, 2015). Also, z-source converter has been examined under coupled inductor.

In Figure 2.22, the winding turn ratio can be adjustable to achieve high gain. But the EMI noise can be occurred and efficiency can be decreased because of voltage stress. Voltage stress can be arised from leakage inductance.

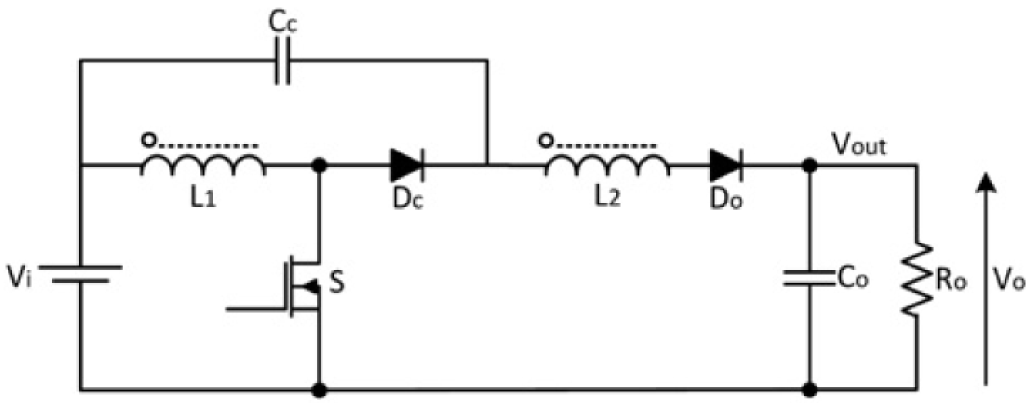

Figure 2.22: Coupled inductor topology (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017)

These problems can be resolved by Figure 2.23. to decrease voltage stress, clamp capacitor has used. This solution is low cost reliable and basic. Another problem is the max Do diode voltage is very high. As a result, expensive semiconductors should be used.

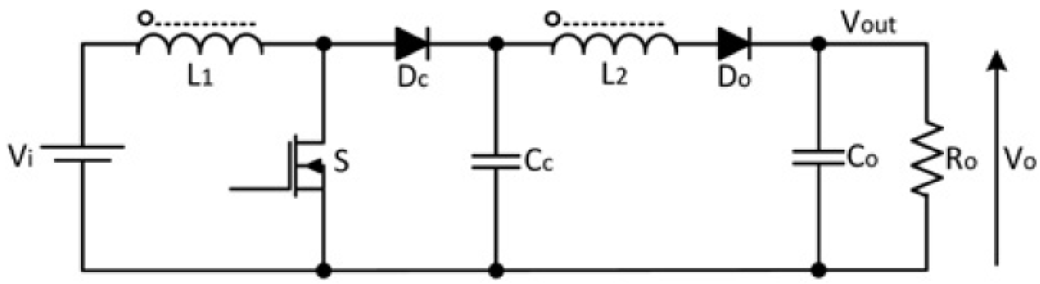

Figure 2.23: Improved coupled inductor

Another coupled inductor based converter is the flyback converters. flyback converters can suply high gain. But the because of leakage inductance is efficiency is reduced (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017).

2.2.7.1 Flyback Converter

The flyback converter is the converter that using transformer instead of inductor. The isolation has been provided by transformer between input and output. The output can be reached to high voltage using transformer.

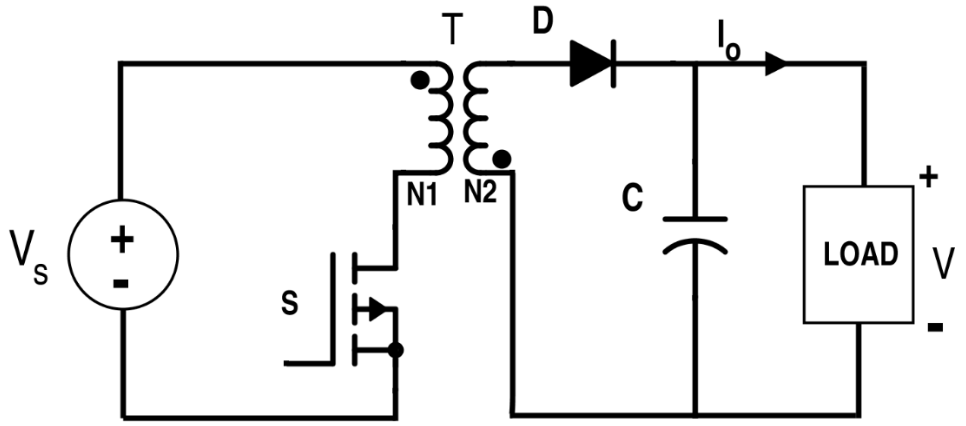

Figure 2.24: Flyback converter

When the S switch is ON state, input side of the transformer will be conducted to voltage source and the input current of transformer will be increased. Transformer will be started to store energy. The capacitor will be transferred energy to the load.

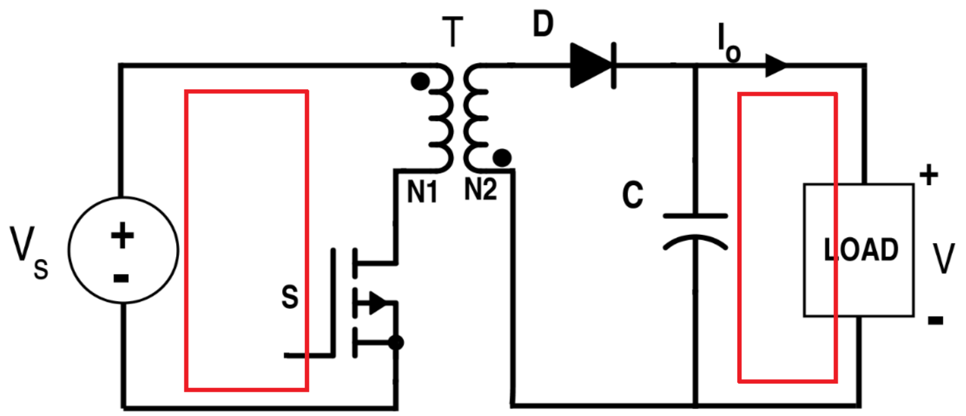

Figure 2.25: Flyback converter switch turn ON state

When the S switch is OFF state, the input current of transformer will be reduced. The diode will be forward biasing and current will be flow and capacitor will be started to store energy.

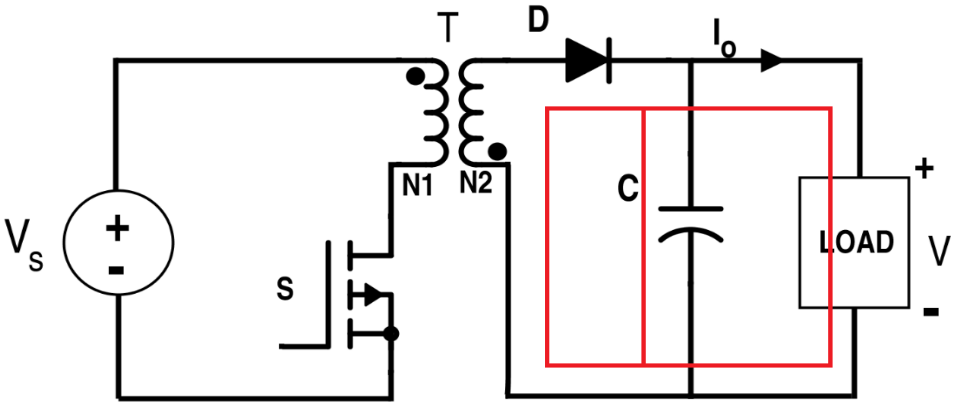

Figure 2.26: Flyback converter switch turn OFF state

Advantages of flyback converter;

- Isolation between input and output.
- Multiple outputs.
- Low cost.
- High voltage.

Disadvantages of flyback converter;

- Lower bandwidth has been required.
- Turn on and turn off durations is very important for efficiency (Erikson, 2001).

2.3 Comparison of Topologies

Every area of electronic world, dc to dc converters are necessary to satisfy demand. Both high voltage and low voltage levels, converter topologies should be designed to operate properly and stable. Also, cost is very important for sales. Another important matter is the efficiency. Because every application or every voltage level in brief, all demand needs specific topology to keep efficiency highest. Throughout the thesis, all converter types have been researched and described. In the light of this researched, a table appeared. In this chapter, comparison of topologies will be achieved.

If topologies are evaluated as dimensions, swiched capacitor topology is simple technique. Its light and cheap. Also, it has a small size. Besides switched inductor topology has a lot of passive components. This brings heavier than switched capacitor. Moreover, multi-stage needs excessively components. Amount of components reflect to cost. The cost increases as the quantity increases. Integration and modularity is also important. According to this perspective, switched capacitor topology is easy to integrate. Besides, multi-stage converters have modularity structure (Forouzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2016), (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017).

Switched capacitor has inrush currents, as the converter is first started to operate. Besides the equivalent series resistances (ESR) is very important for switched capacitors. Besides, it has fast dynamic response. But it can be applied high gain applications. In voltage multiplier topologies, voltage stress on components becomes very high. Furthermore, to achieve high gain, one stage doesn't enough. It requires more than one stage. Despite that advantage a being a cell. Switched inductor and voltage lift technique can be applied high gain dc-dc applications neverthless, not suitable for high power applications. Leakage inductance occurs in magnetic coupling topologies. But high efficiency can be achieved. The couled magnetic design is sensitive. Besides its bulky. It has a wide application area such as high voltage applications, dc microgrids, telecommunication, bidirectional, regenerative and space. In last topology multi-stage, efficiency can be reduced, as the stages increase. But its reliable and efficient. It can be applied high voltage dc transmission, renewable systems. High power dc supply (Forouhzesh, Siwakoti, Gorji, Blaabjerg, & Lehman, 2017).

2.4 Advantage of the Z-source Converter

There are a lot of advantage of the z-source converter. Advanteges of z-source converter can be listed.

- High efficiency.
- High gain.
- High power applications.
- Buck-boost operations.
- Can be reached to high output voltage.
- Perfect stability.
- Low noise.
- EMI (ElectroMagnetic Interference) does not effect z-source.
- Reduced inrush currents and harmonics.

- Applicable to all ac-dc, dc-ac, dc-dc, ac-ac conversions.
- Low cost.
- Pwm used.
- Small circuit size.

CHAPTER 3
Z-SOURCE DC TO DC CONVERTER

Empedance source dc to dc converter has described in this chapter. Detailed decription, description of application, design of the converter, desigh of the inductor and efficiency analysis will be included.

3.1 Detailed Description of the Converter and Operation

The z-source topology is the converter that converts voltage level to upper or lower levels. It means that is dc to dc boost converter or buck converter. Z shaped inductors and capacitors can couple the system (Sarode & Kadwane). When it does that, it uses unique inductor-capacitor network that has an empedance. Thus, the harmonic distortion and inrush current have been reduced to minimal value (Fang, 2008). Z-source inductors and capacitor have been chosen same value. So, they can be used symmetrical. The inductor voltages and capacitor voltages will be equalized due to symmetrical properties. So, the voltages will be following equation.

VL1= VL2= VL and VC1= VC2= VC

Inductor-capacitor (LC) filter used to take down output voltage ripple (Sarode & Kadwane). Z-source dc to dc topology shown in Figure 3.1.

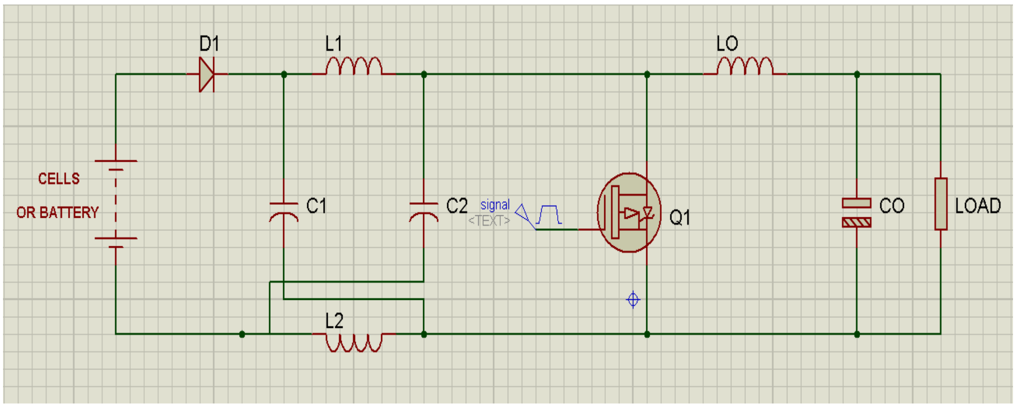

Figure 3.1: Schematics design of z-source dc to dc converter

3.2 Description of Application

Working principle of the circuit will be explained in 2 working steps. For step 1, D1 is in conduction and Q1 is turned off state. Supply voltage (Vs) (cells or battery) supply energy to the z-source capacitors. Simultaneously, z-source inductors transfer their energy to the load.

Step 1 interval: (1-d)T.

d; duty cycle

T; switching cycle, period.

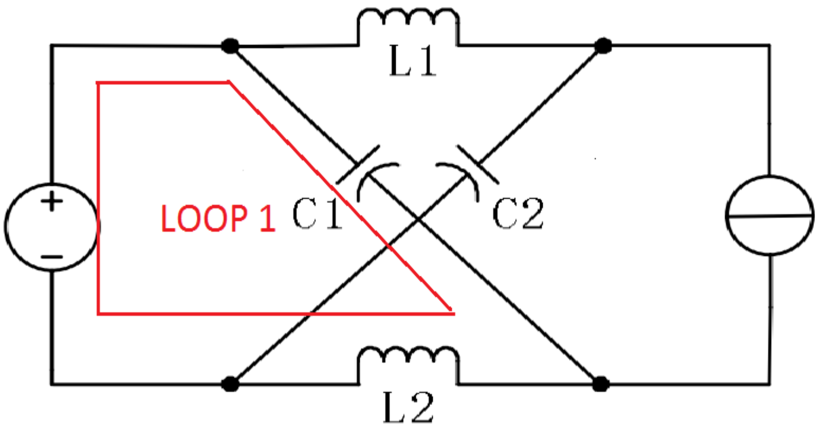

Figure 3.2: Z-source LOOP 1 switch turn OFF state (Fang, 2008)

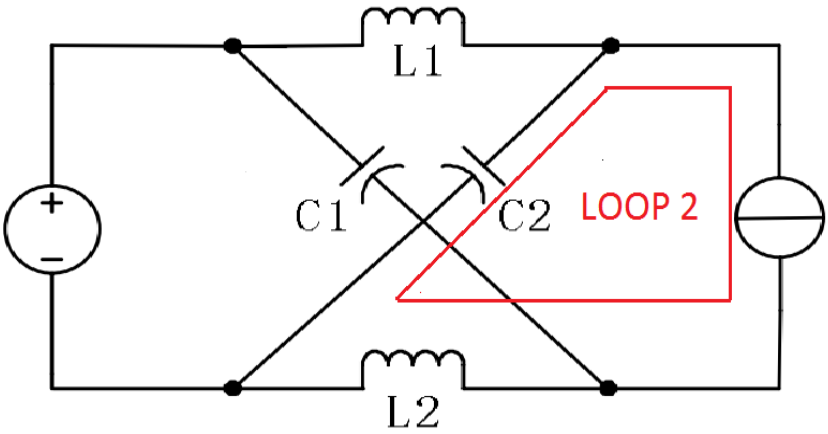

Figure 3.3: Z-source LOOP 2 switch turn OFF state (Fang, 2008)

In this step, z-source capacitor and output voltage can be written as Figure 3.2 and Figure 3.3;

LOOP 1; $Vc=Vs-V_L$ (3.1)

LOOP 2; $Vo=Vc- V_L=Vi- V_L - V_L= Vi-2V_L$ (3.2)

For step 2, D1 is in nonconduction mode and Q1 is ON. Inductor starts to store energy for release it towards to the load.

Step 2 interval; dT

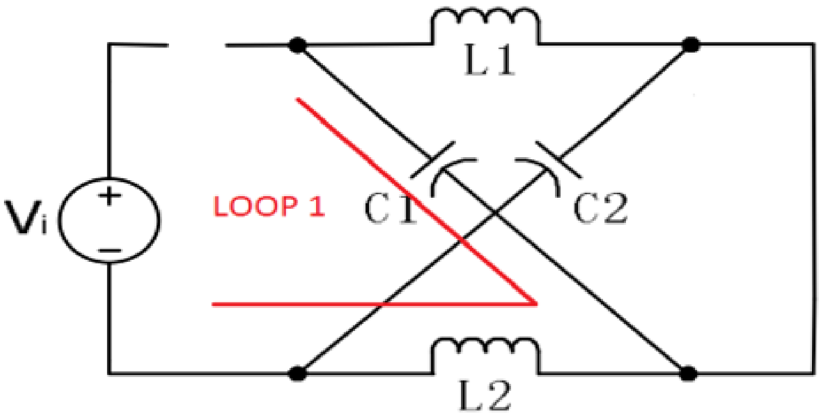

Figure 3.4: Z-source LOOP 1 turn ON state (Fang, 2008)

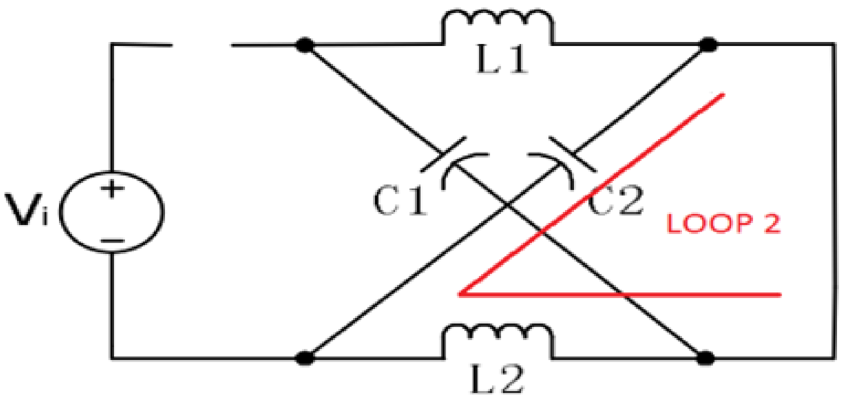

Figure 3.5: Z-source LOOP 2 turn ON state (Fang, 2008)

As seen on schematics, the path will be;

LOOP 1; $Vc= V_L$ (3.3)

LOOP 2; $Vo= Vc- V_L = V_L - V_L = 0$ (3.4)

The step 2 can also be shown in Figure 3.6.

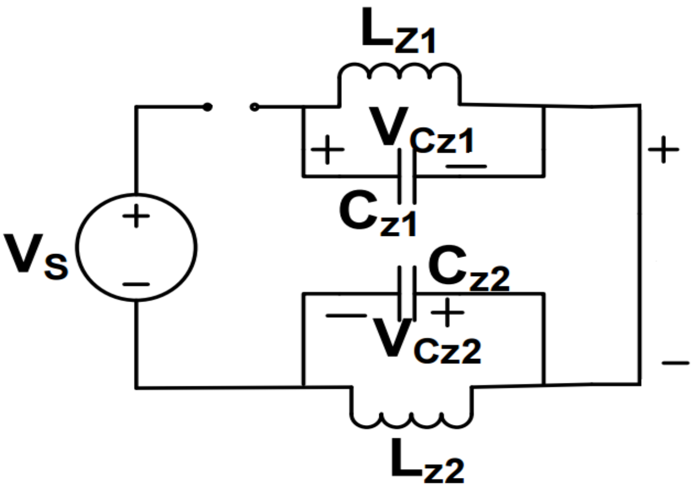

Figure 3.6: Equivalent of step 2

The voltage on inductor in step 2 is;

V_L=L × (di/dt), in step 2 inductor voltage is equal to the capacitor voltage Vc. So the equation will be;

V_L=Vc=L × (di/dt). (3.5)

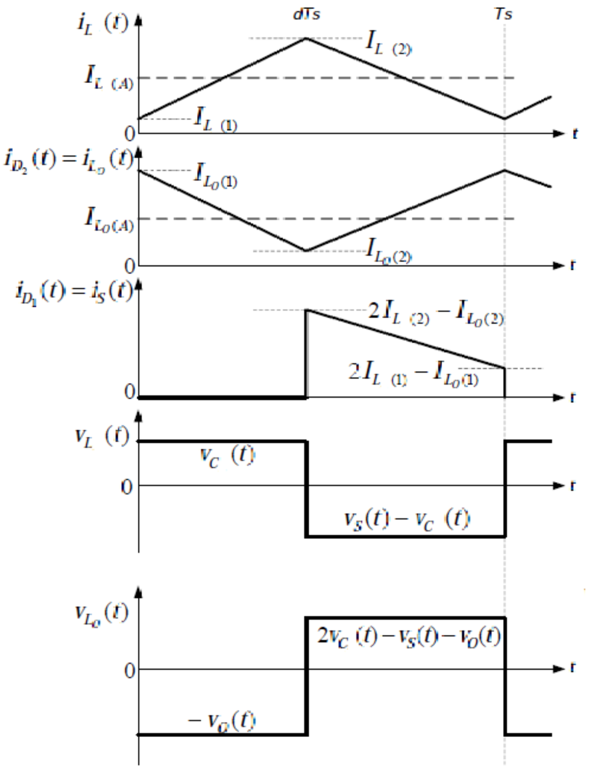

Figure 3.7: Waveforms of several parameters (Pekuz, 2010)

Waveforms of parameters can be shown in Figure 3.7 for each step 2 and step 1, respectively. And now the new equation can be written as;

$$V_L = Vc = \frac{L \times (IL2 - IL1)}{dT} \tag{3.6}$$

dT will be multiplied both side.

$$dT \times Vc = L \times (I_{L2} - I_{L1}) \tag{3.7}$$

In step 1, the time interval is (1-d)T and inductor voltage is Vs-Vc. Then the equation can be written as;

$$(1-d)T \times (Vs-Vc) = L \times (I_{L2} - I_{L1}) \tag{3.8}$$

When the inductor voltage complete one period, T is taken down to the zero. So, both equations will equal to zero.

$d \times Vc = 0,$

$$(1-d) \times (Vs-Vc) = Vs-dVs-Vc+dVc=0 \tag{3.9}$$

Now we can sum both equations.

$dVc + Vs - dVs - Vc + dVc = 0$ lets make common brackets.

$$(1-d)Vs - (1-2d)Vc = 0, \tag{3.10}$$

$(1-d)Vs = (1-2d)Vc,$

Then, final equation will be;

$$Vc = \frac{(1-d)Vs}{(1-2d)} \tag{3.11}$$

If kvl rule is applied to all circuit, the V_{LO} can be found and Vo relation can be extracted from it.

$$Vo = \frac{(1-d)Vs}{(1-2d)} \tag{3.12}$$

This equation is the proof of Vc is equal to Vo. Therefore, this equation shows that the output voltage can be adjustable from input voltage to infinity.

Thus, output inductor current ripple and ouput capacitor current ripple can be equal to each other.

$\Delta i_{LO} = \Delta i_{CO}$ (3.13)

From equation 3.12, we have reached that the duty cycle is;

$D = {(Vo - Vs)}/{(2Vo - Vs)}$ (3.14)

From equation 3.15to obtain Δi_{LO};

$Lo * {(ILo2 - ILo1)}/{Dt} = V_{Lo}$ =-Vo -Vo=V_{Lo} from applying KVL to output section of circuit in step 2.

Then,

$\Delta i_{LO} = (I_{Lo2} - I_{Lo1}) = {Vo \times dT}/{Lo}$ (3.15)

The average value of the output capacitor current;

$I_{Co} = {\Delta iLO}/{4} = Vo \times dT / 4Lo$ (3.16)

I_L can be obtained from state vectors.

$I_L = {((d - 1)2 \times Vs)}/{(RL \times (1 - 2D)2)}$ (3.17)

L_L can be obtained from equation 3.20

$Vc = {L \times (IL2 - IL1)}/{dT}$ (3.18)

$\Delta i_L = I_{L2} - I_{L1}$ (3.19)

$L_L = {(Vo \times d \times T)}/{\Delta iL}$ (3.20)

Also;

$L_{Lo} = {Vo \times dT}/{\Delta iLo}$ (3.21)

And

$I_{Lo} = {((1 - d) \times Vs)}/{(RL \times (1 - 2D))}$ (3.22)

The equations clearly show that ripple current of inductor is an important point. The load depends to ripple current of inductor.

The voltage of output capacitor Vco is;

$$V_{co} = (1/C_o)\int I_{Co}\,dt + V_{co}\ (\text{at } t=0) \qquad (3.23)$$

After that to calculate output voltage ripple;

$$\Delta V_{co} = V_{co} - V_{co}(0) \qquad (3.24)$$

$\Delta V_{co} = (1/C_o)\int(\Delta i_{LO}/4)\,dt$ boundaries are from 0 to T/2

Final ripple equation will be;

$$\Delta V_{co} = (\Delta i_{LO} \times T)/(8 \times C_o) \qquad (3.25)$$

3.3 Design of the Converter

the important parameters of design a z-source converter are the passive components, duty cycle and switching frequency. Low frequency means that the passive components will be increased, and physical dimension of the circuit will increase. On the other hand, to keep low the sizes of passive components, also will decrease the physical dimension of circuit. Therefore, the frequency should be high, however, the losses will be increased and efficiency problem will be emerged. The frequency has been choosen 50 kHz for the following example.

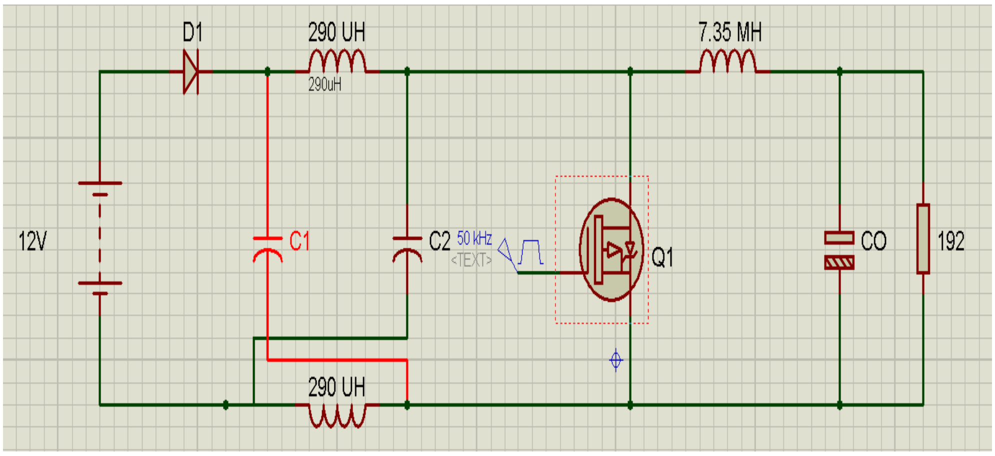

Figure 3.8: ISIS proteus schematic z-source circuit

In the example circuit, 12 V input voltage, 200 V output voltage and 208 W output power will be provided. The calculations will be depended to these parameters.

Vs=Vin=12 V

Vo= 200 V

Po= 208 W

R_L = 192 Ω

f= 50 kHz

I_{Load} = V / R = 200 / 192 = 1.04 A

To find duty cycle, equation 3.14 will be used

$D = {(Vo - Vs)}/{(2Vo - Vs)} = {(200 - 12)}/{(2\times200 - 12)}$

d= 0.4845= 0.49

To find inductor value of z source network, inductor current ripple of z-source network should be calculated. To calculate inductor current ripple of z-source network, inductor current of z-source network should be calculated. The following equation for I_L;

$I_L = {((d - 1)2 \times Vs)}/{(RL \times (1 - 2D)2)}$

$I_L = {((0.49 - 1)^2 \times 12)}/{(192\times (1 - 2 * 0.49)^2)}$

$I_L = {3.12}/{0.076}$

I_L= 40.625 A   is the z-source network inductor current.

The z-source inductor ripple has been assigned to 20%.

Then,

Δi_L =8.12 A for 20%.

To find z-source inductor value;

$Lz = {(Vo \times d \times T)}/{\Delta iL}$

Lz= $(200 \times 0.49 \times 0.00002)/_{8.12}$

Lz=241×10^{-6} H

To find output inductor value of the circuit, output inductor current ripple of the circuit should be calculated. To calculate output inductor current ripple of the circuit, output inductor current of the circuit should be calculated. The following equation for I_{Lo};

I_{Lo}=$((1-\mathrm{d}) \times \mathrm{Vs}) / (\mathrm{RL} \times (1-2\mathrm{D}))$

I_{Lo}= $((1-0.49) \times 12) / (192 \times (1-2\times 0.49))$

I_{Lo}= $6.12/_{3.84}$

The final result of the output inductor current will be;

I_{Lo}= 1.59 A

The output inductor current ripple has been assigned to 20%.

The 20% of the output inductor current ripple is 0.32A

Δi_{LO} = $\mathrm{Vo} \times \mathrm{dT}/_{\mathrm{Lo}}$

Lo = $\mathrm{Vo} \times \mathrm{dT}/_{\Delta \mathrm{i}Lo}$

Lo= $200\times 0.49 * 0.00002/_{0.32}$

Lo= 6.125 mH is the output inductor value.

Next step is the calculation of capacitor values.

C= $\mathrm{Iav} \times \mathrm{T}/_{\Delta \mathrm{Vc}}$ (3.26)

Equation 3.26 is the capacitance formula of the z-source network. To find it, Iav and ΔVc must be calculated.

Iav is the average current of z source inductor.

Iav= $Po/_{Vin}$

Po is the output power.

Vin is the input voltage.

Iav= $^{208}/_{12}$

Iav= 17.3 A

ΔVc is the voltage ripple on the z-source capacitors. It is 20% percent of Vc.

ΔVc= 40 V

Cz= $^{17.3 \times 0.00002}/_{40}$

Cz= 8.65 uF

ΔVco is the voltage ripple on the output capacitor. It is 20% percent of Vc.

$$\Delta Vco = {}^{(\Delta iLO \times \mathrm{T})}/_{(8\ *\ \mathrm{Co})} \tag{3.27}$$

$$\Delta Vco = {}^{(Vs \times (1-d) \times d \times \mathrm{T2})}/_{(8 \times Co \times Lo \times (1-2d)} \tag{3.28}$$

The Co can be written as;

$$Co = {}^{(Vs \times (1-d) \times d \times \mathrm{T2})}/_{(8 \times \Delta Vco \times Lo \times (1-2d)} \tag{3.29}$$

3.4 Design of the Inductor

Coupled inductors have wide application area in power electronics especially in boost-buck operations. It has many advantages such as decrease the circuit dimension, provide high efficiency and fast transients. So the coupled inductor has been used for z-source inductors. Coupled inductor design has been described in this section.

3.4.1 Coupled inductor design

Coupled inductors can prevent input voltage source get damaged by shoot through state. Besides, it limits the input current ripple of converter. Besides, it decrease the circuit size (Zakis, Vinnikov, & Bisenieks, 2011).

First of all, the inductance and inductor current should be known. The inductance of coupled inductor have been calculated in 3.3 and current has been calculated in 3.1. After calculated the inductance and current, the magnetic core selection should be choosen. There are wide core shapes and sizes in inductor world but EE, EI, L, UU, CC shapes appropriate for high power applications (Chan, Cheng, Cheung, & Cheung, 2006).

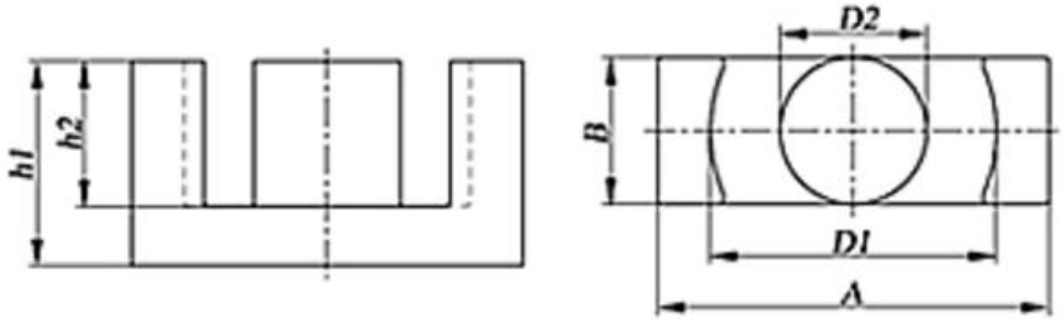

Figure 3.9: Core shape and cross sectional (Chan, Cheng, Cheung, & Cheung, 2006)

These shapes are also cheaper than the other shapes because of making of winding (Zakis, Vinnikov, & Bisenieks, 2011). After choosing the core, calculation of coupled inductor design will be done using Core geometry, Kg.

$$Ipk = I_{LZ} + \Delta iL/2 \quad (3.30)$$

$$Energy = (Lz \times Ipk^2)/2 \quad (3.31)$$

After calculated the energy-handling capability, the electrical conditions coefficient Ke calculates.

$$Ke = 0.145 \times P_O \times Bm^2 \times (10^{-4}) \quad (3.32)$$

Final Kg core geometry coefficient is;

$$Kg = (Energy^2)/(Ke \times \alpha) \quad (3.33)$$

Then, the core can be selected. The table shows us core geometry of cores.

Table 3.1 ETD cores (McLyman, 1978)

ETD, Ferrite Cores (Ferroxcube)											
Part No.	**W_{tcu} grams**	**W_{tfe} grams**	**MLT cm**	**MPL cm**	**W_a / A_c**	**A_c cm^2**	**W_a cm^2**	**A_p cm^4**	**Kg cm^5**	**A_t cm^2**	***AL mh/1K**
ETD-49	126.2	124.0	10.3	11.4	1.62	2.11	3.43	7.2453	0.591	107	1909
ETD-54	186.9	180.0	11.7	12.7	1.60	2.80	4.50	12.612	1.210	133	2273
ETD-59	237.7	260.0	12.9	13.9	1.41	3.67	5.18	19.069	2.127	163	2727
*This AL value has been normalized for a permeabilityof 1K. For a close approximation of AL for other values of permeability, multiply this AL value by the new permeability in kilo-perm. If the new permeability is 2500, then use 2.5.											

After select the core, Current density, J, can be calculated using the area product, Ap, of selected core.

$$J= {2 \times Energy \times (10^4)} \Big/ {Bm * Ap * Ku} \quad (3.34)$$

To calculate bare wire area, first, rms current should be calculated.

$$Irms= (Io^2 \times \Delta IL^2)^{1/2} \quad (3.35)$$

$$A_{w(B)}= {Irms} \big/ {J} \quad (3.36)$$

Table 3.2 Wire size table (McLyman, 1978)

Wire Table												
AWG	**Bare Area**		**Resistance** $\mu\Omega$/ cm 20 ℃	Heavy Synthetics								
	cm^2 (10^{-3})	cir-mil		**Area**		**Diameter**		**Turns-Per**		**Turns-Per**		**Weight**
				cm^2(10^{-3})	cir-mil	cm	Inch	cm	Inch	cm^2	$Inch^2$	gm/cm
1	2	3	4	5	6	7	8	9	10	11	12	13
10	52.6100	10384.00	32.7	55.9000	11046.00	0.2670	0.105	3.9	10	11	69	0.46800
11	41.6800	8226.00	41.4	44.5000	8798.00	0.2380	0.094	4.4	11	13	90	0.37500
12	33.0800	6529.00	52.1	35.6400	7022.00	0.2130	0.084	4.9	12	17	108	0.29770
13	26.2600	5184.00	65.6	28.3600	5610.00	0.1900	0.075	5.5	13	21	136	0.23670
14	20.8200	4109.00	82.8	22.9500	4556.00	0.1710	0.068	6.0	15	26	169	0.18790
15	16.5100	3260.00	104.3	18.3700	3624.00	0.1530	0.060	6.8	17	33	211	0.14920
16	13.0700	2581.00	131.8	14.7300	2905.00	0.1370	0.054	7.3	19	41	263	0.11840

After selection of wire size, effective windows area can be calculated.

$$W_{a(eff)} = Wa \times S_3 \quad (3.37)$$

Now, required information has been gathered to calculate turn number and air gap of core (McLyman, 1978).

$$N = \mathrm{Wa(eff)} \times (S2) / Aw \quad (3.38)$$

$$l_{gap} = \left(0.4 \times \pi \times (N^2) \times Ac \times (10^{-8}) / L \right) - \left(MPL / \mu r \right) \quad (3.39)$$

S2=S_2= Fill factor.

μ_r= magnetic permeability of air= 1

μ_o= magnetic constant= $4\Pi \times 10^{-7}$

3.4.2 Example of coupled inductor design.

$L=241 \times 10^{-6}\ \mu H$

$I_L=40$ A

$Ipk = 40.625 + 8.12/2 = 44.685$ A

$Energy = 241 * (10^{-6}) \times (44.685^2)/2 = 0.2399$ watt-seconds

$Ke=0.145 \times 8125 \times (0.8^2) \times (10^{-4}) = 0.0754$

Bm is 0.8 T

$Kg = (0.2399^2)/0.0754 = 0.7632\ cm^5$

ETD-54 core can be selected according to Kg.

$J = 2 \times 0.2399 \times (10^4)/0.8 \times 12.61 \times 0.4 = 1189\ amps/cm^2$

$Irms = (40.625^2 + 8.12^2)^{1/2} = 41.43$ A

$A_{w(B)} = 41.43/1189 = 0.035\ cm^2$

AWG=12

Bare, $A_{w(B)} = 0.03308\ cm^2$

Insulated, $A_w = 0.03564\ cm^2$

$W_{a(eff)} = 4.505 \times 0.75 = 3.38\ cm^2$

$N = 3.38 \times (0.6)/0.02836 = 56.9 = 57$ turns.

l_{gap} $= \left({0.4 \times \pi \times (57^2) \times 2.8 \times (10^{-8})} \big/ {241 \times (10^{-6})} \right) - {12.7} \big/ {2500} = 0.61 - (5 \times 10^{-3}) =$ 0.465cm.

CHAPTER 4
SIMULATION AND EXPERIMENTAL RESULTS

Simulation results, experimental results, efficiency calculation and comments will be reviewed. Simulation results will be shown in different graphs and waveforms. Also MATLAB simulink schematic design and obtaining of waveforms and graphs will be described.

4.1 Simulation Results

The simulation results will be discussed in this section. The simulation test has achieved in MATLAB Simulink. To simulate the z-source dc to dc converter, values of all components should be calculated before. Also, arrangement of parameters will be explained in this chapter. The aim of the simulation is explained in matters;

- The understanding of circuit operating principle.
- Understanding of efficiency.
- Provement of the calculations.
- Waveforms of parameters.
- Comparing of calculation results and simulation results.

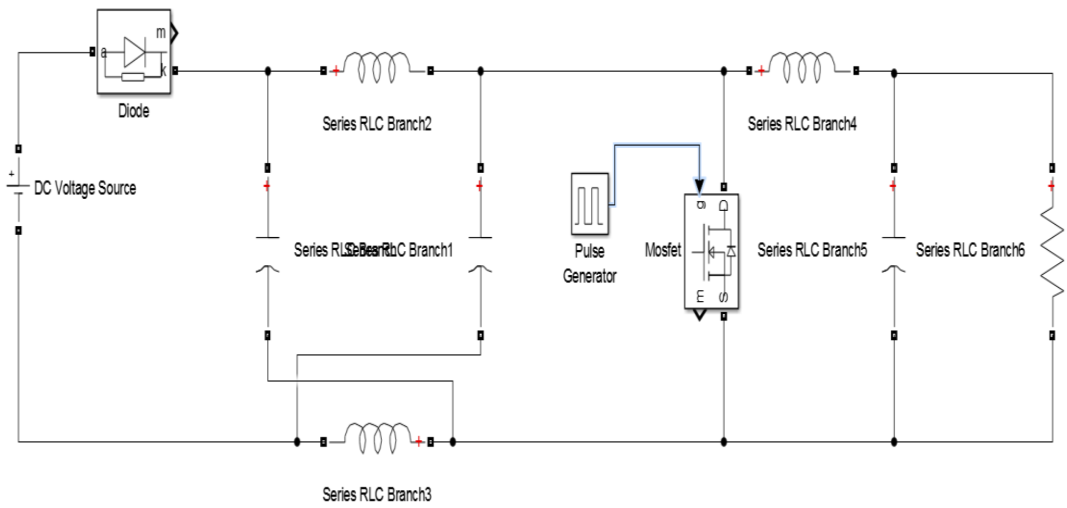

Figure 4.1: MATLAB schematics of z-source converter

Specifications and values of the simulation circuit have been written in tables.

Table 4.1: Design specifications

	Value
Input voltage	12 V
Output voltage	200 V
Frequency	50 kHz
Duty cycle	0.49
Output power	208 W

Table 4.2: Parameters of components

	value
Z-source inductor	240 uH
Z-source capacitor	8.65 uF
Output inductor	6.12 mH
Load	192 Ω

Schematic design starts up;

All parameters have been chosen from library browser and can be searched by name. To set capacitor, resistor and inductor, series rlc branch has been chosen from library browser and to define and set the values, double click has applied to series rlc branch. Diode should be chosen similar with Figure 4.1. After the diode has been set to the schematics, double click has applied to diode to set the values. After block parameters window is opened, values should be set as shown in Figure 4.2.

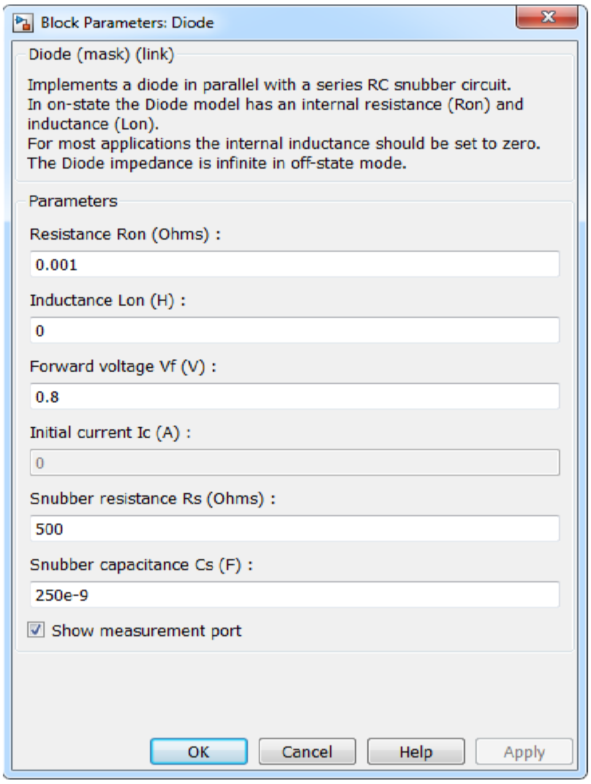

Figure 4.2: Block parameters of diode

After the complete diode parameters, mosfet have been added to schematics. To set the parameters of mosfet, double click can be applied to mosfet on schematics.

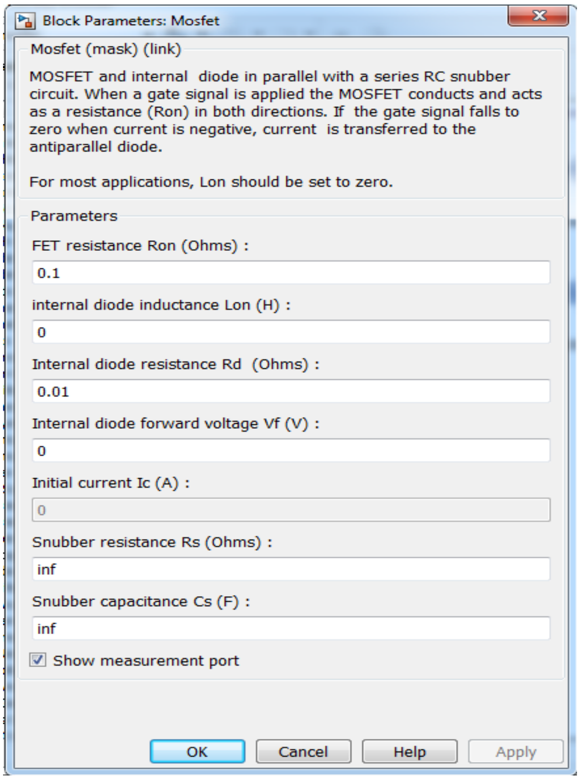

Figure 4.3: Block parameters of mosfet switch

Figure 4.3 shows us the parameters of mosfet. After placed the components on schematics, the wiring can be done. Next step of the simulation is the placing of voltage measurement and current measurement elements to the schematics. Voltage measurement unit can be found in simulink library browser as a voltage measurement. Besides current measurement unit can be found in simulink library browser as a current measurement. When double clicking, units can be added to circuit. To measure the voltage of any components, paralel network can be linked to voltage measurement unit. Besides, to measure the current of any components, series network can be linked to current measurement unit. But the adding of measurement units don’t enough to get waveforms. The scope should be added and linked to the measurement units. Scope connection can be shown in Figure 4.4.

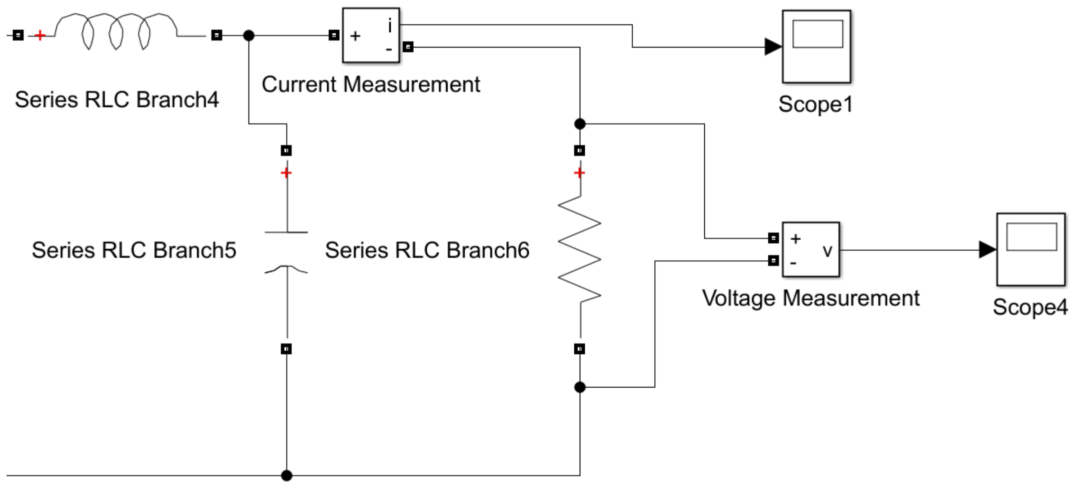

Figure 4.4: Voltage measurement and current measurement connections

This achievement opens our way to obtain waveform of voltages and currents of any components. Last adjustment before starting simulation is the start and stop time interval of simulation.

Figure 4.5: Simulation set up bar

In Figure 4.5, the red circle shows us time interval. 0.2 second is enough to see voltage and current changes. After complete all schematics, the simulation can be ran. Output voltage, output current, z-source inductor current and z-source capacitor voltage can be shown in figures respectively.

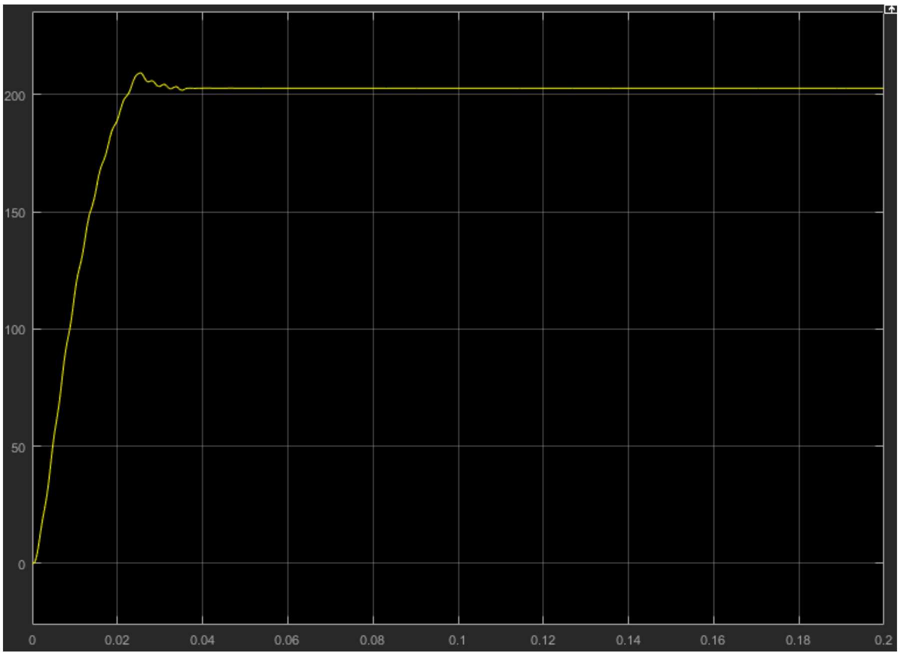

Figure 4.6: Graph of output voltage

In Figure 4.6, it can be seen clearly, it takes only 0.04 second to reach desired voltage level 200 V. Besides, the output voltage is pure and noises are very low.

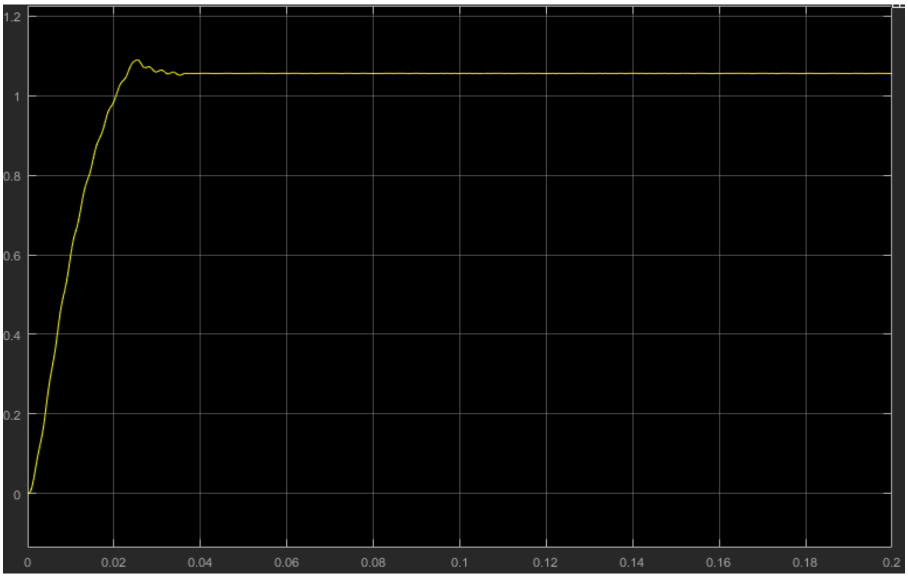

Figure 4.7: Graph of output current

The output power is 208 W. As it calculated before, the output current is 1.25 A and its clear in the graph, the output current of simulation is 1.04 A.

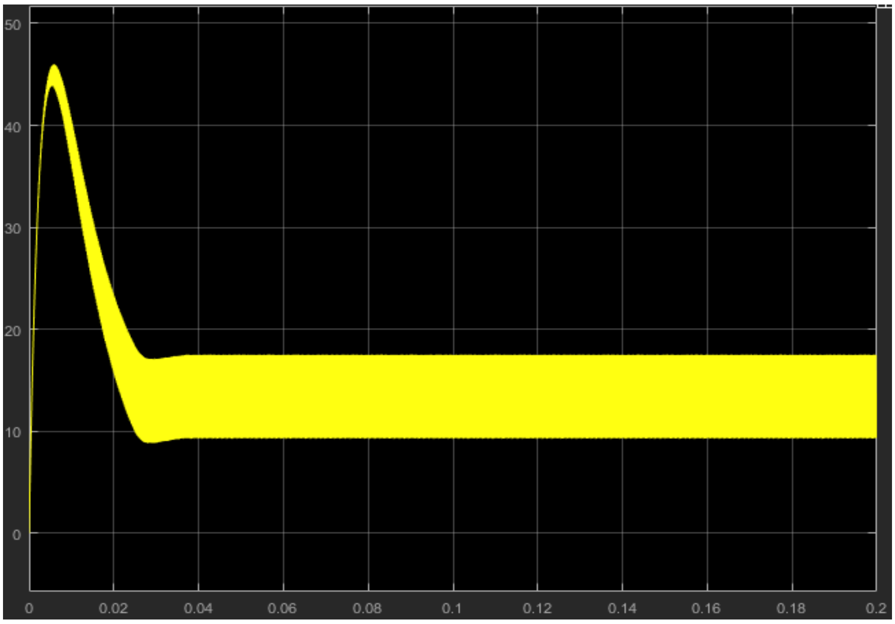

Figure 4.8: Graph of z-source inductor current

The current of the z source inductor is 40.625 A but the average current of the z source inductor is 25 A. In graph of z-source inductor current, it is hard to see average current.

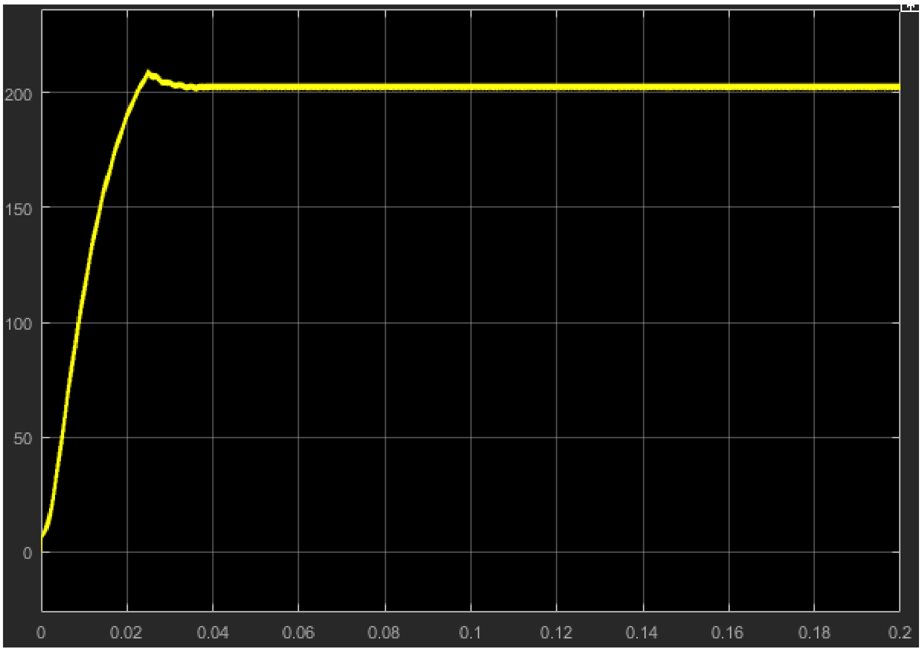

Figure 4.9: Graph of z-source capacitor voltage

The voltage on z source capacitors are 200 V.

Several components waveform have been shown in Figures 4.10, 4.11, 4.12, 4.13, 4.14, 4.15, 4.16. Time intervals have been choosen randomly to show waveforms of component parameters.

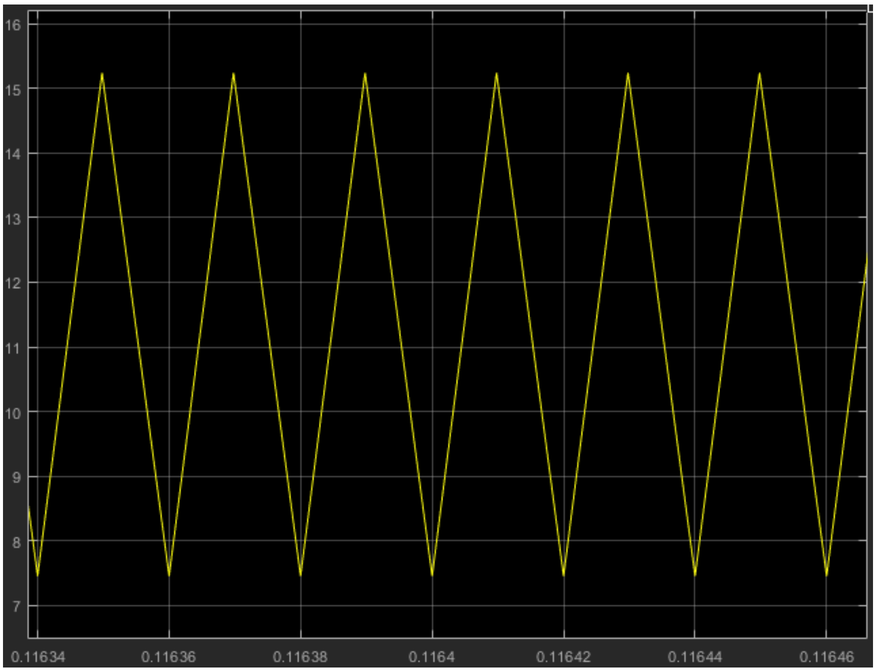

Figure 4.10: Waveform of z-source inductor current

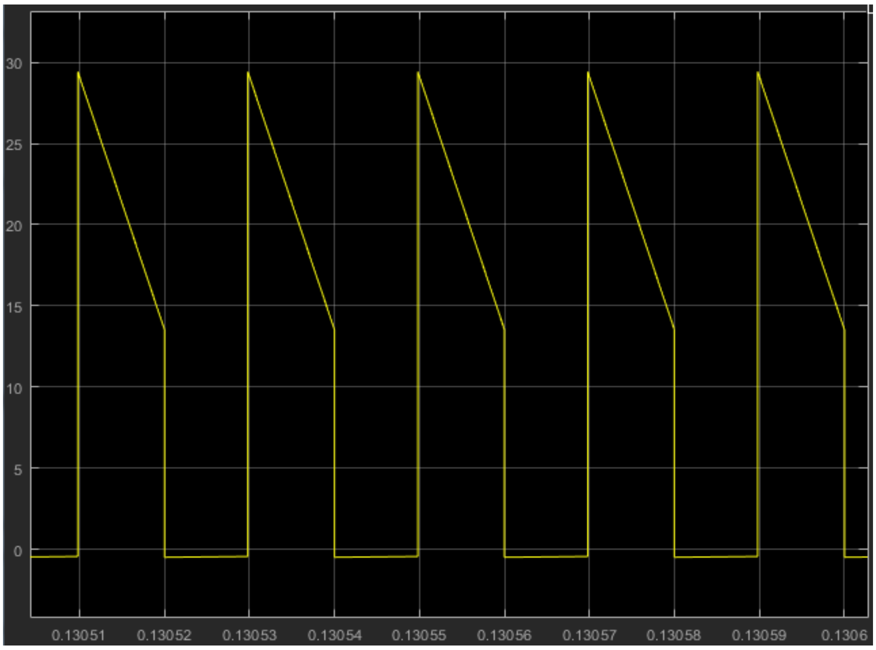

Figure 4.11: Waveform of diode current of z source

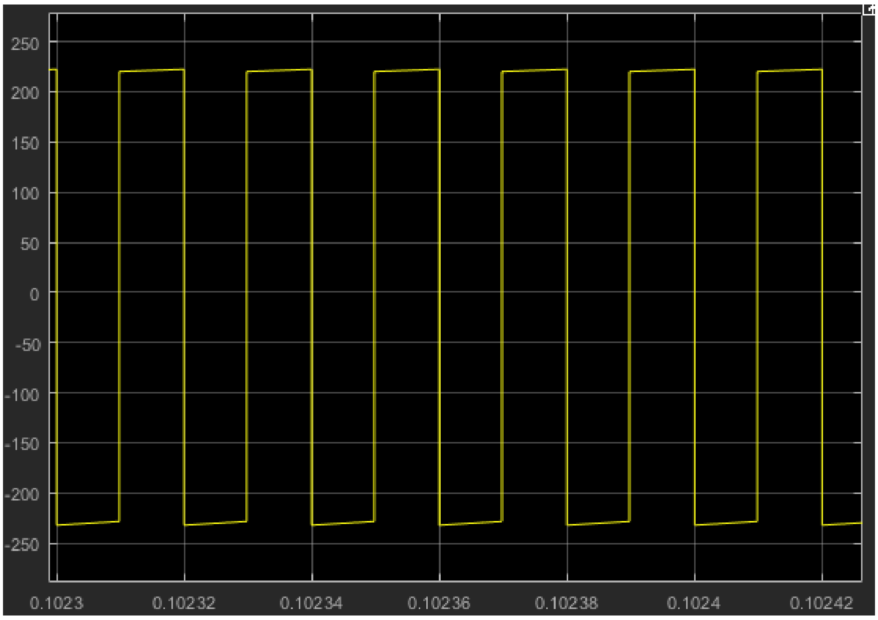

Figure 4.12: Waveform of Z-source inductor voltage

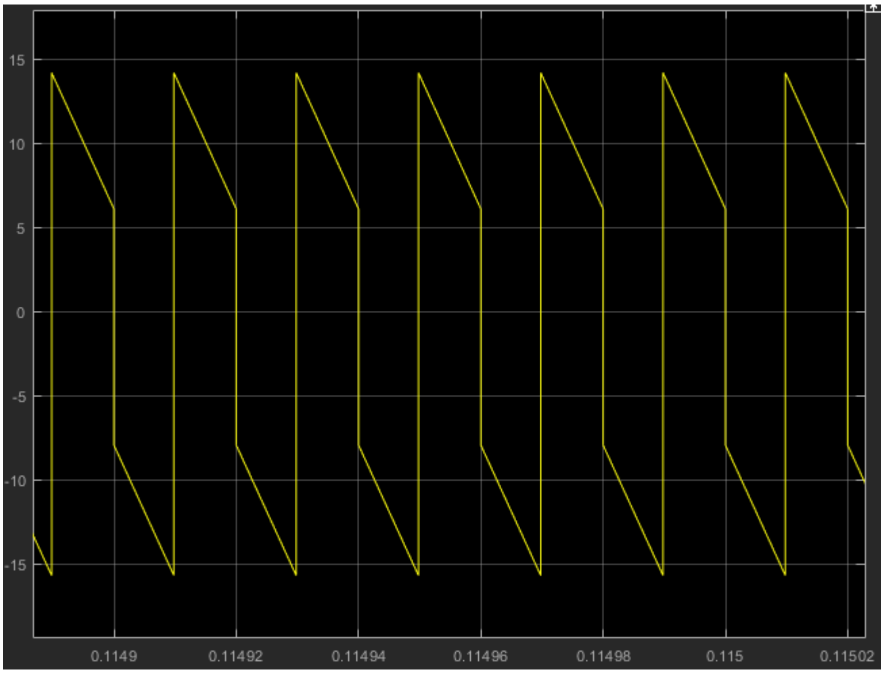

Figure 4.13: Waveform of Z-source capacitor current

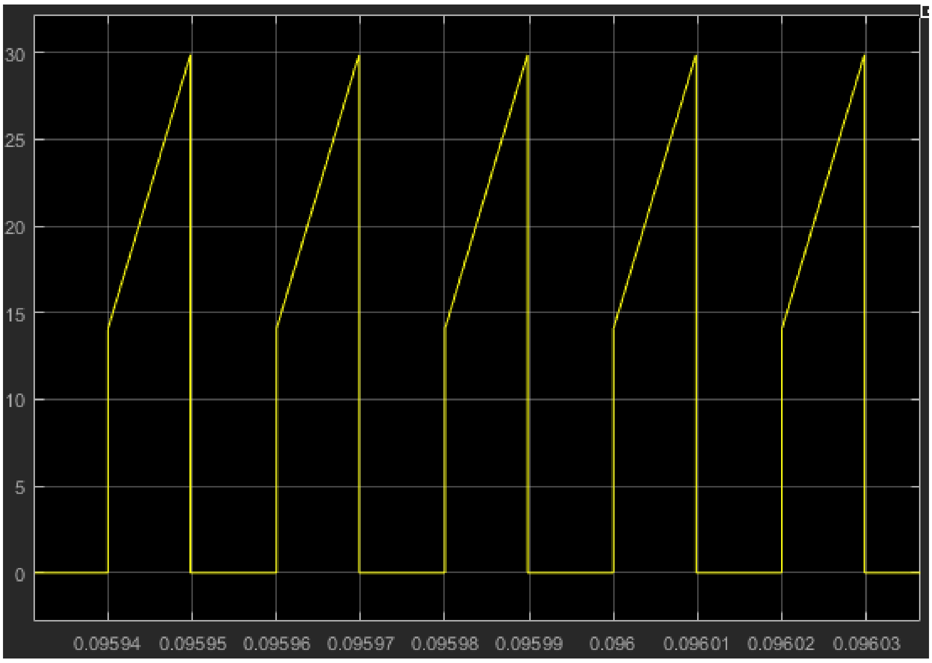

Figure 4.14: Waveform of switch (mosfet) current

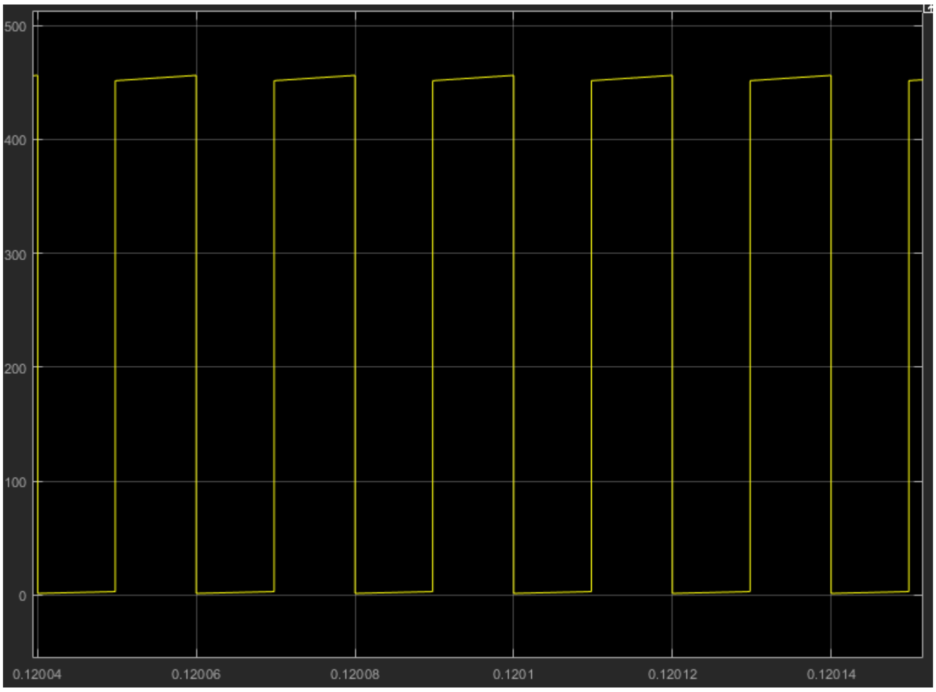

Figure 4.15: Waveform of switch (mosfet) voltage

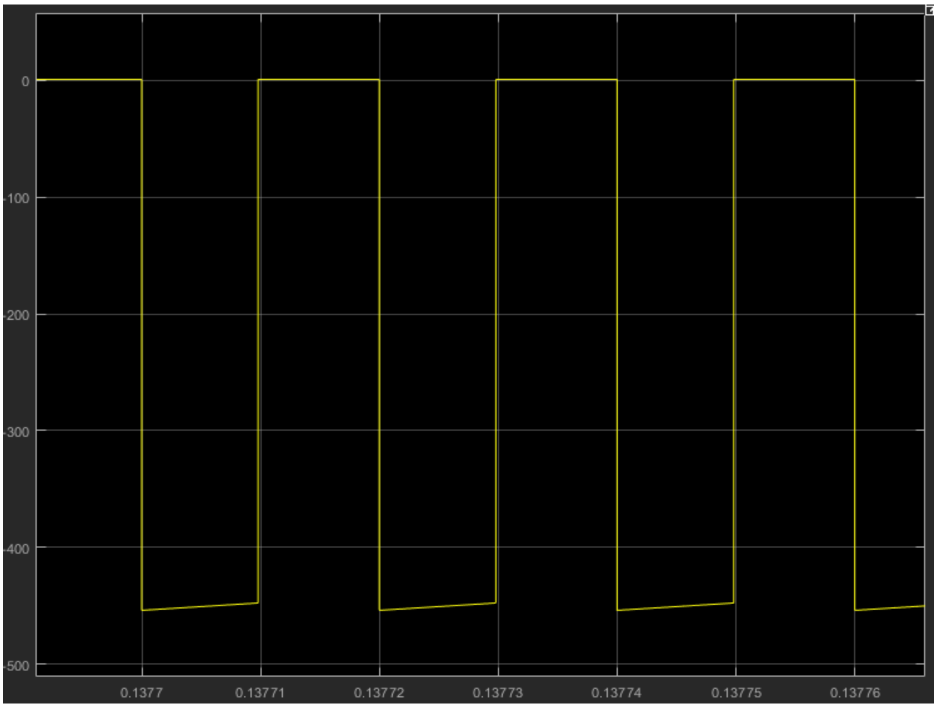

Figure 4.16: Waveform of diode voltage

4.1.1 PID control mechanism of output voltage

To provide protection of circuit, control mechanism has been applied to the circuit. The main idea of control strategy is reading of output voltage, comparing it with reference voltage and producing PID (proportional-integral-derivative) output to the pwm generator. Ideal switch and resistor have been added paralel to test the PID control mechanism.

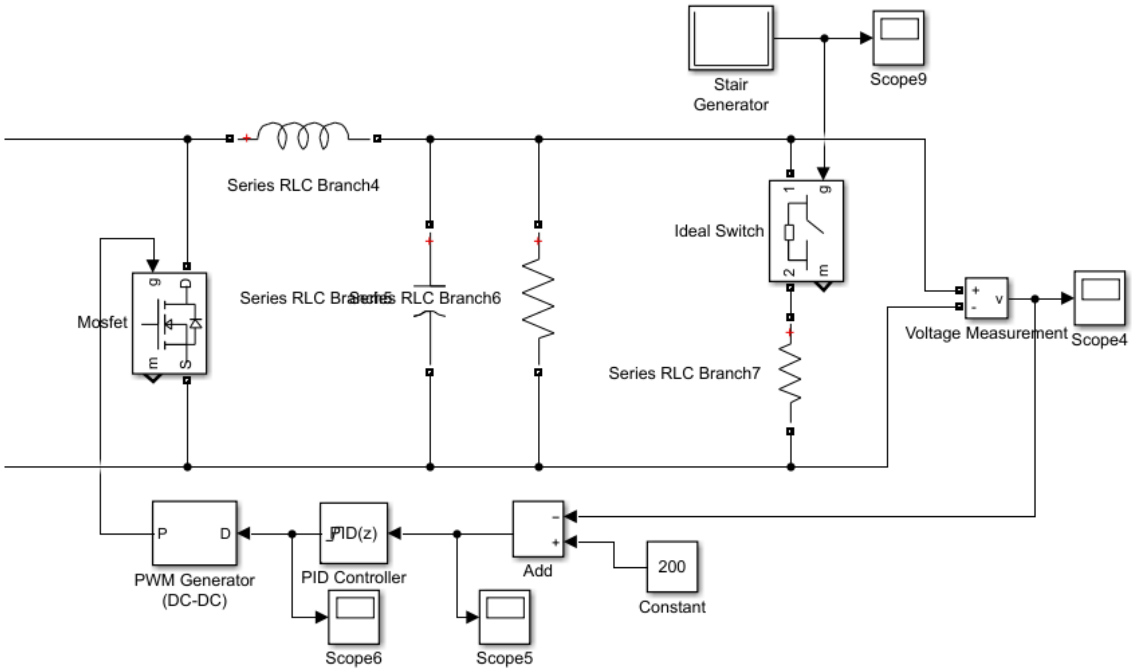

Figure 4.17: Control mechanism of z source dc to dc converter

In Figure 4.17, testing of pid control unit has been shown. Stair generator switches the ideal switch by specific intervals. It means that branch 7 can be added to the circuit and removed from circuit with specific intervals. The feedback loop measures output voltage and it subtracts from reference voltage (constant). PID controller read the error between the output voltage and reference voltage and produce number between 0 and 0.5. Finally, the PWM generator produces pwm according to input with fixed frequency.

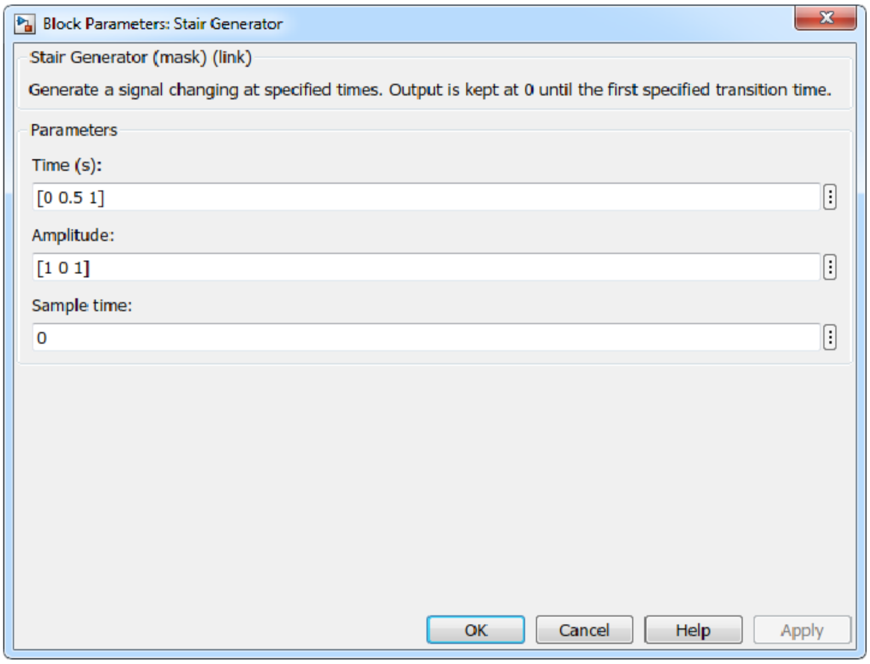

Figure 4.18: Stair generator

In Figure 4.18, stair generator parameters can be seen. These parameters means that the output will high between 0 and 0.5 seconds. After 0.5 s, output will be low until 1 s.

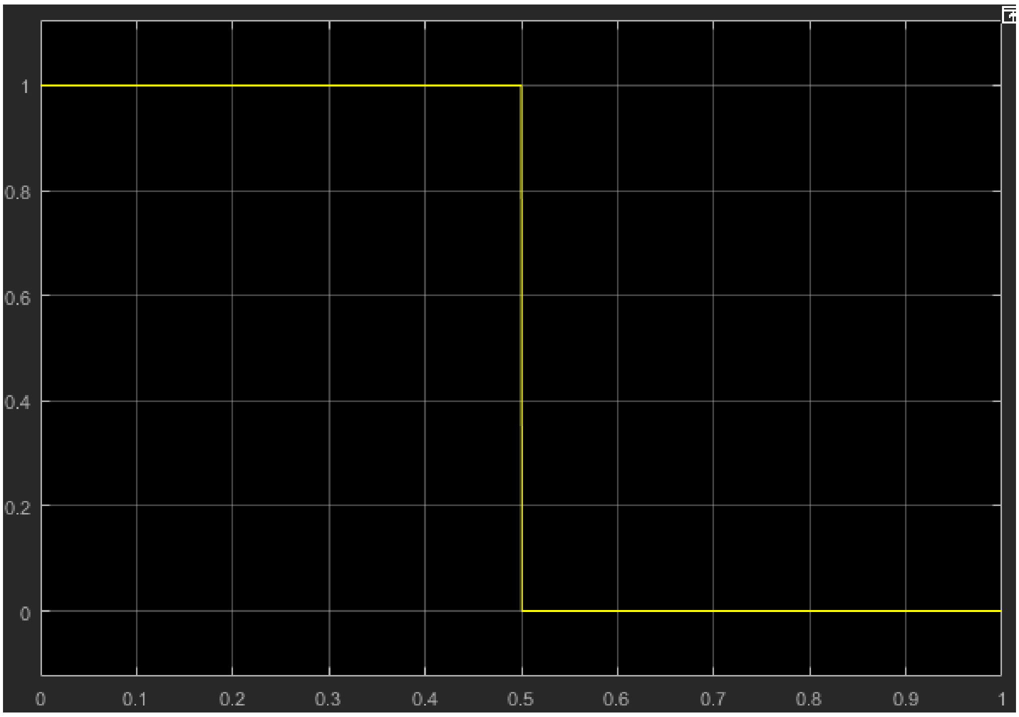

Figure 4.19: Stair generator output waveform

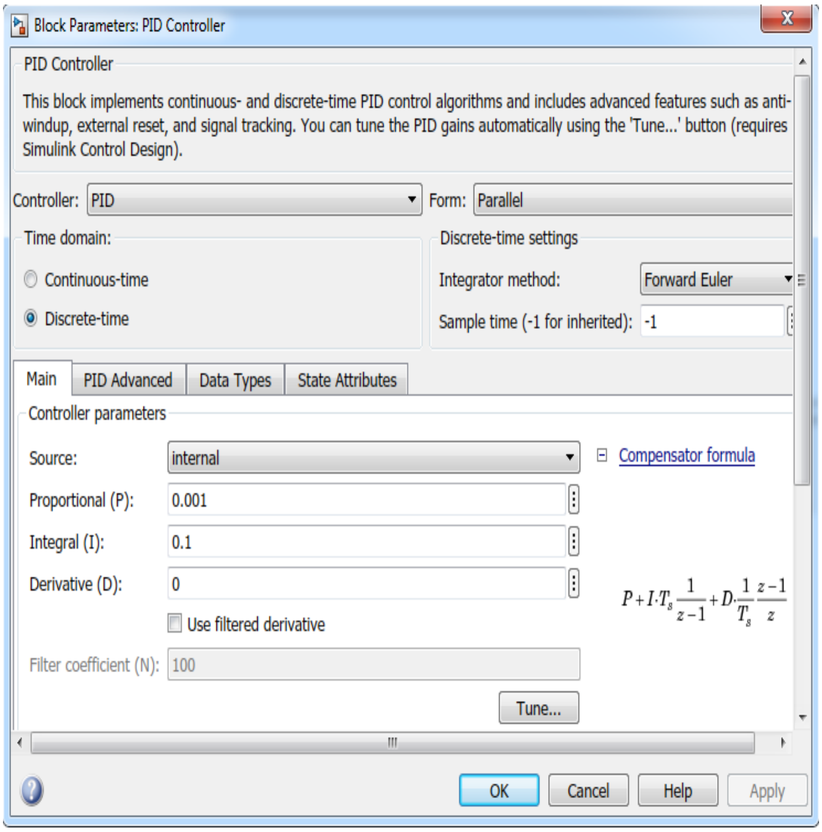

Figure 4.20: PID controller parameters

PID parameters can be calculated with Ziegler-Nichols method, can be evaluated with trial and error method or can be obtained with SIMULINK PID tuner. Proportional is 0.001, integral is 0.1 and derivative is 0 in this case. In PWM generator, switching frequency has been set to 50 kHz.

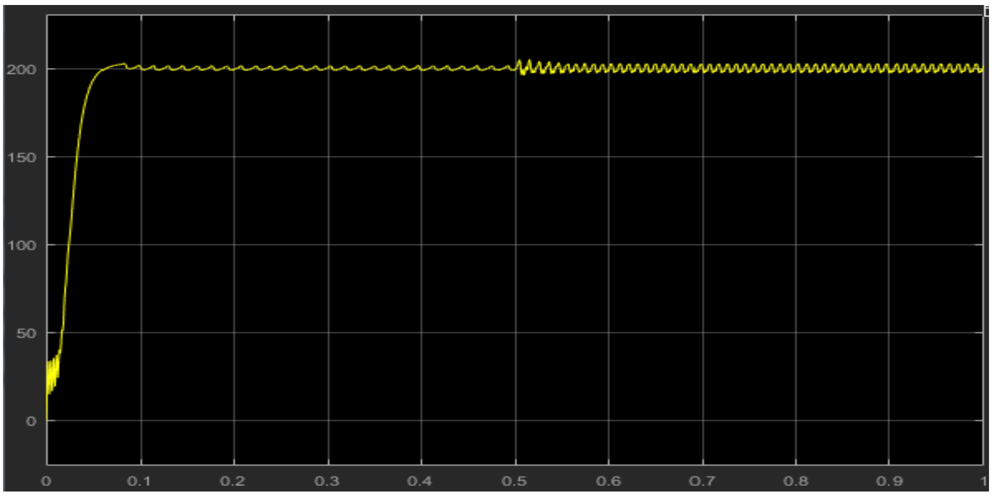

Figure 4.21: Output voltage

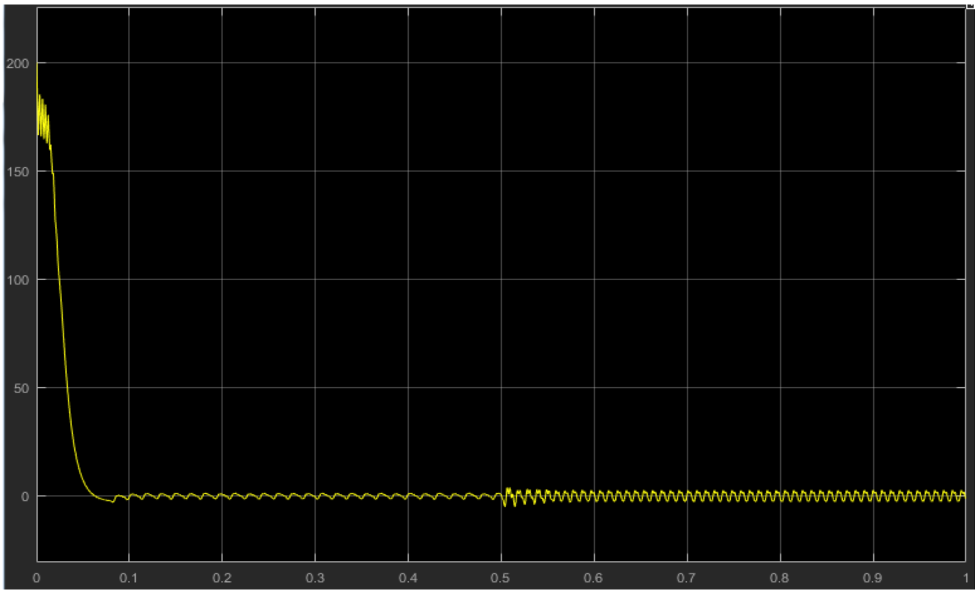

Figure 4.22: Error output

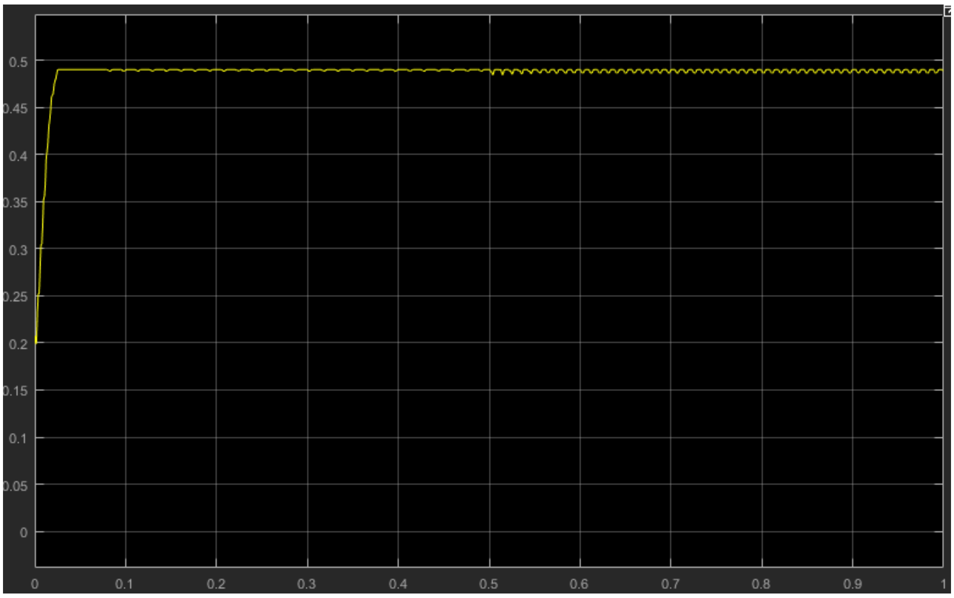

Figure 4.23: PID output

In Figure 4.21, the output voltage increases beacause of feedback loop response. After 0.5 seconds, additional parallel resistor removed from circuit. In Figure 4.22, it can be clearly seen error decreses because of output voltage. In Figure 4.23 PID output increases until the error become zero.

4.2 Efficiency Calculations

Efficiency is dependent to more than one parameters. Power loss on passive components, semiconductors, connectors, pcb ways, operating temperature, humidity and more parameters affect the efficiency. To keep efficiency highest, these all parameters should be cared by designer. Calculations should be done carefully.

The efficiency of the z-source dc to dc converter can be found by dividing the output power to the input power.

$$\eta = {Pout}/{Pin} \tag{3.27}$$

The output power can be calculated by multiplying the average input voltage to average input current. Average input current is the sum of average z source capacitor current and average z source inductor current. But the z source capacitor current is zero because of total current time area. It can be seen in Figure 4.13. As a result, the average input current is equal to average z source inductor current. The same situation is valid for output power. The average output current is equal to sum of the average output filter inductor current and average output filter capacitor current. But the average output filter capacitor current is zero. Thus, the average output current is equal to average output filter inductor current. As a result, the final equations and calculations has been shown.

$$Pin = I_{Lz} * Vin \tag{3.28}$$

$$Pout = I_{Lo} * Vo \tag{3.29}$$

Pin= 40.625 * 12= 487.5 W

Pout= 1.59 * 200= 318 W

The efficiency is;

$\eta = {318}/{487.5} = 0.65 = 65\%$

And the power dissipation can be calculated as;

Pdiss= Pin-Pout= 487.5-318= 169.5 W

CHAPTER 5
CONCLUSION AND FUTURE WORK

5.1 Conclusion

As a conclusion, objectives of thesis have been achieved. In explanation section, importance of high gain has been described. Also, different high gain voltage boost techniques and topologies have been described one by one. Comparison of converters have been done. Z-source dc to dc converter advantages have been explained. It shows that the z source converter has specific features. These specific features make z source ahead of other topologies.

In design of converter section, all mathematical equations has been shown and all mathematical calculations have been achieved. The components sizes have been obtained. It clearly shows that the z-source inductor and capacitor requirement is low. The voltage gain of the design is 16.6. This is very high gain. Low voltage can be boosted up to 200-250 volts when the duty cycle approach to 0.5. Also, converter can be used as a buck mode. But this high voltage creates high voltage stress on components. As a result of voltage stress on components, the power loss or power dissipation achive.

In simulation section, all graphs and waveforms have been obtained; obviously the calculated parameters and outcome of simulations conform with each other. The waveform obtained as a result in simulation part, was explained in the description section. The efficiency calculation has been calculated as 65%. This efficiency can be interpreted as a not high. But actually, its high for this type conversion. Because the circuit boosts the voltage from 12 to 200. It means the efficiency decreases due to high gain and losses. If the output voltage decreases, the efficiency will be increased but the gain will be decreased.

5.2 Future Work

Because of the increasement of the demand to renewable energy or DC electricity, dc to dc converters become more popular recent years. It means that the applications will need more efficient and higher gain converters. There are a lot of parameters to affect the appropriate topology. Size, cost, losses, efficiency, gain, reliabilty, durability are some of them. Z source has a potential to find most appropriate parameters. To keep working on z source topology, will improve and develope all parameters.

In terms of capability of this topology, the research can be expanded. There are several z-source based converter and inverter types. All of these converters have advantages by itself. The future works can tend to increase efficiency and reduce the voltage stress on components to prevent power losses. This improvements make the z source very special.

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