ANALYSIS AND SIMULATION OF ZVZCSBUCK-BOOST CONVERTER

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

By
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ABSTRACT

For last decades, the demand of power electronic converters in renewable energy applications has witnessed a dramatic increase. Power electronic-converters are used in such applications as an interface between the source and loads. Despite their suitability, hard switching used in vast majority of these converters tend to limit their performance because of the excessive losses. To handle these issues soft switching methods in which switching transitions are delayed and take place only at zero voltage (ZVS) or zero current (ZCS) was employed. By using soft switching these issues are significantly minimized and the applicability of converters has been extended. In this thesis, analysis and simulation of zero-voltage-zero-current switching (ZVZCS) based dc/dc buck-boost converter is presented. The major target is to investigate the problems and challenges imposed on dc/dc converters by hard switching and the difficulties with regards to implementation of soft switching in dc/dc converters.

Keywords:Dc-dc converter; hard switching; soft switching, ZCS; ZVS; ZVZCS

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To my family…

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For last decades, the demand of power electronicconverters in renewableenergy applications has witnessed a dramatic increase. Power electronic-converters are used in such applications as an interface between the source and loads. Despite their suitability, hard switching used in vast majority of these converters tend to limit their performance because of the excessive losses. To handle these issues soft switching methods in which switching transitions are delayed and take place only at zero voltage (ZVS) or zero current (ZCS) was employed. By using soft switching these issues are significantly minimized and the applicability of converters has been extended. In this thesis, analysis and simulation of zero-voltage-zero-current switching (ZVZCS) based dc/dc buck-boost converter is presented. The major target is to investigate the problems and challenges imposed on dc/dc converters by hard switching and the difficulties with regards to implementation of soft switching in dc/dc converters.

Keywords:Dc-dc converter;hard switching; soft switching, ZCS;ZVS;ZVZCS

ÖZET

On yıldan fazla bir süredir, yenilenebilir enerji uygulamalarında güç elektroniği dönüştürücülerine olan talep çarpıcı bir artışa şahit olmuştur.Güç elektroniği dönüştürücüleri, kaynak ve yükler arasındaki arayüz gibi uygulamalarda kullanılır.Uygunluklarına rağmen, bu dönüştürücülerin büyük çoğunluğunda kullanılan sert anahtarlama, aşırı kayıplardan dolayı yeteneklerini sınırlama eğilimindedir.Bu sorunları ele almak için anahtarlama geçişlerinin geciktirildiği ve sadece sıfır gerilimde (ZVS) veya sıfır akımda (ZCS) gerçekleştiği yumuşak anahtarlama yöntemleri kullanılmıştır.Yumuşak anahtarlama kullanarak bu konular önemli ölçüde en aza indirilir ve dönüştürücülerin uygulanabilirliği genişletilir.Bu tez çalışmasında, sıfır gerilim-sıfır akım anahtarlama (ZVZCS) bazlı dc-dc bock-boost konvertörünün analizi ve simülasyonu sunulmuştur.Başlıca hedef, dc-dc dönüştürücülere getirilen sorunları ve zorlukları sert anahtarlama ile ve dc-dc dönüştürücülerdeki yumuşak anahtarlamanın uygulanmasındaki zorlukları araştırmaktır.

Anahtar Kelimeler:DC / DC çevirici; sert anahtarlama; yumuşak anahtarlama, ZCS; ZVS; ZVZCS

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LIST OF ABBREVIATIONS

AC: Alternating Current

BJT: Bipolar Junctions Transistor

DC: Direct Current

EMI: Electromagnetic Interference

IGBT: Insulated Gate Bipolar Transistor

MOSFET: Metal Oxide Silicon Field Effect Transistor

MRC: Multi-Resonant Converters

QRC: Quasi-Resonant Converters

PSCAD: Power System Computer Aided Design

ZVZCS: Zero Voltage Zero Current Switching

CHAPTER 1

INTRODUCTION

1.1 Introduction

The main function of power electronics devices is to condition electrical power taken from a power source to the form suitable for user loads. Hence, power electronics converters serve as interface between user loads and the source. The converters are classified into ac-ac, ac-dc, dc-ac and dc-dc converters. The classification is based on nature of the input source and output load. For instance, a dc-dc converter is used to connect a dc input source to a dc load.

Power electronic converter circuits are generally composed of energy storing components such as capacitors and inductors, control devices and semiconductor elements like diodes and transistors. The semiconductor devices such as Bipolar Junctions Transistors (BJTs), Insulated Gate Bipolar Transistors (IGBTs) and Metal Oxide Silicon Field Effect Transistors (MOSFETs) are used as switches (Mousavi, 2013).

DC-DC converter, converts DC voltage from one level to another. The most common topologies are the buck, boost, buck-boost and Sepic converters. A buck converter steps down a voltage, producing a voltage lower than the input voltage. On the hand, boost converter steps up a voltage, producing a voltage higher than the input voltage. A buck-boost converter steps a voltage up or down, producing a voltage equal to or higher or lower than the input voltage. A Sepic converter is used for similar applications as the buck-boost, but provides some advantages in some applications (Maker.io, 2016).

Many electronic equipment such as, servo-motor drives, computer periphery power supplies, high-intensity-discharge (HID) lamps for automobile headlamps X-ray power generators, the dc back-up energy system for an uninterruptible power supply (UPS), and fuel cells required dc–dc converters with a high step-up voltage ratio (Zhao & Lee, 2003).

1.2 Hard Switching

Energy losses are in evitable in real semiconductor devices and therefore the switches used in converters produces power losses. These losses include switching losses and conduction losses. In practical converters, during switching (turn-off and turn-on) the switch current and voltage do not go to zero immediately. The current through the switch and the voltage become high simultaneously for some time within the switching process (turn-off and turn-on). This result in a power loss which is equivalent to overlapping area of the switch current and voltage waveforms at the time of turn-off or turn-on. Switching the power electronic converters with these power losses is referred to as “hard switching”. Fig. 1.1 demonstrate the graph of switch gate, voltage and current within a switching cycle.

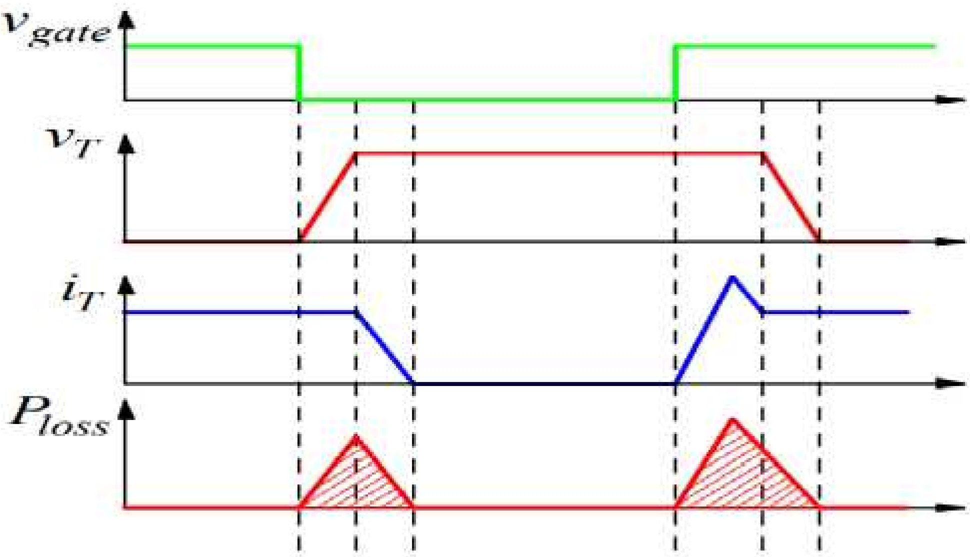


Figure 1.1: Loss of Power during hard switching(Mousavi, 2013)

1.3 Soft-switching

By using soft switching techniques, the issues of switching losses due to hard-switching in classical converter operation can be solved. In power electronics soft-switching is considered as set of techniques by which switching processes are controlled and made to be gradual so that either the current or voltage are zero during the switching. This means that switching transitions take place when the device current or voltage is zero in soft-switching.

There are two types of soft-switching: zero current switching (ZCS) and zero voltage switching (ZVS). In zero voltage switching, the switch voltage is forced to zero before applying the gate voltage during turn-on. Whereas, in zero current switching, the switch current is forced to zero during turn-off before removing the gate voltage. By proper use of soft-switching, switching losses, switch stress, and electromagnetic interference (EMI) are significantly reduced (Al-Saffar, Ismail, & Sabzali, 2013). Electromagnetic interference is decreased by soft-switching since the sudden switching transitions (from off-to-on and on-to-off) are avoided, the transitions are made gradually. On the other hand, switching losses and stress are decreased because the power loss during the switching transition is proportional to the overlap between the current passing through the switch and the voltage across it. In soft-switching, transitions take place when the device current or voltage is zero, hence, the overlap between current and voltage is eliminated and therefore, no switching losses.

1.4 Problem Statements

In recent years, renewable energy utilization has grown dramatically. However, the utilization of such energy sources is constrained by the interfacing devices required to conditioned power from these sources and make it suitable for user loads. For instant, fuel cells which is one of the promising renewable energy sources has problem of slow response to load dynamics. Therefore, the interfacing device should have the ability to respond very well to the load demand with excellent dynamic performance, low EMI and high efficiency. DC–DC converters and inverters have been designed and used for interfacing fuel cells with the load (Ellabban & Abu-Rub, 2016; Jurado, 2005; Peng, 2003; Tekin, Hissel, Péra, & Kauffmann, 2007; Tuckey & Krase, 2002; Vinnikov & Roasto, 2011). However, power loses and stresses with EMI limits their practical applications. This and many other demands make the design of soft switched dc-dc converters open and interesting challenge to power electronics industries and researchers.

Designing a soft switched dc-dc converter impose so much difficulties considering the nature of the input voltage (dc). However, soft switching is possible by adding auxiliary circuit consisting of resonant elements, passive and active components and switches to a basic dc-dc converter. The auxiliary circuit is added to create a proper current and voltage conditions in the circuit (Forrai, Funato, Yanagita, & Kato, 2005). Although resonant elements help to force the current/voltage of a switch to zero prior to a switching transition they introduce high-current/voltage stresses in the switch.

Many soft-switched converters have been discussed in the literature to address the additional stresses imposed by the auxiliary circuits. For instance, the resonant capacitor is bypassed for a given time interval by using active switch, the output voltage can be regulated and controlled (Wai, Duan, Lee, & Liu, 2005). Another method is by controlling the resonance period, the output is regulated by using the controllable period called “extended-period” (Barbi, Julio, Denizar, & Martins, 1990). In doing so, both the converters achieved lossless transition with simple PWM control. However, the main switch in both the converters suffers from capacitive turn-on loss. To further address this issues (Divakar, Cheng, & Sutanto, 2009) presents a new buck-boost converter that provides zero-voltage turn-on and zero current turn-off which is better than pure ZVS or ZCS converter.

1.5 Objectives

The main objectives of the thesis are analysed and simulate a zero-voltage switching and zero current switching (ZVZCS) dc-dc buck-boost converter. To explore the challenges regarding the analysis of such converters and provide a simple means of their analysis and evaluation. The objectives are subdivided into the following steps:

i. ZVZCS dc-dc converter circuit description and operation

ii. Steady state analysis of the converter circuit with associated waveforms and equivalent circuits

iii. Simulation of the converter using PSCAD software

1.6 Organization

The thesis consists of four chapters organized as follows:

Chapter 1: This chapter gives a general introduction on the thesis topic including the problem statement and objectives.

Chapter 2: Provides a comprehensive review on conventional and soft-switching converters proposed in the literature.

Chapter 3: Presents ZVZCS circuit design, steady state analysis and simulation results.

Chapter 4: Conclusion and recommendation

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The implementation of converter circuits always contains switching devices. These switching devices are turn-on and turn-off during the power conversion. To achieve good result and optimal size for the converter components such as capacitors, inductors and transformer, the switching-frequency must be high. However, the switching at high rate result in high power losses (because of high losses associated with the switching process) and affect the converter efficiency.

The power losses resulting from the switching process occur as the result of an overlap between the switch-current and switch-voltage at the time of switching transition (from on-off and vice vasa). Theoretically speaking, this power losses can be eliminated by avoiding the overlap, which can be achieved by making sure that either the switch's current or the switch's voltage is zero at the time of the transition. In power electronics, the methods that are used to realize these switching conditions are known as "soft-switching techniques".

Over the past years, several methods of soft switching had been introduced and applied in dc/dc converters as can be seen in literature. Numerous advantages have been recorded in power electronics by the use of soft switching strategies in dc/dc converters. Among the advantages are; minimizing power losses in the switch, reducing "electromagnetic interference (EMI)" and converter volume as well as increasing the power density.

In this chapter, a brief review of some of the existing soft-switching-based dc/dc converters is presented. The chapter begins by defining the type of switches often used in dc/dc converters, followed by explanation of the major type of losses in semi-conductor switches. The chapter also explain in detail the concept of hard switching and soft switching in converters before finally enumerating examples of dc/dc converters where soft switching strategies are used. Integration of soft switching in Z-network based converters is also briefly discussed. Finally, a number of applications involving the use of soft-switching-based converters with their merits and demerits is also explore.

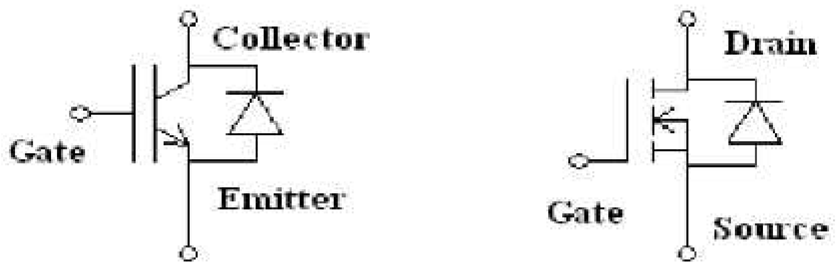
2.2 Semiconductor Switches in Power Electronics Converters

In power electronic converter design, semiconductor elements such as “Bipolar Junctions Transistors (BJTs), Insulated Gate Bipolar Transistors (IGBTs) and Metal Oxide Silicon Field Effect Transistors (MOSFETs)” are used as switches (Mousavi, 2013).

BJTs are current controlled elements, and were popularly used in switch-mode power supplies around 1980. However, because the switching of SMPS requires high frequency, they are not used anymore. MOSFETs are charge controlled elements, and operates faster compared to BJTs. When turned on, BJT behave as a voltage source (equal to its collector-emitter saturation voltage ($V_{C,S}$)), whereas MOSFET behaves as resistance when switched-on (equivalent to its source-drain resistance (R_D)). Losses in MOSFETs are directly proportional to square of their conducting current, while BJT losses proportional to the current it is conducting.

The IGBTs are behaves as hybrid, combining MOSFET and BJT. It’s switch-on is similar to MOSFET and their switch-off is similar to BJTs. However, they are slower compared to BJTs and faster in comparison to MOSFETs. Compared with MOSFETs, IGBTs have lower operating frequency but higher current and voltage ratings, therefore it is suitable in applications requiring high power.

In power electronics applications MOSFETs and IGBTs are more popular than BJTs. They have been used in AC-motor drives, dc-dc converters, inverters, to achieve high efficiency and high frequency. Figure 2.1 (a) and 2.1 (b) show the circuit diagram IGBT and MOSFET switches respectively.



(a) IGBT (b) MOSFET

Figure 2.1: Semiconductor switches (Mohammed Dobi, Sahid, & Sutikno, 2019)

2.3 Hard-switching Techniques

Hard switching in classical converters also leads to a number of losses and damages including higher voltage stress and electromagnetic interference (EMI). During the switch transition from on-to-of and vice vasa, in converters, the switch current and voltage do not go to zero immediately. The current through the switch and the voltage become high simultaneously for some time interval. This result in a power loss which is equivalent to overlapping area of the switch current and voltage waveforms at the time of turn-off or turn-on. Switching the power electronic converters with these power losses is referred to as "hard switching". Figure 2.2 demonstrate the graph of switch gate, voltage and current within a switching cycle.

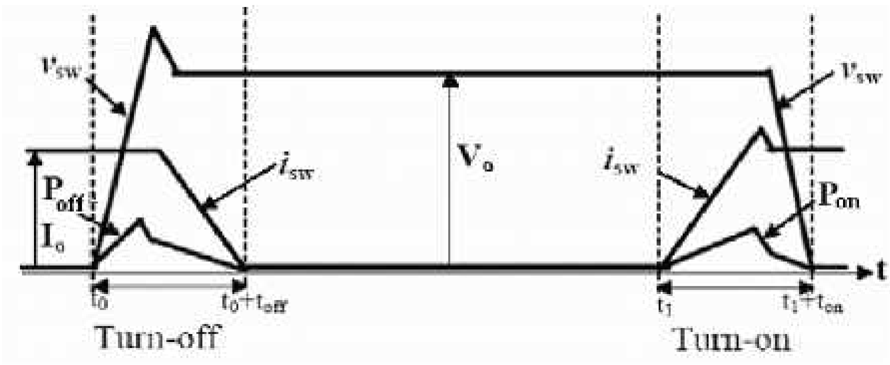


Figure 2.2: Loss of Power during hard switching (Steigerwald, 2002)

2.4 Soft-switching Techniques

In power electronics soft-switching is considered as set of techniques by which switching processes are controlled and made to be gradual so that either the current or voltage are zero during the switching. This means that switching transitions take place when the device current or voltage is zero in soft-switching. There are two types of soft-switching: zero current switching (ZCS) and zero voltage switching (ZVS). In zero voltage switching, the switch voltage is forced to zero before applying the gate voltage during turn-on. Whereas, in zero current switching, the switch current is forced to zero during turn-off before removing the gate voltage. By proper use of soft-switching, switching losses, switch stress, and electromagnetic interference (EMI) are significantly reduced (Al-Saffar et al., 2013). Electromagnetic interference is decreased by soft-switching since the sudden switching transitions (from off-to-on and on-to-off) are avoided, the transitions are made gradually. On the other hand, switching losses and stress are decreased because the power loss during the switching transition is proportional to the overlap between the current passing through the switch and the voltage across it. In soft-switching, transitions take place when the device current or voltage is zero, hence, the overlap between current and voltage is eliminated and therefore, no switching losses.

2.4.1 Zero-current Switching

Zero current switching (ZCS) can be explain by using the waveforms in figure 2.3. MOSFET switch is used, however the same explanation holds for IGBTs. As can be seen from the figure, an inductor is connected in series with the switching device in order to make the drain-voltage $V_d$zero before the device current rises at turn on. As the result the switching loss is kept minimum at turn on.

Furthermore, at the time of turn off, voltage across the drain/source is reversed and brought to zero using additional circuitry (such as resonant circuit). At the time of current reversal, the switch gate is turn-off in order to make sure that the device is off at the time the voltage is re-applied. In this way the switch off losses are eliminated [1,2]. For practical applications:

i. To avoid re-triggering in case of GTO and minimize electro-magnetic interference (EMI), the rate at which the voltage($d\ \ /d\ \ $)is applied has to be limited.
ii. The time interval for which the diode current is reversed should be enough to permit the recombination of the device charges is case of BJTs.

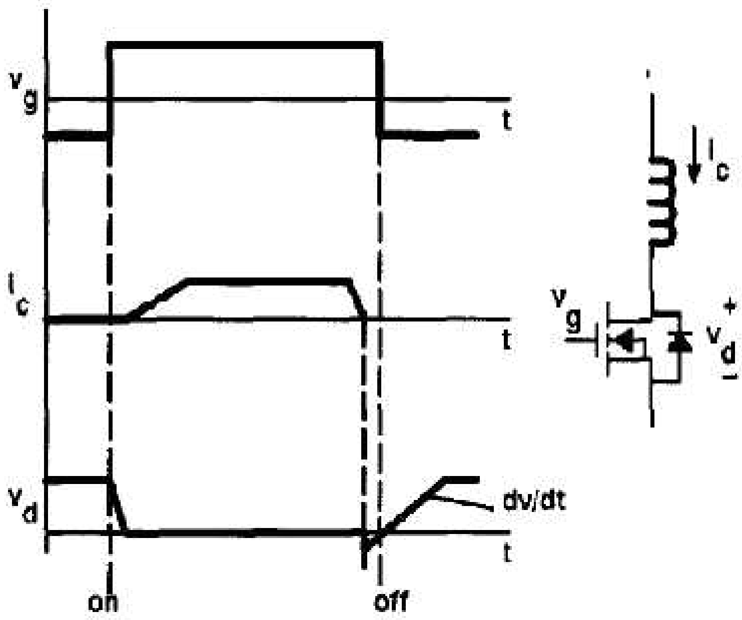


Figure 2.3: Zero-current Switching (Steigerwald, 2002)

2.4.2 Zero-voltage Switching (ZVS)

To explain the zero-voltage-switching (ZVS) condition we use figure 2.4. As can be seen from the figure, a capacitor is used in parallel with the switching device in order to make sure the turn on losses are kept minimum.

Both ZVS and ZCS may be used in applications with low switching frequency and high-power. However, for applications where the switching rate is high ZVS based converters are preferred. Furthermore, ZVS based dc/dc converters are easier to control compared to ZCS based. Classical dc/dc converter topologies can be operated with ZVS by incorporating very few elements.

The selection of the soft switching technique (ZVS or ZCS) is done by considering the type of switch in the circuit, required size, switching-frequency and complexity of the control technique.

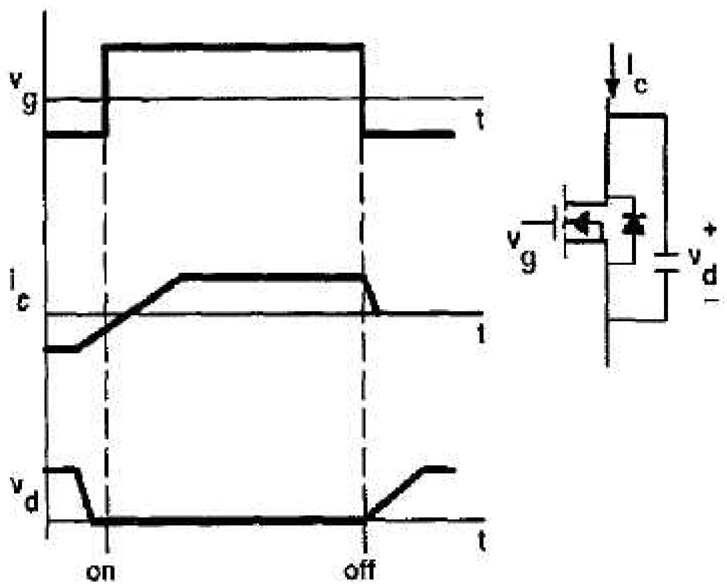


Figure 2.4: Zero-voltage switching (Steigerwald, 2002)

2.5 Classification of Soft-Switching Converters

The soft switching converters considered for this review are categorized as shown in figure 2.5. They categorized in to resonant, zero voltage switching (ZVS), zero current switching (ZCS) and ZVZCS based converters.

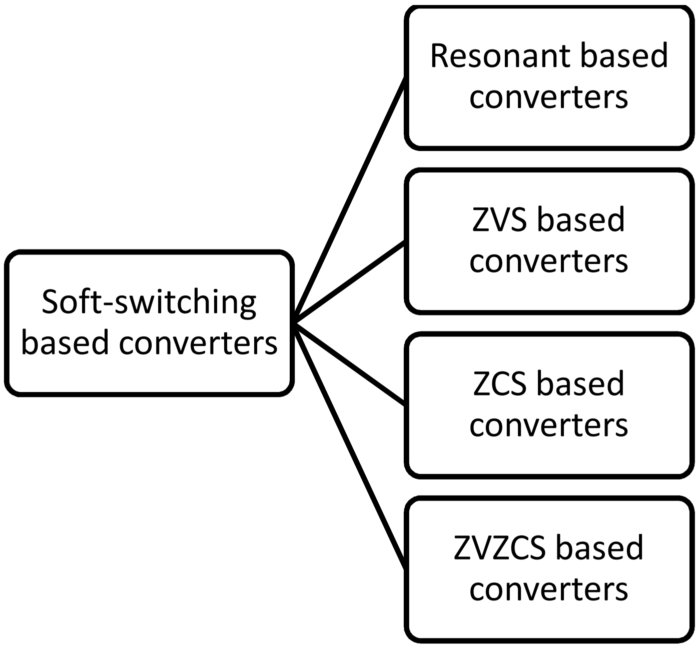


Figure 2.5: Classification

2.5.1 Resonant Converter topologies

One of the techniques used to create soft switching in classical PWM converter topologies is by adding resonant circuit in hard switching topologies. When resonant circuit is combined with classical PWM converter topologies the resultant structure is referred as "resonant converter". Resonant converters therefore possess the important characteristics of classical converters and resonant based converters.

In this section three category of resonant converters are considered. These classifications are by considering the number of resonant elements used in the circuit, their location (switch/load side) and switching technique (ZCS/ZVS). This is shown in figure 2.6.

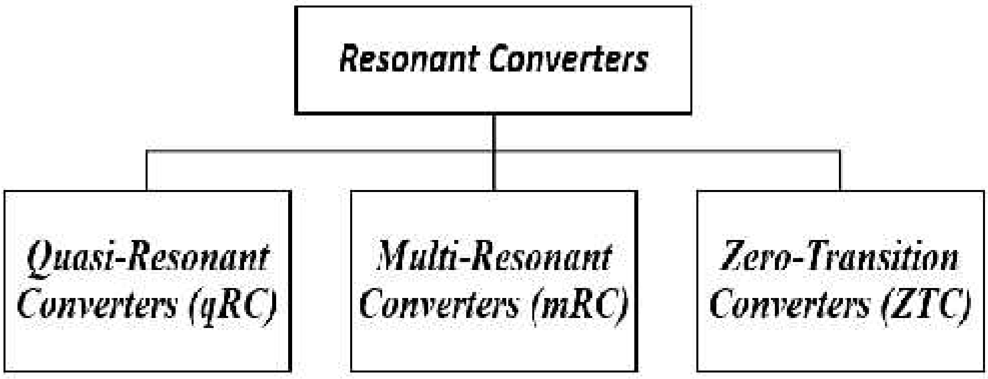


Figure 2.6: Resonant converters

2.5.1.1 Quasi-Resonant Techniques Based Converters (qRTC)

This category of resonant-converters are made by using just two additional resonant elements; a resonant capacitor C_r and resonant inductor L_r. These complementary elements are used in order to realize "zero-voltage switching (ZVS) or zero-current switching (ZCS) or zero voltage transition (ZVT) or zero-current transition (ZCT)". Considering the application and specific target of the converter and other specifications, the resonant elements may be arranged in cascade or parallel or combination (cascade-parallel). Moreover, they may be located at the switch side or the load side (Abu-qahouq & Batarseh, 2000).

In figure 2.7 a quasi-resonant based converter is shown in which a capacitor is connected in parallel with main-switch so as to obtained zero-voltage switching. On the other hand, as shown in figure 2.8 two inductors are used in cascade with the two switches in the converter, in this case zero-current-switching can also be obtained.

The main advantage of this resonant converters is that their structure is simple which make their design, implementation and control so easy, also there is very low current-stress on the switches. Nevertheless, with this configuration it’s not possible to achieve soft switching for both the diode and the switch at the same time. In addition, for some topologies in this category (qR-ZVS) there is too much voltage stress on the switch which limits their applications to only applications with small power requirements.

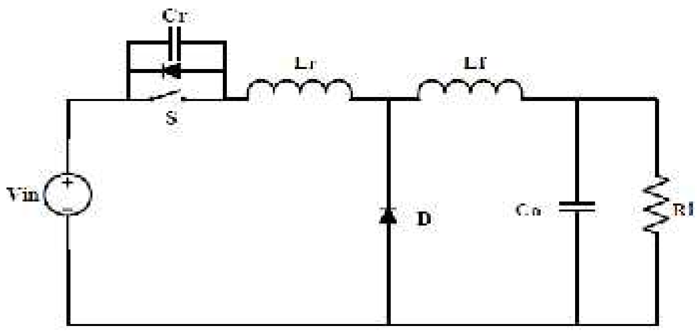


Figure 2.7: qR-ZVS converters (Abu-qahouq & Batarseh, 2000)

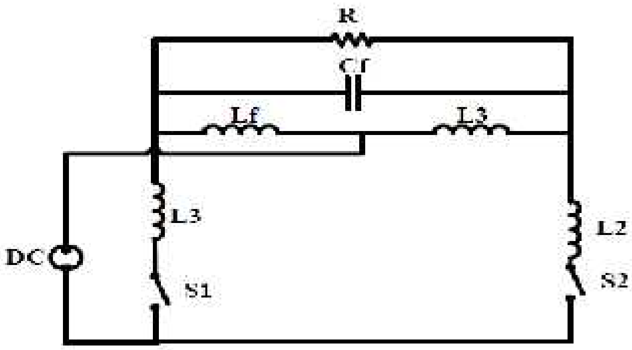


Figure 2.8: qR-ZCS converter (T. S. Wu, Bellar, Tchamdjsu, Mahdavi, & Ehsani, 1996)

2.5.1.2 Multi Resonant Techniques Based Converters (MRTC)

In multi resonant techniques the quasi resonant technique is improved by using two inductive elements instead of just one. Figure 2.9 shows an example of this type of converter, where two inductive elements L_m and L_s are used along with a capacitor C_s.

With the additional inductive element in this topology it's possible to achieve soft switching (ZCS/ZVS) for both the diode and the switch at the same time. Because of their ability to perform simultaneous soft switching on the diode and switch they are often referred "double zero current switching (double-ZCS) or double zero voltage switching (double-ZVS)". Since the semiconductor components are all operated under ZVS, there is significant reduction in switching-losses and circuit's noise.

However, there is increase in conduction-losses because of increasing current. In this topology there is higher current/voltage stresses. It is suitable for applications with high frequency requirements. More examples on this category can be found in (Converters, Zhang, Member, & Sen, 2003; Wang, Yang, Li, & Tu, 2018; Yang, Chen, Huang, & Chiou, 2017).

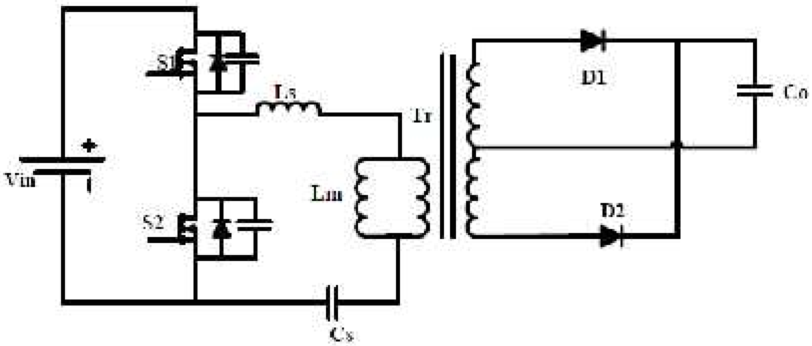


Figure 2.9: LLC-MRT based converters (Gu, Hang, Chen, & Du, 2004)

2.5.1.3 Zero Transition Based Resonant Converters (ZT-RC)

In this category of zero-transition based resonant converters, two resonant-tanks (L, C) are often employed with at least four resonant energy storing elements along with two additional switches. Two soft switching conditions are created; these converters can operate with zero current or zero voltage transitions (ZCT/ZVT). In the later, the aim is to make the switching transition of the main converter switch from off state to on state as at when the switch's voltage is zero, and the former is to make sure the main converter switch transit from on state to off state as at when the switch's current is zero. The converter circuit for ZVT and ZCT are shown in figure 2.10 and 2.11 respectively. More examples can be found from (Burak & Bodur, 2011; Martins, Russi, & Hey, 2005; Martins, RUSSI, PINHEIRO, & HEY, 2006).

The main disadvantages associated with this category are:

i. The two additional switches are mostly operated with hard-switching
ii. They have limitation on the voltage gain
iii. High current as well as voltage stresses
iv. High switching and conduction losses

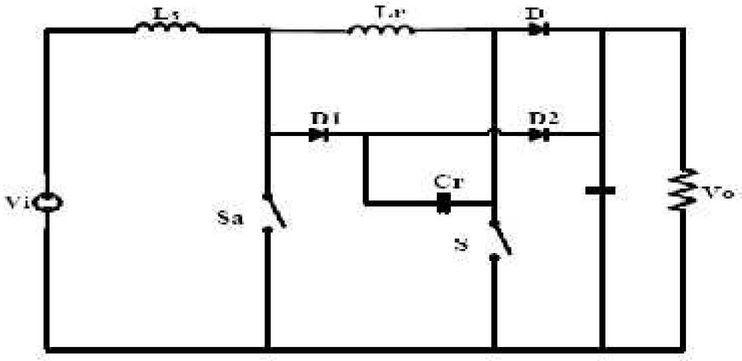


Figure 2.10: ZVT based resonant converter (Burak & Bodur, 2011)

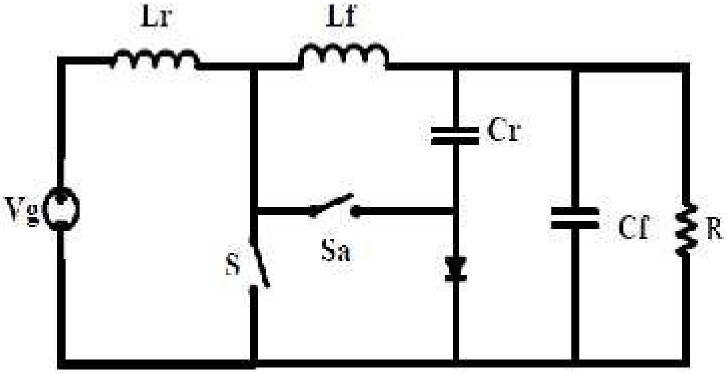


Figure 2.11: ZCT based resonant converter (Martins et al., 2005)

It is worthy to mention that for the vast majority of converters ZVS is only feasible within a certain range of switching voltage. Comparison between these three classes of resonance converters is presented in table 2.1. The comparison is made based on number of components count, stresses over the semiconductor elements and associated losses. It is evident from this table that quasi resonant based converters qRTC have the lowest number of additional elements while zero transition based resonant converters ZTRC. However, there is lower stresses and switching losses in the later compared to others. In addition, qRTC has the lowest conduction losses because of the limited current circulating in their circuit.

Table 2.1: Comparison between qRTC, MRTC and ZTRC (Martins et al., 2005)

Attributes	***qRTC***	***MRTC***	***ZTRC***
No. of capacitors	1	2 or1	1
No. of inductors	1	2 or 1	1
No. of complementary switches	0	0	2
No. of complementary elements	2	3	4
Current stress	low	moderate	low
Voltage stress	high	moderate	low
Switching losses	high	low	low
Conduction losses	low	high	high

2.5.2 ZVS Based Converter Topologies

As explained in the beginning of this chapter the basic concept behind zero voltage soft switching-based converters is that, the switching of the device is delayed and slowed down until the switch voltage is zero, meaning that the current rises only at the moments the switch voltage is made zero. by making the switch voltage zero. In ZVS-based converters switching-losses and capacitor turn on losses are minimized.

This soft switching method is has been widely used in isolated converter topologies to obtained both voltage-scaling and safety isolation (Corradini et al., 2011; Dc et al., 2017; Lin, Member, & Hsieh, 2007; Ma et al., 2009) and no isolated converter topologies (Cláudio & Duarte, 2002; Radmehr, Tahmasebi, & Yousefian, 2016). Figure 2.12, illustrates a basic single-ended type ZVS constant voltage (CV) converter.

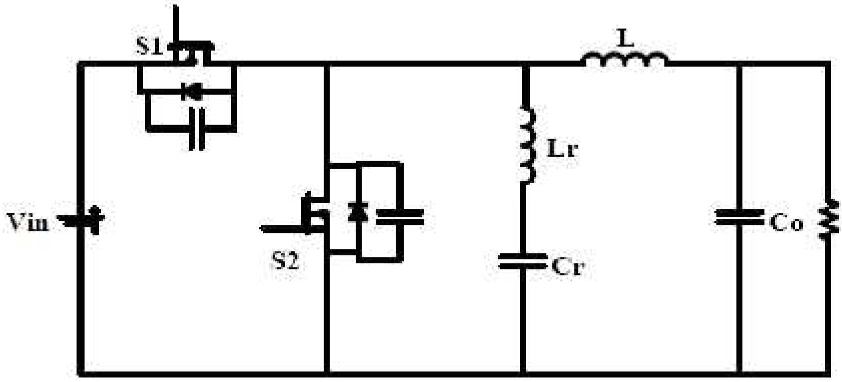


Figure 2.12: Basic single-ended type ZVS-CV converter (Mohammed Dobi et al., 2019)

ZVS has been applied in (Chandran, Mohan, & Alina, 2018) to manage the problem of high heat associated with classical diode-rectifiers in bridge less converter used for power-factor-correction (PFC). In this topology as shown in figure 2.13 this converter acts as a hybrid and work in PWM as well as resonant modes.

In this topology with efficient control strategies a unit power-factor is achieved. It uses no diode rectifier (hence bridge-less). Since there are no diode bridges the number of components is reduced and also the conduction losses are reduced. Furthermore, because of the fact that ZVS is used for the switches the losses related to switching is minimized.

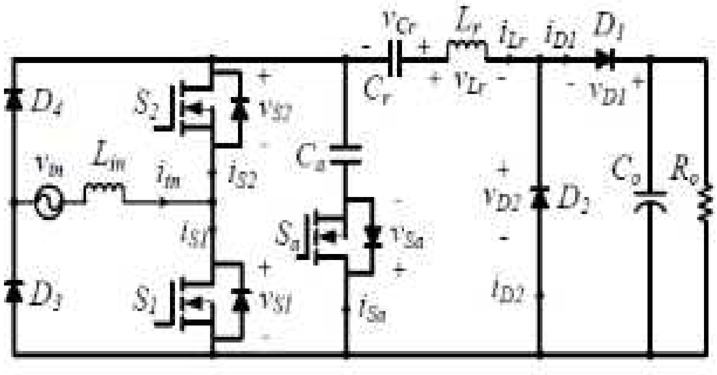


Figure 2.13: Bridgeless PFC boost converter (Chandran et al., 2018)

2.5.3 ZCS Based Converter Topologies

In ZCS method the switching device is turn off (rising the drain/source voltage to turn off state) drain-source voltage increase from zero to turn-off static value) as at when the current is confirmed to be zero. Because of this turn off switching-losses are minimized.

ZCS method help in removing the charges stored in the switch during turn off. Despite the reduction in switching-losses, there is an increase in conduction-losses because of the energy introduced by the series resonant-inductor used. In addition, this makes the switch and the diodes vulnerable to large current and voltage stresses

Compared to ZVS techniques, ZCS methods are more often used in "IGBTs" to handle the switching-losses especially for applications requiring low-frequencies and high power. ZCS based boost converter circuit with full diode bridge is shown in figure 2.14, and figure 2.15 illustrated similar circuit with auxiliary elements arranged in parallel. More examples can be found in (Cancelliere, Delli, ColliRoberto, Fabrizio, & Marignetti, 2007; Canesin & Barbi, 1997; Choi, Member, Cho, & Member, 2002; Mousavi, Das, & Moschopoulos, 2012).

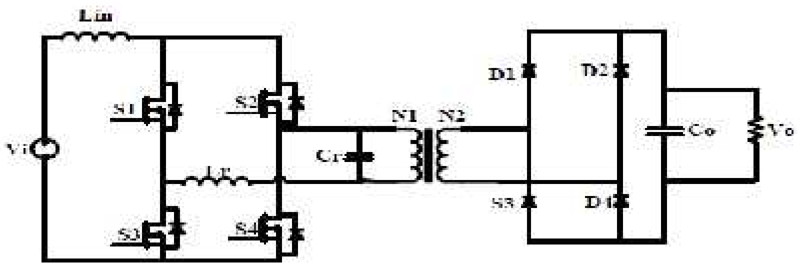


Figure 2.14: Resonant ZCS full-bridge converter (Mousavi et al., 2012)

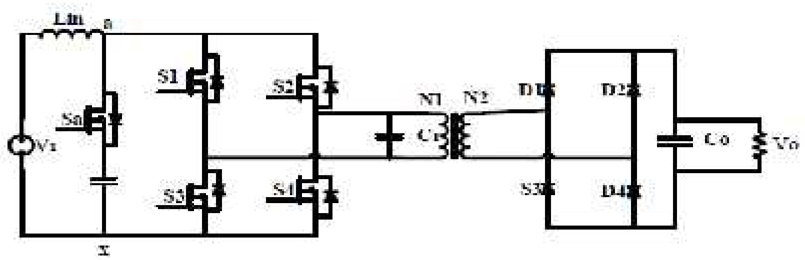


Figure 2.15: Resonant ZCS full-bridge converter with parallel elements (Mousavi et al., 2012)

2.5.4 ZVZCS Based Converters

Several converters have combined both ZVS and ZCS methods to form a technique also known as "ZVZCS soft switching". In such converters both the diode and main-switches are operated under ZVZCS at the same time.

In this technique, ZVS is employed all the semi-conductor components (both passive and active) at the time of turn on and turn off. While the additional components are operated under ZCS. Although they offer great advantage of reduced current and voltage stresses, these converters are not reliable if there is variation in operating frequency.

Figure 2.16 figure 2.17 depicted the circuit diagrams of ZVZCS based interleaved and isolated boost converters. More examples on both isolated and non-isolated may be obtained from ("A Soft-Switching Scheme for an Isolated D-DC Converter With Pulsating DC Output for a Three-Phase High-Frequency-Link PWM Converter," 2009; X. Wu, Xie, Zhao, Qian, & Zhao, 2008) and (Ashique & Salam, 2017; K.D, Daniel, & Unnikrishnan, 2017; Xinbo Ruan & Yangguang Yan, 2002) for isolated and non-isolated respectively.

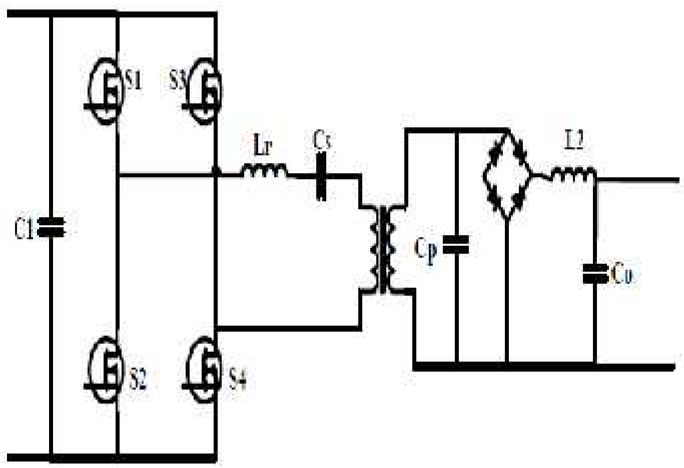


Figure 2.16: ZVZCS based isolated converter (X. Wu et al., 2008)

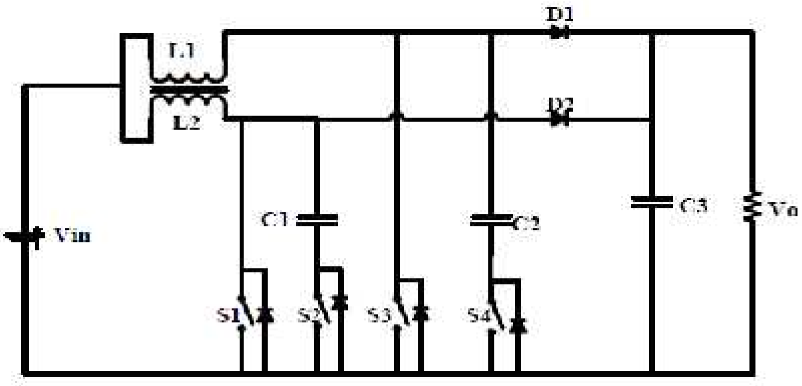


Figure 2.17: ZVZCS based interleaved boost Converter (K.D et al., 2017)

Ting and Nihan presented a ZVZCS based bridge-less boost-converter for PFC, the converter operates in continuous-current mode (CCM) and used a passive-snubber circuit to achieve the soft switching. In this topology, the main-switch is turn on using ZCS and turn off by ZVS with aid of the passive-snubber circuit. In addition, the main-diode is turn on with ZVS and turn off with ZCS.

The presented converter structure shows many advantages such as small component-count, large power-density, easy to control and less expensive. The control of the output-voltage and current by the power-factor correction converter is done over wider range of load and line. Because of these advantages this converter displays minimal harmonic-distortion and large power-factor (Ting & Nihan, 2017). The circuit diagram is illustrated in figure 2.18.

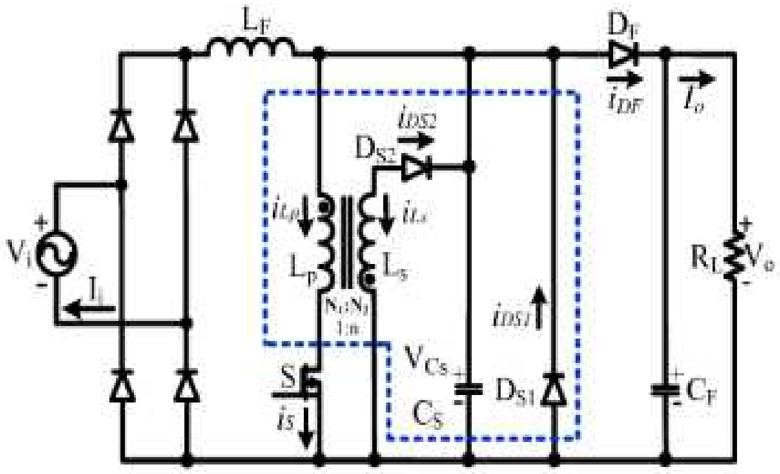
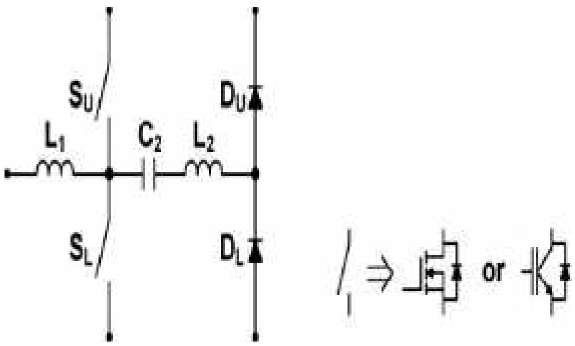
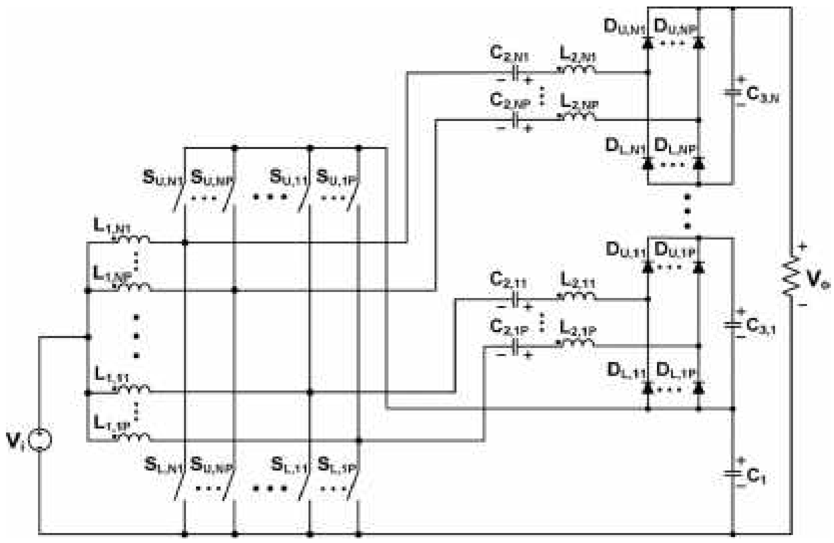


Figure 2.18: Soft-switching PFC boost-converter (Ting & Nihan, 2017)

Park et al proposes a multiphase dc-dc converter design by incorporating a soft-switching strategy, the new topology is convenient for applications where large output voltage and high power output are prerequisite (Park, Park, & Choi, 2011).The proposed converter is configured with proper numbers of series and parallel connected basic cells, so as to ensue high component attainability and simple heat distribution, which result in increased flexibility in device choice.



(a)



(b)

Figure 2.19: Soft switching based interleaved high step-up dc–dc converter(Park et al., 2011)

The static voltage gain of the new power circuit is (N+1) multiple of the static gain of ordinary step-up converter. Since reduced duty ratio leads to reduced current stresses on the components. This is a very desirable feature in high step-up applications, resulting in increased efficiency.

The propose converter offers a number of advantages including; soft-switching of switches in continuous conduction mode, minimizing stresses across diodes as well switches, small ripples as result of interleaving strategy, flexibility in voltage gain and output power.

2.6 Soft-switching in Half-bridge Converters

Soft-switching techniques are also employed in half-bridge inverters to enhance their performance and achieved a better result (Abe, Yamamoto, & Ninomiya, 2016; Guillaume, Viet, Paul, Jean, & Yves, 2006; Li, Zhao, Xu, & Zheng, 2018; Rustom, Wu, Qiu, &

Batarseh, 2002; Zhang, Thomsen, & Andersen, 2013). Figure 2.20 and 2.21 show soft-switched half-bridge converters with isolation transformer. The converter topology presented in (Guillaume et al., 2006), is used to interface a fuel cell to a user load. The ability of the converter to exhibit zero voltage and zero current switching makes it suitable and it solve the drawbacks of the classical. It gives benefits such as reduced losses, modularity and increased efficiency.

Similarly, in (Sullivan & Sanders, 1997) ZVS half-bridge converter with constant frequency is design and implemented. By using magnetic element square waveform is produced with which the output-voltage is can be controlled. The use of soft-switching couple with the square wave has greatly reduced the voltage stress across the semiconductor and improve efficiency. Both the main switch and the rectifier in the output are switch at zero voltage. The main switches (MOSFETs) are drive by a constant frequency at constant duty ratio, which makes the control relatively easy.

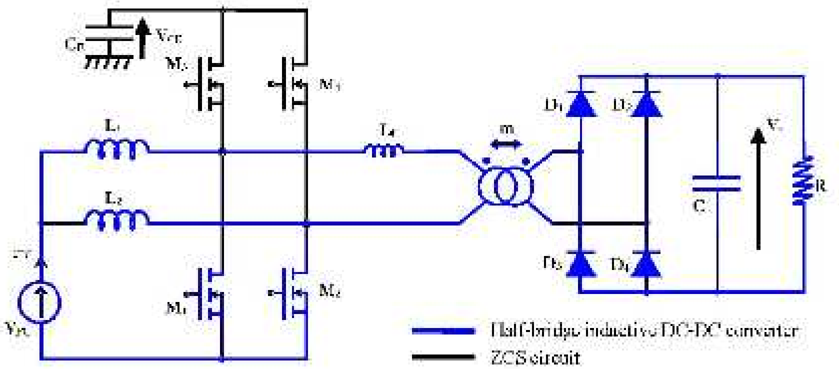


Figure 2.20:ZCS Half-bridge inductive(Guillaume et al., 2006)

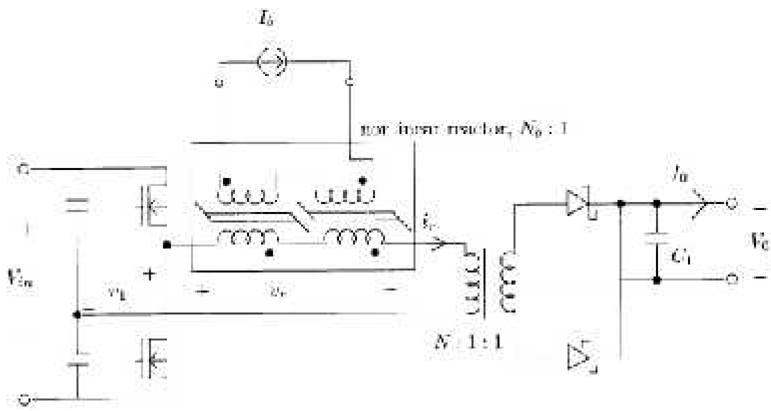
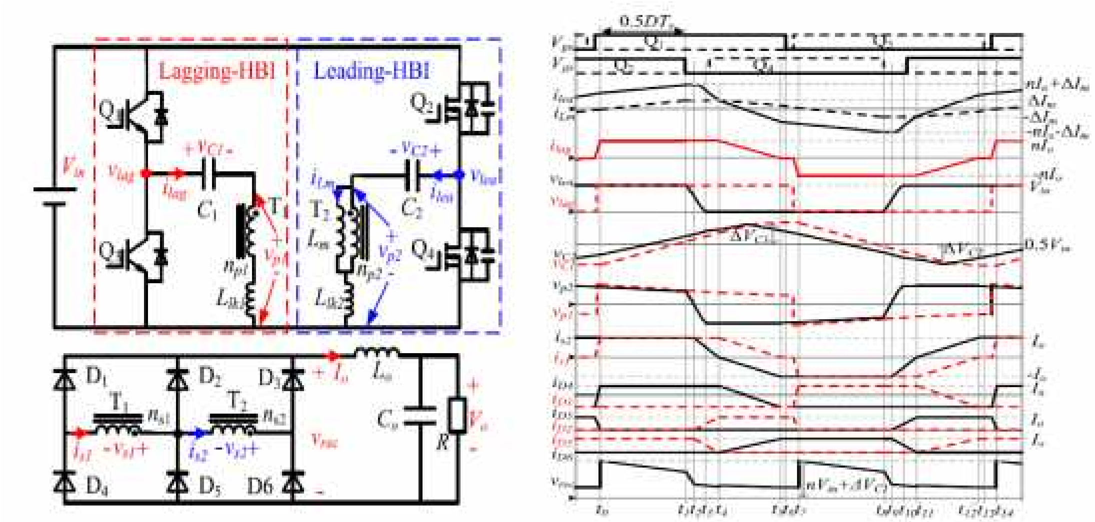


Figure 2.21: Soft-switched square-wave half-bridge dc-dc converter(Sullivan & Sanders, 1997)

In another article, soft-switch based half bridge resonant converter is presented and applied to operate a heating load, to achieve high efficiency. Similarly, the zero-voltage-switching (ZVS) is employed in the switching elements (Phankong, Chudjuarjeen, Bhumkittipich, & Hikihara, 2017). In (Li et al., 2018) dual half bridge converter with phase shift is presented and shown here in figure 2.22. It employs zero current switching for the switches in lagging leg and zero voltage switching for the switch in the lead leg. The capacitor is used to provide the zero current switching condition, while the zero voltage condition is provided by the combination of leakage and filter inductors. With this arrangement wider switching operation range is obtained.



(a) (b)

Figure 2.22: ZVZCS dual-half-bridge converter (a) Circuit (b) waveform(Li et al., 2018)

CHAPTER 3

CIRCUIT DESIGN, ANALYSIS AND SIMULATION RESULTS

3.1 Introduction

In this chapter the design, analysis and simulation of zero voltage and zero current switching (ZVZCS) buck-boost converter is presented.The chapter first described the converter circuit development. This is followed by the mathematical analysis of the converter circuit operating under steady state. The results obtained from the simulation conducted using PSCAD software is also presented.

3.2 ZVZCS Buck-boost Converter Circuit Design

The circuit shown in figure 3.1 depicted the ZVZCS buck-boost converter. This converter is proposed to achieved zero voltage and zero current switching (ZVZCS) in the main switch S_2. To realize that complementary devices are added to the conventional dc-dc buck-boost converter shown in figure 3.2.The complementary devices include diodes $D_3$and D_4, capacitors $C_1$and C_2, inductor $L_r$and switch S_1. The complementary switch S_1 is also desired to undergo ZVZCS to avoid extra switching losses. The complementary devices function as follows: (1) to provide ZVS switching $L_r$and C_1 are used to form a resonant tank, (2) $L_r$and D_3 provide a path to remove the charge across the main switch to ensure ZVS condition is achieved, and (3) to ensure ZVS at the time of turn-off, capacitor C_2 is connected inparallel across the main switch S_2.

In order to avoid current/voltage stress across the components following strategies are considered in the development of this converter topology.

1. Resonance is avoided between the resonant components L_r, $C_1$and C_2, while one of them is initially charged.
2. A path is created via diode D_3 for the inductor for L_r current, so as to discharge energy stored across switch S_1.
3. To ensure zero-capacitive losses during S_1 and S_2 turn-on, resonance is created between the three resonant elements L_r, $C_1$and C_2.

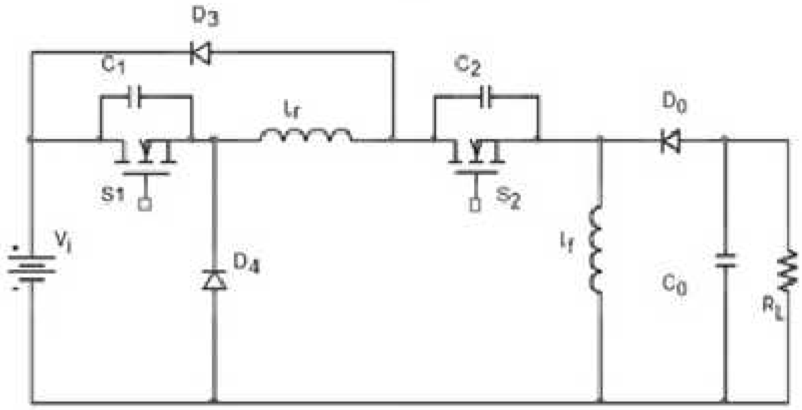


Figure 3.1:ZVZCS Buck-boost Converter Circuit

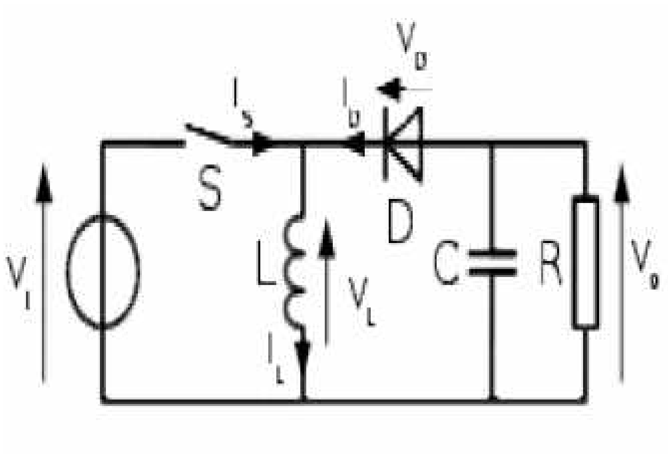


Figure 3.2: Classical DC-DC Buck-boost Converter Circuit

3.3 ZVZCS Buck-boost ConverterSteady-state Analysis

This section presents steady state analysis of the converter to establish the equation of the conversion ratio and other parameters relationships. For this purpose and for the sake of simplicity the filter inductor L_f is modelled as constant current sink, whereas the filter capacitor C_O along with the load R_L are modelled as constant voltage source respectively. Furthermore, following definitions are considered:

$$Z = \sqrt{\frac{L_r}{C_1}} \tag{3.1}$$

$$\omega_r = \frac{1}{\sqrt{L_r C_1}} \tag{3.2}$$

The converter operates in seventopological modes within one switching period. The switching waveform is shown in figure 3.3, with corresponding equivalents circuits explained in subsection below.

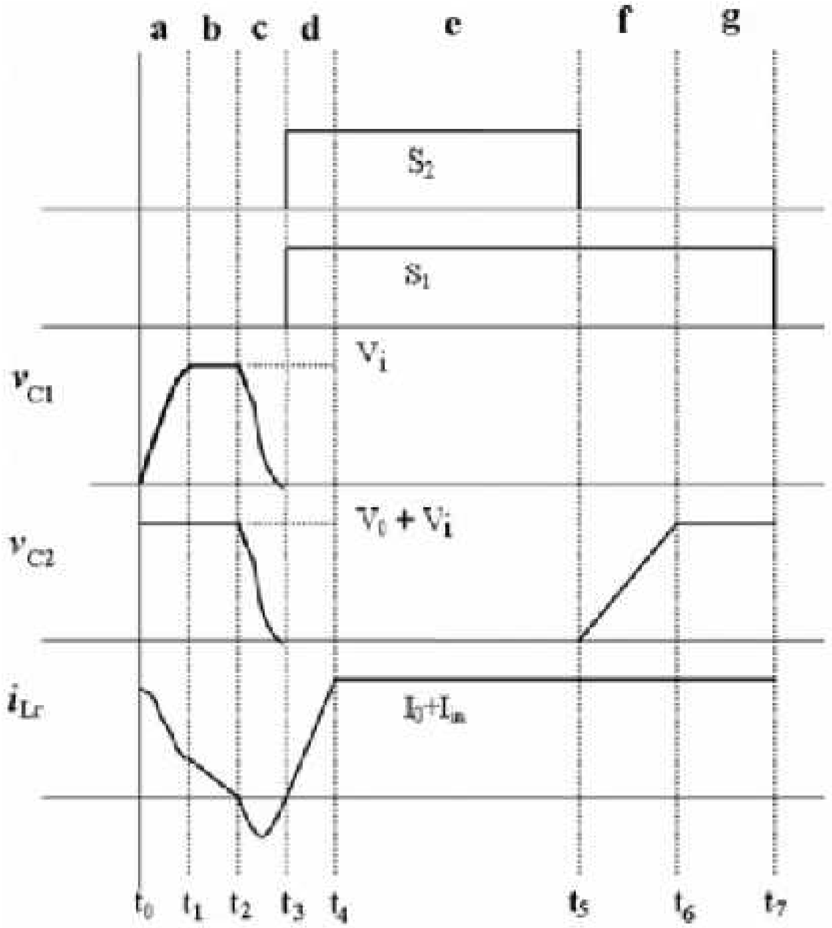


Figure 3.3:ZVZCS Converter Waveforms(Divakar et al., 2009)

Mode a: $t \in [t_0, t_1]$: The equivalent circuit for this mode is shown in figure 3.4, before this mode starts, diodes $D_0$and D_3, and switch S_1 are turn-on, the main switch S_2 is turn-off. While capacitor C_2 is charged to $(V_0 + V_i)$ as shown in figure 3.3. The inductor current i_{L_r} flows through $D_3$and S_1 . At the beginning of this mode S_1 is turn-off with ZVS and the capacitor C_1 charges from inductor L_r and therefore current i_{L_r}. Finally, D_4 conduct and clamp v_{C_1}at V_i, as shown in figure 3.3.

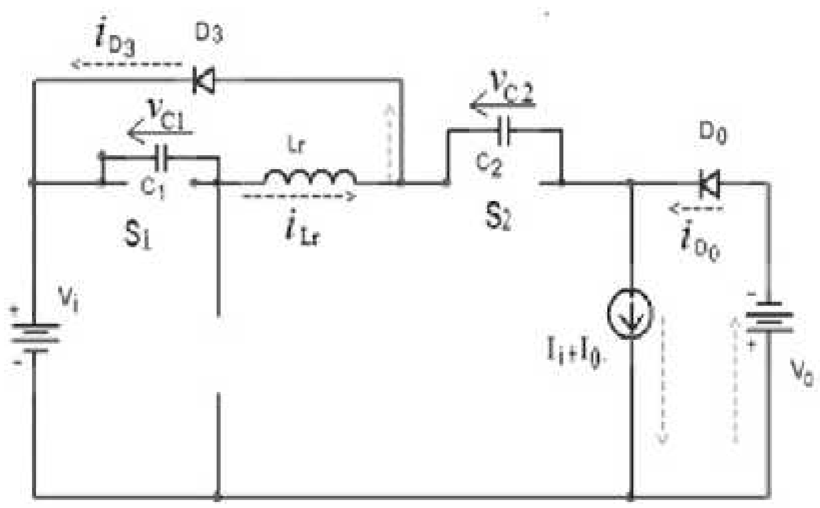


Figure 3.4: Converter Equivalent Circuit in Mode a

At time $t = t_C$, we have the following initial conditions:

$$v_{C2}(t_C) = V_i + V_o \tag{3.3}$$

$$v_{C1}(t_C) = 0 \tag{3.4}$$

$$i_{L_r}(t_C) = I_i + I_o \tag{3.5}$$

From the equivalent circuit figure 3.4, by applying KVL at $t > t_C$

$$v_{C_1} + v_{L_r} = 0$$

$$v_{C_1} = -v_{L_r} \tag{3.6}$$

$$v_{C_1} + L_r \frac{di_{L_r}}{d} = 0 \tag{3.7}$$

But,

$$i_{C_1} = i_{L_r} \tag{3.8}$$

By using (3.7) into (3.6), we get

$$v_{C_1} + L_r \frac{di_{C_1}}{d} = 0 \tag{3.9}$$

Substituting for $i_{C_1} = C_1 \frac{dv_{C_1}}{d}$ in to (3.8) and multiplying by $\frac{1}{L_r C_1}$, we have

$$\frac{d^2 v_{C_1}}{d\ ^2} + \frac{1}{L_1 C_1} v_{C_1} = 0 \qquad (3.10)$$

Which is a second order ODE with general solution of the form

$$v_{C_1} = A \quad \omega_r t + B \quad \omega_r t \qquad (3.11)$$

Solving (3.10) using the boundary conditions we get

$$v_{C_1} = (I_i + I_o) Z \quad \omega_r t \qquad (3.12)$$

Similarly,

$$i_{L_r}(t) = i_{C_1} = (I_i + I_o) c \quad \omega_r t \qquad (3.13)$$

And also, from the figure 3.4 using KCL

$$i_{D_o}(t) = (I_i + I_o) - i_{L_r}(t) \qquad (3.14)$$

Where Z and ω_r are as given in equations (3.1) and (3.2) respectively.

At the end of this mode

$$v_{C_1}(t_1) = V_i \qquad (3.15)$$

The final time for this mode t_1 is obtained by substituting (3.14) into (3.11);

$$(I_i + I_o) Z \quad \omega_r t_1 = V_i,$$

$$t_1 = \frac{s\ ^{-1} \propto}{\omega_r} \qquad (3.16)$$

With $\propto = \frac{V_i}{(I_i + I_o) Z}$

Mode b: $t \in [t_1, t_2]$: The equivalent circuit for this mode is shown in figure 3.5, when this mode starts the input voltage is charged by the inductor L_r through diodes D_3 and D_4. At the final stage of this mode diodes D_3 and D_4 are turned-off at ZCS and ZVS.

The key event that takes place during this mode is that inductor current i_L decreases to zero, as depicted in figure 3.3.

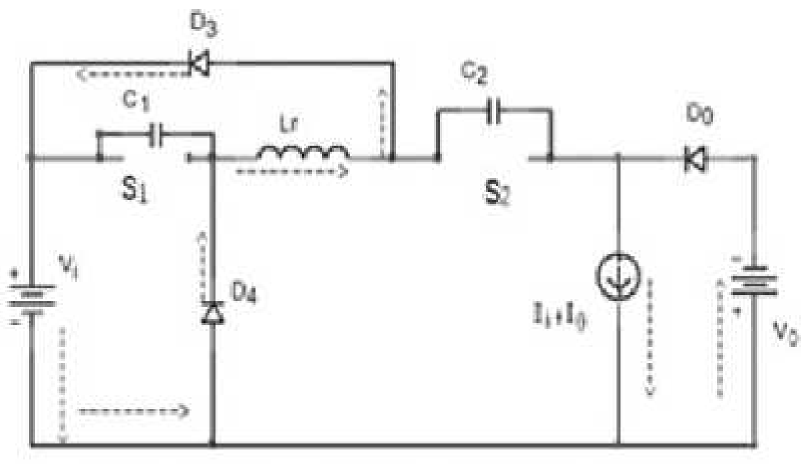


Figure 3.5: Converter Equivalent Circuit in Mode b

At time $t = t_1$, we have the following initial conditions:

$v_{C_1}(t_1) = V_i$

Using (3.6) and (3.15)

$$v_{L_r}(t_1) = -v_{C_1}(t_1) = -V_i \tag{3.17}$$

Using (3.13) and (3.16)

$$i_{L_r}(t_1) = (I_i + I_o)\cos \omega_r t_1$$

$$= (I_i + I_o)\cos \omega_r \left(\frac{\sin^{-1} \propto}{\omega_r}\right)$$

$$= (I_i + I_o)\cos (\sin^{-1} \propto)$$

Using trigonometric identity,

$$= (I_i + I_o)\sqrt{1 - \alpha^2} \tag{3.18}$$

At $t > t_1$ we have

$$L_r \frac{di_{L_r}}{d} = -V_i$$

$$i_{L_r}(t) = \int \frac{-V_i}{L_r} d$$

$$= \frac{-V_i}{L_r} t + i_{L_r}(t_1) \quad (3.19)$$

By applying KCL to the equivalent circuit

$$i_{D_0}(t) = I_i + I_o \quad (3.20)$$

At the end of this mode the inductor current is zero;

$$i_{L_r} = 0 \quad (3.21)$$

The final time for this mode t_2 is obtained by substituting (3.21) and (3.18) into (3.19) and solving for t_2;

$$i_{L_r}(t_2) = \frac{-V_i}{L_1} t_2 + (I_i + I_o)\sqrt{1 - \alpha^2} = 0,$$

$$t_2 = \frac{(I_i + I_o)L_1}{V_i} \sqrt{1 - \alpha^2} \quad (3.22)$$

Mode c: $t \in [t_2, t_3]$: The equivalent circuit for this mode is shown in figure 3.6, In this mode resonance take place making i_{L_r}, v_{C_1} and v_{C_2} go to zero simultaneously. This condition produces ZVS and ZCS to turn-on the switches $S_1$and S_2. Because the switches are switched on at zero voltage and current no capacitive turn-on loss is experienced around the switches.

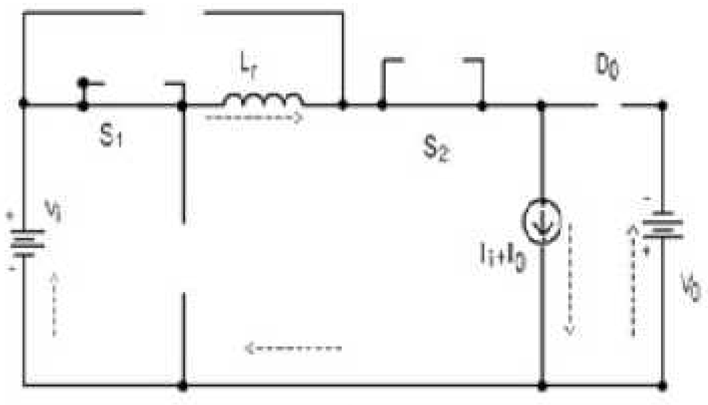


Figure 3.6: Converter Equivalent Circuit in Mode c

During this mode the equations for the voltages and currents are given as:

$$i_{L_r}(t) = \frac{V_i}{\sqrt{(2L_r/C)}} \sin \omega_c t \qquad (3.23)$$

$$v_{C_1}(t) = V_i(1 + \cos \omega_c t) \qquad (3.24)$$

$$v_{C_2}(t) = \frac{(V_0 + V_i)}{2}(1 + \cos \omega_c t) \qquad (3.25)$$

$$i_{D_0}(t) = (I_i + I_0) + i_{L_r} \qquad (3.26)$$

Where

$C = C_1 = C_2$, and

$$\omega_c = \frac{1}{\sqrt{L_r(C/2)}} \qquad (3.27)$$

At the end of this mode

$$i_{L_r}(t_3) = v_{C_1}(t_3) = v_{C_2}(t_3) = 0 \qquad (3.28)$$

And the expression for the final time t_3 is given as

$$t_3 = \frac{\pi}{\omega_c} \qquad (3.29)$$

Mode d: $t \in [t_3, t_4]$: The equivalent circuit for this mode is shown in figure 3.7, with the switches S_1 and S_2 turned on inductor L_r is charge until its current equal to the output filter current. And finally, D_0 is switched off with ZCS.

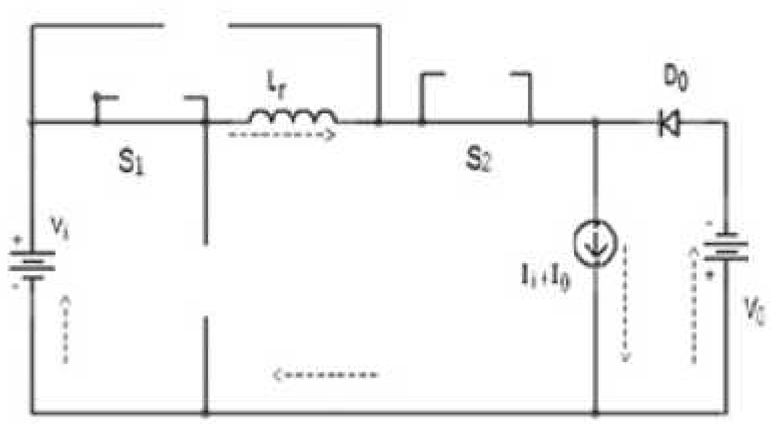


Figure 3.7: Converter Equivalent Circuit in Mode d

$$i_{L_r}(t) = \frac{(V_0+V_i)}{L_r}t \qquad (3.30)$$

$$i_{D_0}(t) = (I_i + I_o) - i_{L_r}$$

At the end of this mode

$$i_{L_r}(t_4) = I_i + I_o \qquad (3.31)$$

The final time for this mode $t_4$is

$$t_4 = \frac{(I_i+I_o)L_r}{(V_0+V_i)} \qquad (3.32)$$

Mode e: $t \in [t_4, t_5]$: The equivalent circuit for this mode is shown in figure 3.8, throughout this mode output side is isolated from the input side and therefore constant current flows to the filter from input. By using feedback loop the duration of this mode is controlled to regulate output voltage.

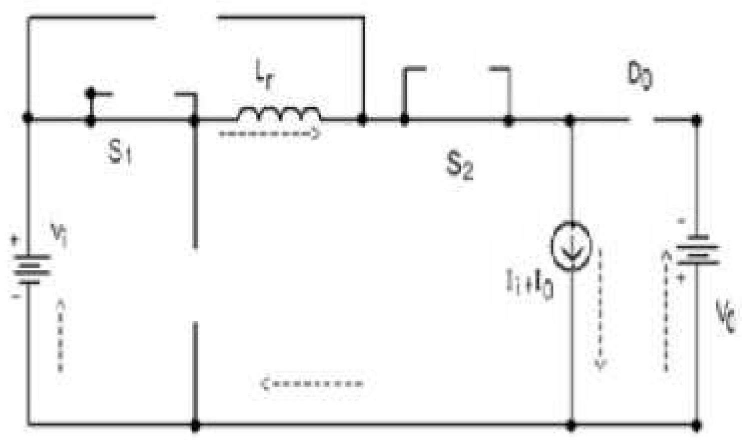


Figure 3.8: Converter Equivalent Circuit in Mode e

$$i_{L_r}(t) = I_i + I_o \qquad (3.34)$$

$$i_{D_0}(t) = 0 \qquad (3.35)$$

The circuit duty circle is

$$D = \frac{t_5 - t_4}{T} \qquad (3.36)$$

Mode f: $t \in [t_5, t_6]$: The equivalent circuit for this mode is shown in figure 3.9, At the beginning of this mode S_2 is switched off at ZVS so as to charge capacitor C_2 with constant current. This mode ends while $v_{C_2} = V_i + V_o$ and diodes D_3 and D_C start to conduct.

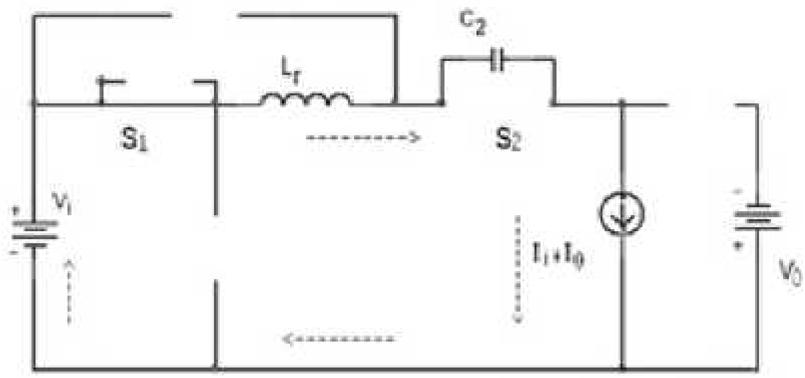


Figure 3.9: Converter Equivalent Circuit in Mode f

$$v_{C_2}(t) = \frac{(I_i + I_o)t}{C_2} \tag{3.37}$$

$$i_{L_r}(t) = I_i + I_o \tag{3.38}$$

$$i_{D_0}(t) = 0$$

At the end of this mode

$$v_{C_2}(t_6) = (V_i + V_o) \tag{3.39}$$

The final time for this mode $t_6$is

$$t_6 = \frac{(V_o + V_i)C_2}{(I_i + I_o)} \tag{3.40}$$

Mode g: $t \in [t_6, t_7]$: The equivalent circuit for this mode is shown in figure 3.10, In this mode, inductor current i_{L_r} freewheels via S_1 and D_3 whereas filter inductor discharged its stored energy to the output capacitor. And the current is:

$$i_{L_r}(t) = i_{D_0}(t) = I_i + I_o \tag{3.41}$$

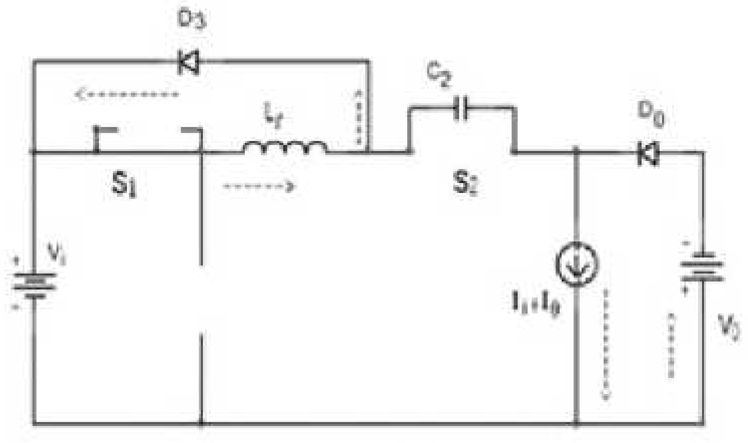


Figure 3.10: Converter Equivalent Circuit in Mode g

3.4 Relationships BetweenConversion Ratio and Duty Ratio Relationship

Assuming the converter is ideal, the duty ratio D can be express in terms of the voltage gain ratio M by equating the converter input and output average power. The voltage conversion ratio M is defined as

$$M = \frac{V_0}{V_i} \tag{3.42}$$

Considering the voltage-second equilibrium for an inductor, for the two filter inductors we've:

$$V_C(t_1 + t_2 + t_3 + t_4 + t_6 + t_7 - t') = V_i(t_5 + t') \tag{3.43}$$

Where t' is the time interval in which the voltages of the two inductors are zero after t_6. From the converter circuit in figure 3.3 we know that;

$$v_L = V_i - \frac{I_i + I_0}{L} t' = 0 \tag{3.44}$$

And therefore,

$$t' = \frac{L V_i}{I_i + I_0} \tag{3.45}$$

From (3.36)

$$D = t_4 - t_5 \tag{3.46}$$

Hence, we can define

$$t_7 = T - D - t_1 - t_2 - t_3 - t_6 \tag{3.47}$$

By using (3.47) in (3.43) we get

$$V_C(t_4 + T - D - t') = V_i(D - t_4 + t') \tag{3.48}$$

Substituting for t_4 and t' from (3.32) and (3.45) respectively, into (3.48) we get

$$V_C\left(\frac{(I_i + I_0)L_r}{(V_0 + V_i)} + T(1 - D) - \frac{L V_i}{I_i + I_0}\right) = V_i\left(D - \frac{(I_i + I_0)L_r}{(V_0 + V_i)} + \frac{L V_i}{I_i + I_0}\right) \tag{3.49}$$

$$\frac{V_C}{V_i}\left(\frac{(I_i + I_o)L_r}{(V_C + V_i)} + T(1 - D) - \frac{CV_i}{I_i + I_C}\right) = \left(D \quad - \frac{(I_i + I_o)L_r}{(V_C + V_i)} + \frac{CV_i}{I_i + I_C}\right)$$

By using (3.42)

$$M\left(\frac{(I_i+I_U)L_r}{(V_U+V_i)} + T(1 - D) - \frac{CV_i}{I_i+I_U}\right) = \left(D \quad - \frac{(I_i+I_U)L_r}{(V_U+V_i)} + \frac{CV_i}{I_i+I_U}\right) \tag{3.50}$$

$$D = \frac{M}{1+M} + \frac{1}{T}\left(\frac{(I_i+I_U)L_r}{(V_U+V_i)} - \frac{CV_i}{I_i+I_U}\right) \tag{3.51}$$

From equation (3.51), for practical values, term in the second bracket are much smaller in comparison to $(M/1 + M)$,and therefore the duty ratio is much similar to the one of conventional buck-boost converter.It can also be seen from this equation that the converter has an excellent load regulation ability and the duty ratio D has very small influence from load variation.

For an ideal converter operation, the average input power is equal to the output power,

$$\frac{1}{T}\int_C^T V_i i_i d \quad = V_C I_C \tag{3.52}$$

And therefore, we can consider

$$I_i \triangleq \frac{1}{T}\int_C^T i_i d \tag{3.53}$$

And subsequently,

$$I_C = \frac{V_U}{R_L} \tag{3.54}$$

Substituting (3.54) and (3.53) in to (3.52) we obtain

$$I_i = \frac{V_U^2}{R_L V_i} \tag{3.55}$$

To achieve ZVS the voltages v_{C_1} and v_{C_2}across the capacitors C_1 and C_2 must be reduced to zero at the end of mode c, and this can only be achieved if $v_{C_1} = V_i$ at the end of mode a, for that to be obtained the design value for the inductor should be

$$L_r = \frac{V_U}{(I_i+I_{Um} \quad)}C \tag{3.56}$$

3.5 Simulation Results

In order to support the theory results and analysis in the previous sections, a simulation is carried out by modelling the converter circuit using PSCAD/EMTDC software. the parameters used in the simulation are summarized in table 3.1.

Table 3.1: Selected Parameters for Simulation

V_i	$24V$
f_s	$100k$
L_f	$150\,\mu$
C_c	$220\,\mu$
L_r	$5\,\mu$
$C_1 = C_2$	$800\,\mu$
R_L	$6\,\Omega$
D	0.333

Figure 3.11 shows the simulation results for the input and output voltages and currents. According to the waveforms, the value for the output voltage is $12V$, for a $24V$ input voltage. Using the theoretical definition of the output current given in (3.54), the output current I_o is obtained as $2A$ which is further confirmed by the simulation result.

According to equation (3.55) and the results and the selected parameters in table 3.1, the average value of the input current $I_i$is $1A$. The simulation waveform shows that the input current initially is zero and increases to a maximum value of $3A$, which satisfy the theoretical fact $i_i = I_i + I_o$.

Figure 3.11: Input/output Currents and Voltage Waveforms

The zero voltage and zero current switching (ZVZCS) of the main switch S_2 and the auxiliary switch S_1 are clearly demonstrated in figure 3.12. From this figure, it is shown that the capacitor voltages v_{C1} and v_{C2} as well as the inductor current i_L are brought to zero at the transition moments of the switches.

According to the figure, the voltage across the capacitor C_1, v_{C1} reaches the maximum value of $24V$, satisfying the theoretical waveform in figure 3.3, i.e. $v_{C1m} = V_i$.

Similarly, the voltage across the capacitor C_2, v_{C2} reaches the maximum value of $36V$, satisfying the theoretical waveform in figure 3.3, i.e. $v_{C2m} = V_i + V_o$.

Figure 3.12: Simulation Result of ZVZCS Buck-boost Converter

Figure 3.13 shows the voltages across the circuit semiconductor devices and currents through them. The maximum values for the current flowing through the diodes D_0, D_3 and D_4 as well as the switches S_2 and S_1 are measured from the simulation software and are obtained as $i_{D0,m} = 3.215A$, $i_{D3,m} = 3A$, $i_{D4,m} = 2.985A$, $i_{S2,m} = 3A$, and $i_{S1,m} = 3A$ respectively. Also, the maximum current through the inductor L_r is measured to be $i_{L1,m} = 3A$, which confirms the theory as indicated in figure 3.3, $i_{L1,m} = I_i + I_o$.

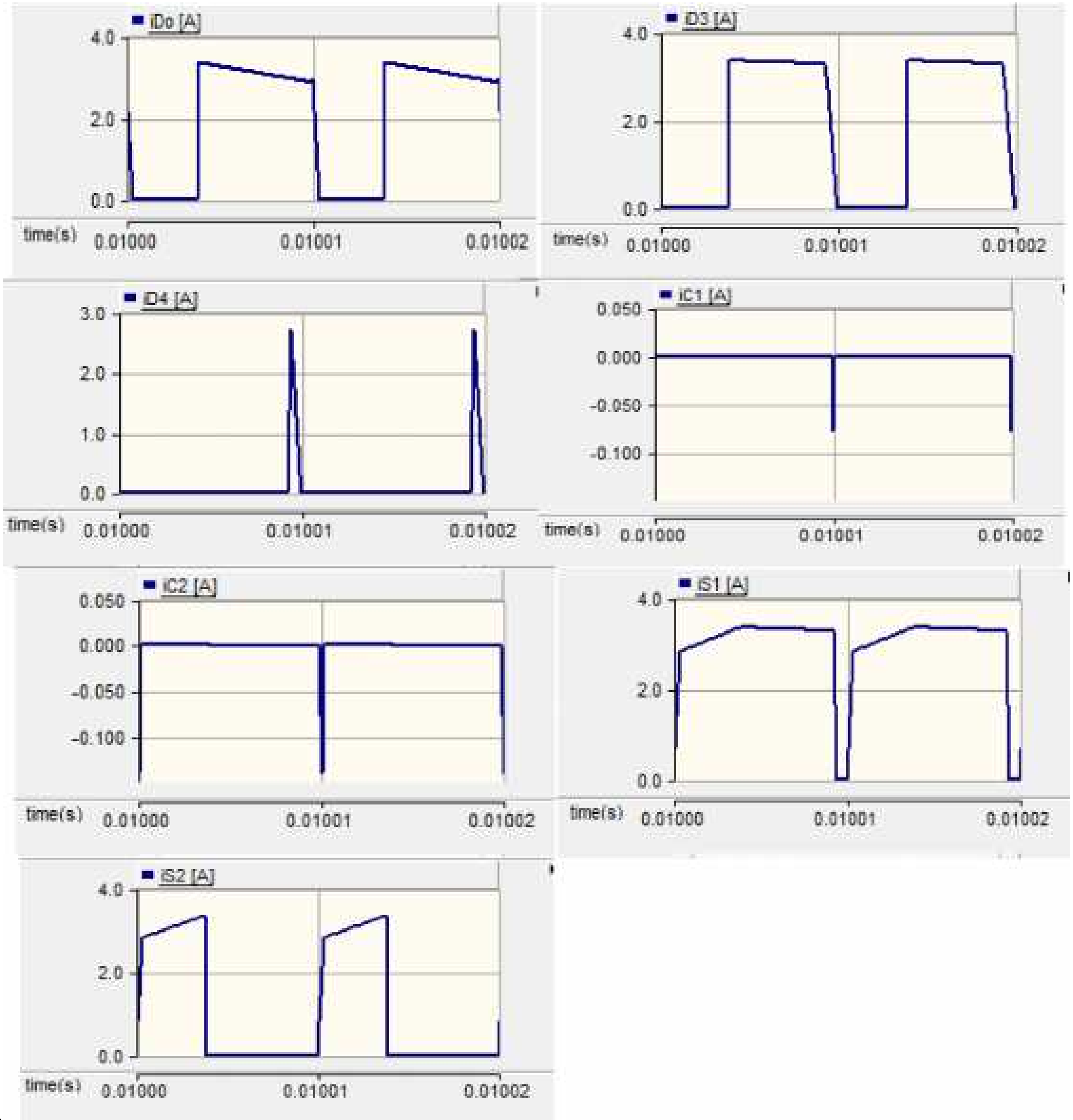


Figure 3.13: Voltage and current of the semiconductor devices

On the other hand, voltages across the components shown in figure 3.14, the maximum values for the voltage across the diodes D_C, D_3 and D_4 as well as the switches S_2 and S_1 are measured and following values are obtained $v_{DC,m} = -36V$, $v_{D3,ma} = -36V$, $v_{D4,m} = -24V$, $v_{S2,m} = 36V$ and $v_{S1,m} = 24V$ respectively.

In all the cases, the simulation results confirm the validity of the proven relationships in the theory.

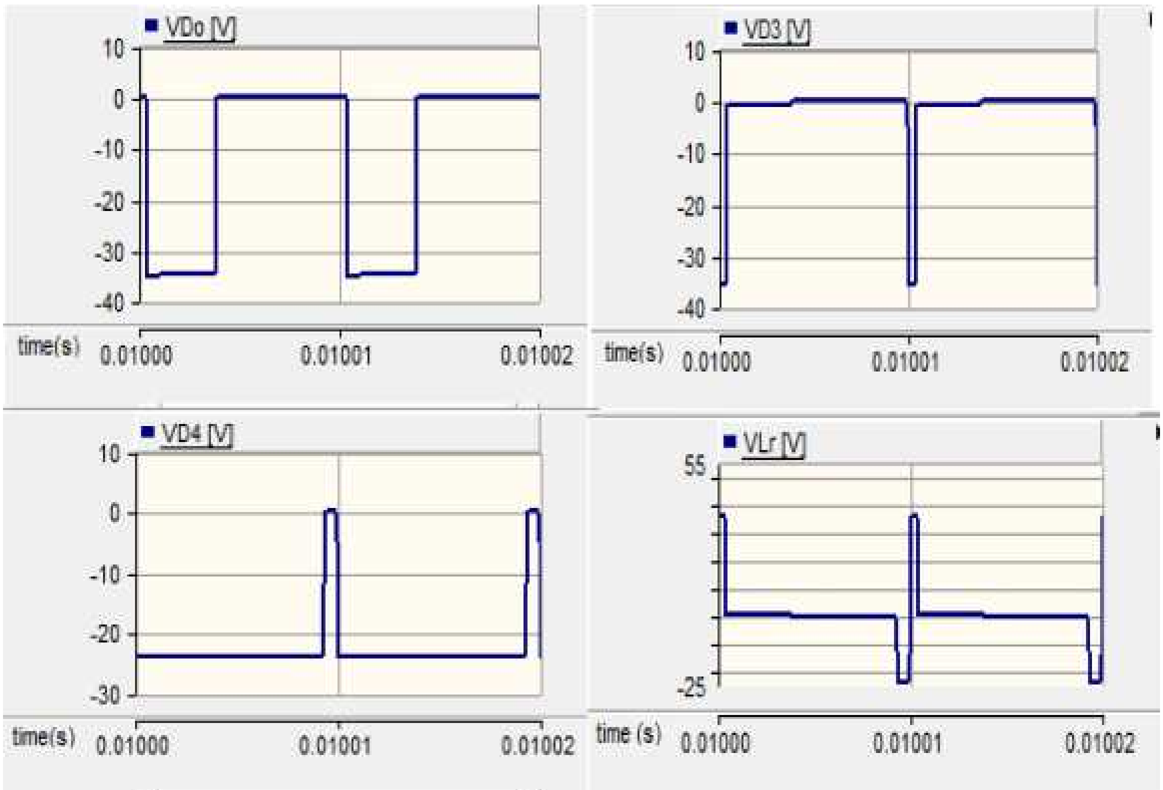


Figure 3.14: Voltage of the semiconductor devices

CHAPTER 4

CONCLUSION

4.1 Introduction

This chapter, presents the conclusion of the thesis work and recommendations for future work and possible improvements that can be made on this thesis. The chapter can also be seen as a summary of the salient points made in the thesis.

4.2 Conclusion

This thesis work has been conducted to carry out the analysis and simulation of zero-voltage-zero-current switching (ZVZCS) based dc/dc buck-boost converter. The major aim is to investigate the problems and challenges imposed on dc/dc converters by hard switching and the difficulties with regards to implementation of soft switching in dc/dc converters. Furthermore, the thesis demonstrated the importance of using simulation in modelling and analysis of power-electronics systems.

The converter circuit discussed in this thesis is formed by adding complementary elements (resonant-elements along with a switch), to a classical basic dc/dc buck-boost converter circuit which is normally operating with hard switching. The complementary elements include two semi-conductor diodes, a switch, an inductive element and two capacitive elements. With this arrangement ZVZCS soft switching is applied to all the semiconductor components including the main-switch, the complementary switch (to avoid extra-switching loss) and all the diodes.

Mathematical analysis of the converter circuit in steady state is carried out to establish the equations for the currents and voltages and also find the expressions for the time at which currents and voltages transitions take place. The converter voltage gain and the conditions on the circuit elements to realize soft switching are also established.

Simulation technique have been used as one of the stages of a design process. The converter circuit is modelled using PSCAD/EMTDC-V4.5 software. This is to validate the results obtained from the mathematical analysis. The simulation results confirmed all the theoretical results. It can be concluded from the simulation that a good simulation will give a reliable information about a system and our simulation results can be relied upon for further implementation of the converter circuit.

The converter used in this study is a unique one among its types, and therefore by analysing this topology a good knowledge of soft switching methods is gained since the converter combined both ZVS and ZCS to turn on/off the switches and the diodes. One of the main problems of normal ZVZCS based converters as identified in the literature is increased capacitive loss and high voltage/current stresses which are solved by this structure.

The increasing demand in environmentally-friendly energy sources has made studies on renewable energy so important over decades. Energy source like fuel cells which are highly non-linear and have slow response to load dynamics have imposed special requirements on the dc/dc converters being used as interface between source and load.

DC-DC Converters in general are used to converts DC voltage from one level to another. A buck dc/dc converter steps down a voltage, producing a voltage lower than the input voltage. On the hand, boost converter steps up a voltage, producing a voltage higher than the input voltage. While buck/boost converter steps a voltage up or down, producing a voltage equal to or higher or lower than the input voltage.

Power-electronic converter circuits are built with energy storing components such as capacitors and inductors, control devices and semiconductor elements like diodes and transistors. Switching is required in converters and is provided by the transistors such as Bipolar Junctions Transistors (BJTs), Insulated Gate Bipolar Transistors (IGBTs) and Metal Oxide Silicon Field Effect Transistors (MOSFETs). However, most applications MOSFETs and IGBTs are more popular than BJTs.

Energy losses are in evitable in real semiconductor devices and therefore the switches used in converters produces power losses. This power loss is equivalent to overlapping area of the switch current and voltage waveforms at the time of turnoff/on. Switching the power electronic converters with these power losses is referred to as “hard switching” and need to be avoided. Soft switching is considered to be a technique by which the switching processes are controlled and made to be gradual so that either the current or voltage are zero during the switching.

Two types of soft switching are used; zero-current-switching (ZCS) and zero-voltage-switching (ZVS). In ZVS, the switch voltage is forced to zero before applying the gate voltage during turn-on. Whereas, in ZCS, the switch current is forced to zero during turn-off before removing the gate voltage. To achieve a better performance these methods are combined to achieve ZVZCS at the same time.

Numerous advantages have been recorded in power electronics by the use of soft switching strategies in dc/dc converters. Among the advantages are; minimizing power losses in the switch, reducing “electromagnetic interference (EMI)” and converter volume as well as increasing the power density.

soft switching in dc/dc converters are achieved by adding auxiliary circuit consisting of resonant elements, passive and active components and switches. These additional components impose high-current/voltage stresses in the switch. To solve this some methods bypassed the resonant-capacitor for a given time interval by using active switch. Some methods consider controlling the resonance period, the output is regulated by using the controllable period called “extended-period”. Nevertheless, the main switch in both the converters suffers from capacitive turn-on loss.

These issues are further addressed in the converter discussed here. By combining ZVS and ZCS techniques the converter can perform both step up and step down operation and therefore its better than pure ZVS or ZCS converter.

4.3 Recommendations

Following observations and recommendations will help in improving thesis in future work:

- A prototype should be implemented to support the simulation result
- Although the converter analyzed offers a lot of advantages but there is increased in conduction losses, therefore future work should be carried out to address this.
- Z source networks are being used in the literature and have achieve wonderful result in enhancing efficiency and output-voltage level. Therefore, combining soft switching with Z network will make a good result.

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