High Gain Non-isolated DC-DC Converter Topologies for Energy Conversion Systems

by

Musa Ahmad (142480)
Ali Moumin (142495)
Fahad Panhwar (142496)
Abdimajid Adam (170033210)

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Department of Electrical and Electronic Engineering
Islamic University of Technology (IUT)
Gazipur, Bangladesh

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Approved by:

Mr. Fahim Faisal
Supervisor and Lecturer,
Department of Electrical and Electronic Engineering,
Islamic University of Technology (IUT),
Boardbazar, Gazipur-1704.

Date:

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List of Acronyms

AC	Alternating Current
ADC	Analogue to Digital Converter
CCM	Continuous Conduction Mode
DC	Direct current
DCM	Discontinuous Conduction Mode
DPG	Distributed Power Generation
DSP	Digital Signal Processor
EMI	Electro-Magnetic Interference
ESS	Energy Storage System
EV	Electric Vehicle
HID	High Intensity Discharge
HEV	Hybrid Electric Vehicle
IGBT	Insulated Gate Bipolar Transistor
KCL	Kirchhoff’s Current Law
KVL	Kirchhoff’s Voltage Law
LTI	Linear Time Invariant
MOSFET	Metal Oxide Field Effect Transistor
MPPT	Maximum Power Point Tracking
PFC	Power Factor Correction
PHEV	Plug-in Hybrid Electric Vehicle
PI	Proportional-Integral
PV	Photovoltaic
PWM	Pulse Width Modulation
RCD	Resistor-Capacitor-Diode
RES	Renewable Energy Sources
RMS	Root-Mean-Square
UPS	Uninterruptible Power Supply
(ZCS)	Zero Current Switching
ZCT	Zero Current Transition
(ZVS)	Zero Voltage Switching
ZVT	Zero Voltage Transition

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Abstract

Emerging applications driven by low voltage level power sources, such as photovoltaics, batteries and fuel cells require static power converters for appropriate energy conversion and conditioning to supply the requirements of the load system. Increasingly, for applications such as grid connected inverters, uninterruptible power supplies (UPS), and electric vehicles (EV), the performance of a high efficiency high static gain power converter is of critical importance to the overall system. Theoretically, the conventional boost and buck-boost converters are the simplest non-isolated topologies for voltage step-up. However, these converters typically operate under extreme duty ratio, and severe output diode reverse recovery related losses to achieve high voltage gain. This thesis presents derivation, analysis and design issues of advanced high step-up topologies with coupled inductor and voltage gain extension cell. The proposed innovative solution can achieve significant performance improvement compared to the recently proposed state of the art topologies.

Two unique topologies employing coupled inductor and voltage gain extension cell are proposed. Power converters utilising coupled inductors traditionally require a clamp circuit to limit the switch voltage excursion. Firstly, a simple low-cost, high step-up converters employing active and passive clamp scheme is proposed. Performance comparison of the clamps circuits shows that the active clamp solution can achieve higher efficiency over the passive solution. Secondly, the primary detriment of increasing the power level of a coupled inductor based converters is high current ripple due to coupled inductor operation. It is normal to interleaved DC-DC converters to share the input current, minimize the current ripple and increase the power density. This thesis presents an input parallel output series converter integrating coupled inductors and switched capacitor demonstrating high static gain. Steady state analysis of the converter is presented to determine the power flow equations. Dynamic analysis is performed to design a closed loop controller to regulate the output voltage of the interleaved converter. The design procedure of the high step-up converters is explained, simulation and experimental results of the laboratory prototypes are presented. The experimental results obtained via a 250 W single phase converter and that of a 500 W interleaved converter prototypes; validate both the theory and operational characteristics of each power converter

Chapter 1

Introduction

1.1 Background

The growing use of renewable energy sources (RESs) and Energy storage systems (ESS), due to global environmental concern, brings new challenges to the energy conversion technology. Because some devices that store or produce electrical energy (e.g., batteries, ultra-capacitors, fuel cells and solar photovoltaic) is often realized using multiple low voltage cells, which are usually connected in series to produce sufficient voltages for the intended application. Unfortunately, series connection of cells degrades the system performance, adds complexity to the system, and possible temperature rise due to fabrication variation and different operating conditions between cells. In batteries, this may be related to the state of charge of a cell. In solar arrays, it may be due to a change in solar irradiance or partial shading of the array.

Many green power supply system calls for a high efficiency, high step-up DC-DC converter in the power conversion stage. Typical applications include grid-connected inverters [1-4], motor drive [5], uninterruptible power supply system (UPS) [6, 7], telecommunication/network server power systems [8], electric vehicle (EV) [9], high intensity discharge (HID) lamps [10, 11] and distributed power generation (DPG) system [12]. Furthermore, high voltage step-up gains usually ten times or higher are increasingly required when the system is powered by low voltage energy sources such as Li-ion batteries, solar arrays and fuel cells. It is necessary or customary to use a relatively high and stable DC voltage in these applications. Besides, considering that the overall cost of a renewable energy system is high, the use of high-efficiency power electronic converter isnecessary.

The boost and buck-boost converters are the simplest non-isolation topologies that produce an output voltage that is greater in magnitude than the source voltage [13, 14]. However, the conventional boost and buck-boost converters must operate at extreme duty ratio to achieve high voltage gain (in particular ten times). This is an undesirable operating point since the output diode sustains short pulse, high amplitude, current pulses which result in severe reverse recovery losses. Besides, as the output voltage increases so must the voltage rating of the semiconductor switching devices and at high duty ratio the conduction losses of the semiconductor device can make a more significant impact to the performance of the system. Furthermore, as the duty ratio approaches unity, the output voltage approaches zero, and the efficiency decreases to zero [14]. Consequently, the converter may suffer poor dynamic response to system parameter changes and potential load variations. This behaviour is typical of converters having boost or buck-boost characteristics. The challenge for any high step-up DC-DC converter is to avoid extreme duty ratiooperation.

Rather than a conventional single stage boost converter, a cascade boost converter is an attractive solution to enlarge the voltage gain without extreme duty ratio operation. However, the controllers must be synchronized, and the stability of the converter is another concern [15]. Moreover, the second stage may experience severe reverse recovery related losses in high power applications. Furthermore, the energy has to be converted twice, which obviously has an impact on overallefficiency.

Classical converters with magnetic coupling such as flyback or push-pull converters can easily achieve higher conversion ratio, by proper choice of the transformer turns ratio. One of the most commonly understood transformer based topologies is the flyback converter. The main drawback of the transformer based topologies is high turn off voltage spike seen by the primary switch, due to the transformer leakage inductance interaction with parasitic capacitor of the switch. To go some way to mitigating these effects, energy recycling techniques must be adopted to recycle the leakage energy [16]. Moreover, the transformer volume and weight is another problem that inhibits developing a compact, high power density converter. Thus, whilst functional, these types of converters do not offer an optimal solution in cost sensitive power supplyapplications.

This thesis is concerned specifically with research into high step-up DC-DC boost converter topologies. There is increasing interest in the use of high step-up DC-DC boost converters for harvesting all available energy, typical applications call for high-efficiency high step-up converters. These two features are the focus of this research. Basic boost and buck boost converters operate with extreme pulse width modulation (PWM) duty ratio to achieve higher conversion ratio of (ten times or higher). Appropriate duty ratio is desirable since extreme duty ratio operation have long been recognised as causing some operational drawbacks to the high step-upconverters.

Some of the major shortcomings of extreme duty ratio operation include reverse recovery loss of the output diode as a result of short pulse current with large amplitude. Furthermore, the output diode reverse recovery problem can lead to higher turn-on switching loss for the power switch. For this reason, there is considerable motivation to improve the performance of high step-up boost converters by alleviating the diode reverse recovery loss so that switching loss can be significantly reduced. Literature has revealed that the power device voltage rating in conventional boost converter is the same as the converter output voltage. Another concern related to the efficiency of high step-up converters is power device rating. A high voltage rated device is not a good choice for the steady state operation because of the high input current (as the power MOSFET rating increases, so does the on-state resistance R_{ds_on}resulting in conduction losses which also degrade the efficiency). The challenge for a high step-up converter is to dramatically reduce the conduction losses. Appropriate duty ratio operation, conduction losses reduction and alleviation of diode reverse recovery problem can greatly improve the efficiency of power conversion. It is the aim of this thesis to investigate methods of improving the performance of high step-upconverters.

1.2 High Step-up DC-DC Converters Applications

Many applications powered by RESs call for a high-efficiency high step-up DC-DC converter in the power conversion stage. Typical examples include grid connected inverters [1-4], high-intensity discharge lamp (HID) [10], electric drives [17] and uninterruptible power supply system (UPS) [6, 7]. Some emerging applications that require high step-up DC-DC power converters are briefly described in the following section.

1.2.1 Grid Connected PhotovoltaicInverter

One of the most important applications of solar photovoltaic (PV) is electricity generation, particularly in countries having a considerable amount of solar radiation. The application could be a stand-alone or grid-connected system. The PV grid-connected power system is a fast growing segment in Europe, with record addition of 1.9 gigawatts in Germany, 2.4 gigawatts for the United Kingdom, 0.9 and 0.4 GW for France and Italy respectively in 2014 [18]. Countries like Japan, China and the U.S have added 9.7, 10.6 and 6.2 GW respectively for the same year under review. This addition brings the total global installed capacity to 177 GW [18].

Figure 1.1 shows the block diagram of a typical grid connected PV power system. PV panels

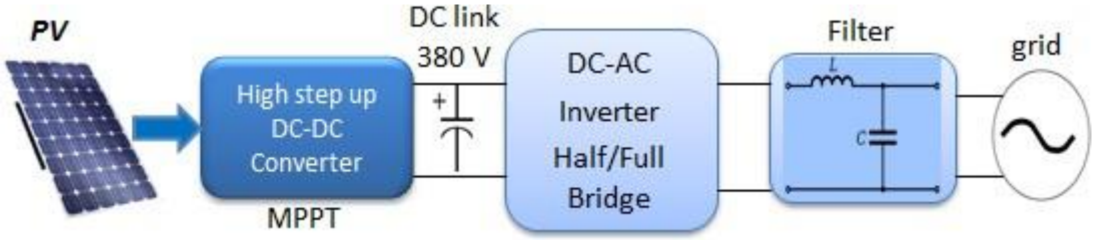


Figure 1.1 Single phase grid connected renewable energy system

are often connected in series to obtain the DC link voltage along with the power converter to track the maximum power point (MPP) range of the PV. However, when partial shading occurs or mismatch, the MPP losses increase significantly. Another configuration is to use a modular approach to reduce the cost and improve the system MPPT efficiency; in this case, an independent module integrated DC-DC converter is used for each PV panel. Thus, decoupling every panel from others to make the system configuration flexible and maximizes the output power. Nevertheless, the topology normally has two power electronic converters. The first converter is the high step-up boost converter that is required to raise the relatively low solar panel DC voltage to a certain level suitable for synthesizing the alternating current AC line voltage, which is typically 380 - 400 V DC. The second converter is the DC-AC inverter that injects sinusoidal current into the grid. The high step-up DC-DC converter along with maximum power point tracking (MPPT) algorithm stabilise the DC bus voltage level and make full utilization of the PV array. The performance of the high step-up DC-DC converter is crucial to the performance of the whole PV system because the DC-DC converter is the core element that interfaces the solar photovoltaic with the DC-AC inverter and manages the powerflow.

The main shortcoming of a grid-connected power system is power contributed by the system to the grid is available only during part of each day since solar energy is available only during the daylight hours. To overcome this problem an energy storage system ESS such as battery is usually employed in the photovoltaic inverter systems to improve the system performance and supply availability [19]. The objective of utilising the ESS is to provide a back-up function, transferring the solar energy to the ESS during the sunny time, whilst delivering energy to the DC bus when the solar energy is not available. As a result, stable and fast response AC power can be provided to the grid. Integrating the grid connected PV system with ESS is achievable with the aid of bidirectional DC-DC converter that has power flow in both forward and reversed directions (boost and buck).

1.2.2 High Intensity Discharge (HID)Lamp

High-intensity discharge (HID) lamp are preferable, instead of conventional halogen lamps for use as automobiles headlamps due to its superior performance and numerous advantages, such as higher efficiency, longer life, good light beam focus and superior colour rendering capability. Although the HID lamp has significant advantages, its operation is similar to the other discharge lamps and requires a ballast to control the lamp power during steady state operation.

Figure 1.2 shows typical ballast circuit for powering and igniting the lamp. The ballast consists of high step-up DC-DC converter, an inverter and an igniter. The HID are powered using the automobile 12 V battery, which provide an input voltage much lower than the operational voltage of the ballast. For this reason, a high step-up DC-DC converter is required in the ballast to step-up the battery voltage to (380V-400V) during startup and in the (60-135 V) range during steady state operation [10, 11]. Therefore, a high step-up DC-DC converter with about tenfold voltage gain is critical for the operation of the lamp.

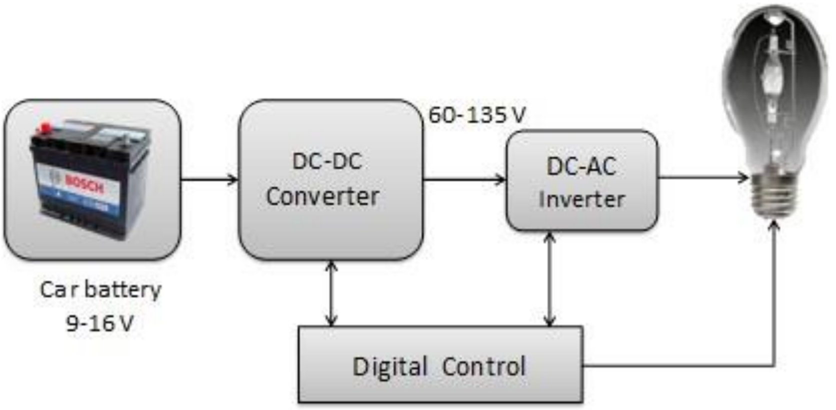


Figure 1.2 High Intensity discharge lamp ballast block diagram

1.2.3 ElectricVehicle

The automotive companies are focused on electric vehicles (EV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and fuel cells vehicles to meet the demand for emission-free vehicles with improved fuel economy, comfort and safety. However, the key challenge lies in the efficiency, cost, size of power electronic converter and machine. In particular, the high step-up DC-DC converter to interface the fuel cell voltage with the battery packs.

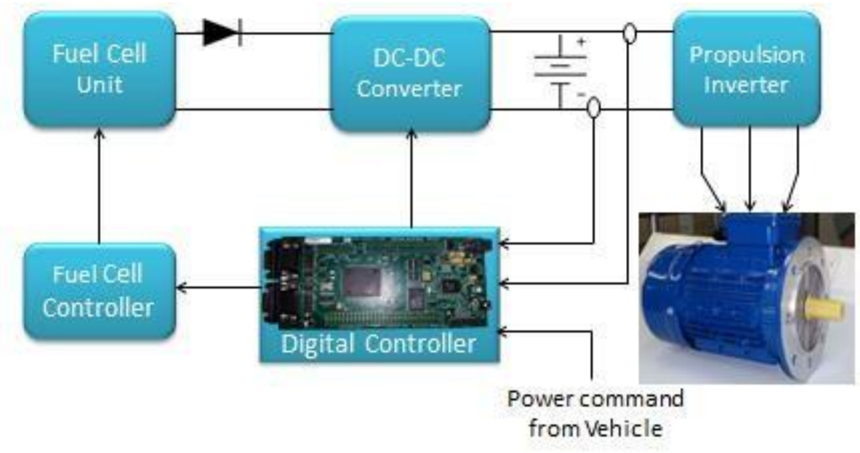


Figure 1.3 Electric vehicle drive train

Figure 1.3 illustrates a typical fuel cell vehicle propulsion system. A high step-up DC-DC boost converter is usually employed to step-up the relatively low DC voltage of the fuel cell to a typical DC link voltage of 400V which is also compatible with the battery. An inverter is then used to drive the propulsion motor. ESS such as: Li-ion batteries are often used to provide supplementary power during vehicle starting, acceleration and hill climbing. Different configurations and classifications of electric vehicle propulsion system can be found in [9]. The use of bidirectional DC-DC converter along with ESS in electric vehicle to achieve power transfer in either direction is demonstrated in [20] The regenerative energy fed back by the electric machine during breaking is absorbed by the battery. Whilst the capacitive energy source is step-up by the converter to compliment vehicle starting andacceleration.

1.2.4 Uninterruptible Power SupplyUPS

The growing use of Uninterruptible power supply (UPS) to supply power to the sensitive loads and protect them during mains outages under normal or abnormal utility power conditions is well documented [6, 7]. UPS has been widely used to supply seamless power to critical loads, such as medical equipment, communication systems computers and servers. All UPS uses specific DC-DC power electronics converters to interface different sources and load. For example, the UPS topology consists of power factor correction (PFC) circuit, which is typically an AC-DC front-end converter that convert the ac-line voltage ($90 - 265\ V_{rms}$) and provides a regulated DC link voltage of (380 - 400 V) required by the inverter. During the mains or utility outage, the UPS enters the backup mode, and the UPS generate AC voltage from the 48 V back-up batteries to supply the load. A high step-up converter is necessary to raise the battery bank voltage to that required by the DCbus.

1.2.5 Telecommunication Power System

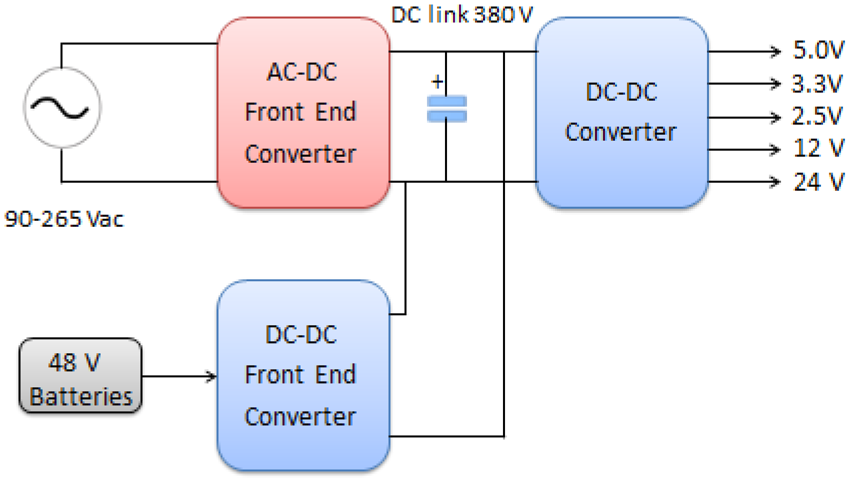


Figure 1.4 Dual front end telecom power system

Typically, UPS provide up to 30 minutes of reserve time; this is far shorter than the reserved time needed by telecommunication power systems. Consequently, using 48 V DC telecom bus has become a natural choice of powering data processing equipment installed in the telecom environment [10]. Figure 1.4 shows a typical Power supply system of telecommunication equipment. The power supply is characterised by high power density, efficiency and has several stages [8]. Traditionally the first stage is AC-DC system powered from AC-line voltage $(90 - 265\ V_{rms})$ and provides a high step-up DC bus voltage of up to (400 V). The AC-DC converter serves as a power factor correction circuit for suppressing the harmonic level. The nominal 380 V bus voltage is converted to a tightly regulated lower voltage of 5, 3.3, 12 and 24 V respectively for the logic circuits. However, during the mains outage the telecommunication industries uses 48V DC battery bank as a conventional choice to provide back-up. In this case, a DC-DC high step-up back-up converter is required to provide a simple and efficient solution of raising the 48V DC battery bank voltage to the 400 V DC link voltage. A high step-up DC–DC converter that generates 400 V DC from 48 V DC batteries is necessary in the telecommunication server power supply system.

1.2.6 Distributed Power system

Distributed power generation (DPG) systems are considered to be the key components of future power grids due to its ability to produce and distribute energy to various loads. For the purpose of robust control, monitoring, power quality improvement, fault detection/isolation and stabilization, DPG uses Micrograds in combination with renewable energy sources such as batteries, photovoltaic panels, fuel cells and loads [12]. Micrograds canoperate autonomously or grid connected depending on the configurations, and there is no doubt that DPG is the building blocks of a smart grid.

Figure 1.5 shows the DPG block diagram. The system requires specific power electronics converters to convert and regulate the generated power before interconnection with the utility grid and/ or onward supply to consumer loads [21, 22]. It is necessary to employ DC-DC converters with various power levels to exploit the locally produced power to meet the requirement of various local loads. In a nutshell, the quality and efficiency of the overall system depend on the performance of these power electronic converters.

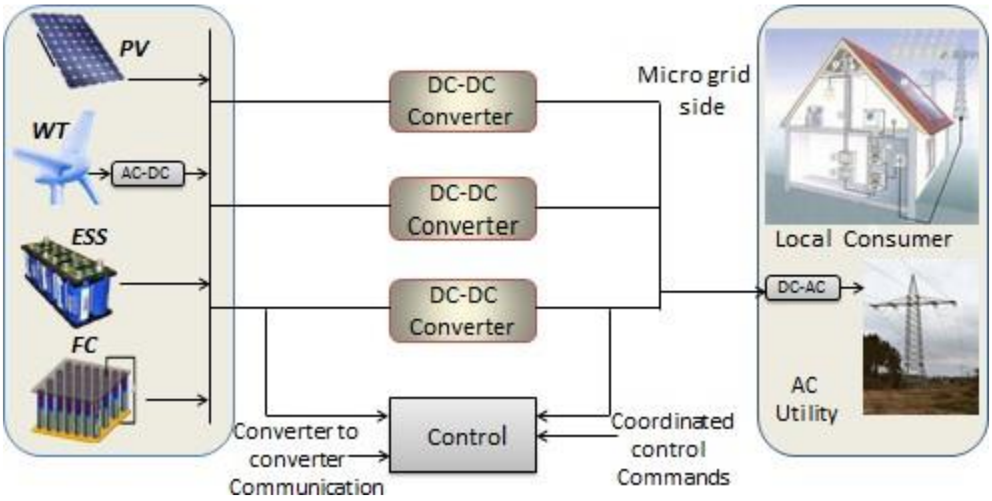


Figure 1.5 Distributed power system

Chapter 2

High Step-up Converters

2.1Characteristics of High Step-up Converters

In general, the performance of high step-up DC-DC converters exhibits high output voltage and large input current. The large input current emanates from low input voltage. Therefore, some of the desirable characteristics of high step-up converters are briefly described in the subsequent sections.

2.1.1 High ConversionRatio

Many applications powered by RESs or ESS call for high step-up DC-DC converters. For example, the output voltage level of the PV array in the grid-connected inverter is typically low 16- 43 V and the DC bus voltage suitable for synthesizing the AC line voltage is 380 - 400 V DC. About ten times (10X) or higher voltage gain is required to raise the array voltage to DC link voltage for steady stateoperation.

2.1.2 High-Efficiency

The large input current is a major concern related to the efficiency of the high step-up DC-DC converters. Low input voltage results in large input current. Therefore, higher peak and root-mean-square (RMS) current stress suffered by the switching components is a primary detriment to increasing the efficiency. To enhance the efficiency of DC-DC converters low rated devices with low on-state resistance are desirable to reduce the conduction loss. In high voltage applications, the reverse recovery problem of the output diode is another concern. Lower rated diodes typically recover faster.

2.1.3 Low Voltage/CurrentRipple

Power electronic converters have an inherent switching characteristic, which causes the current and voltage to fluctuate. For example, in DC-DC boost converter, the switching action of the power MOSFET or IGBT causes the inductor current to have a triangular waveform with a DC offset. The DC component of this inductor current flows through the load and AC components via the output capacitor. A capacitor ripple voltage is produced due to time-varying current through the capacitor. The input current or the output voltage contains some ripple on top of the steady state value. Power electronic converter designers consider the ripple magnitude to be a key parameter in designing such systems. Minimization of the current/ voltage ripple (AC component in the system) which decreases the efficiency lifetime of the converter is essential. In an ideal situation, only DC components should be present at the output.

2.1.4 FastResponse

In a DC-DC converter operating under closed loop control, the duty ratio is determined by the converter nominal operating point based on converter dynamics. Likewise the load resistance, which is also based on DC loads requirement. The load resistance and duty ratio are exogenous quantities that require compensation scheme due to pole-zero variation. The converter should exhibit a fast response in the presence of load/source changes, other external disturbances and must be able to operate in adverse environmental conditions.

2.2 Motivation

Theoretically, conventional boost and buck-boost converters are the simplest PWM controlled topologies for voltage step-up. However, these converters must operate under extreme duty ratio to achieve high voltage gain which severely penalizes the efficiency. In addition, the high output voltage requires higher rated device with large on-state resistance. As the power device rating increases so does the conduction loss which further degrade the efficiency. Furthermore, the output diode sustains a short pulse current with the high amplitude that result in reverse recovery related losses. One of the main challenges of high step-up DC-DC converters is to avoid extreme duty ratio operation so that both switching and conduction losses can be substantially reduced. Finding a way to avoid extreme duty ratio operation in high step-up converters is one of the motivations of thisthesis.

One of the simplest solutions for avoiding extreme duty ratio operation is by using cascade structure. In cascade structure, both stages can achieve step-up function and switch conduction loss is low in the first stage. However, the high output voltage still affects the efficiency of the second stage. Transformers or coupled inductor based converters such as flyback and forward converters can provide higher conversion ratio without extreme duty ratio operation by utilising the transformer turns ratio. A drawback to the use of a transformer is high voltage stress seen by the power device, due to the interaction between the leakage inductance and switch capacitance conventionally requires a snubber. A resistor-capacitor-diode (RCD) snubber can suppress the device voltage stress, but the leakage energy dissipates within the snubber contributing to the losses. A passive lossless or active clamp circuit can recycle the leakage energy and reduce the device voltage stress. Evaluating the performance of leakage energy recycling schemes on the same power converter is anothermotivation.

2.3 Aim and Objectives

Power electronics converters are key components for interfacing and conditioning the power level of source and load in many applications. Direct connection to various voltage levels requires utilizing advanced topologies combined with low-rated high- performance power semiconductor devices.

The aim of this research is to develop a high step-up DC-DC power conversion system to meet the requirement of emerging power supply system in energy delivery andmanagement.

The main objectives and research contributions are:

- To propose a new single phase non-isolated DC-DC boost converter based on coupled inductor and capacitor charge transference with high conversionratio.

- To propose a new high step-up high-efficiency interleaved non-isolated coupled inductor DC-DC boost Converter with ten times (10X) static gain orhigher.
- Application of capacitor charge transference and a coupled inductor turns ratio in high step-up converters to avoid extreme PWM duty ratiooperation.
- To develop models of the interleaved high step-up converter suitable for control designimplementation.
- Experimental assessment of the performance of the proposed single phase and interleaved high step-up converters using a digital signal processor (DSP)platform.

In order to achieve the above goals the thesis proposes the following approach:

a. 2.3.1 Application of active clamp circuit to depress the coupled inductor leakage energy and realize zero voltage switching (ZVS) technique so as to minimize the switching losses under high-frequencyoperation.
    1. Assess the performance of active and passive clamping schemes in recycling the leakage inductor energy with regards to single phase high step-upconverter.
    2. Utilize an interleaved technique to increase the power density and improve the efficiency of high step-upconverter.
    3. Utilizing the inherent leakage inductance of the coupled inductor to alleviate the reverse recovery related losses of thediodes.
    4. Present a comprehensive steady-state operational analysis and design guidelines of theconverters.

Chapter 3

High Step-up DC-DC Conversion Techniques

3.1 Introduction

High step-up DC-DC boost converters are widely used as an interface to transfer power between the low voltage sources to a higher DC bus. In many modern applications, such as HID lamp [10], EV [9] and grid-connected PV systems [2] powered by RESs; it is necessary to utilise converters with high static gain, usually ten times or higher. Since most of these RESs provide a low output voltage, a conventional boost or buck-boost converter can be employed to step-up the source voltage to the voltage level required by the load. However, the conventional boost and buck-boost converters suffer extreme PWM duty ratios to achieve high voltage gains. The output diode sustains short pulse current with high amplitude, which results in severe reverse recovery losses. In addition, as the output voltage increases so must the voltage rating of the semiconductor switching device and because of the high input current that results from the low input voltage, the conduction losses of the semiconductor device can make a more significant impact on the performance of the system. Furthermore, as the duty ratio approaches unity, the converter may suffer poor dynamic response to system parameter changes and potential load variations [23,24].

Various techniques for high step-up conversion have been reported in the literature [10, 23, 25-46]. Depending on the application, they are either isolated [25-35, 47] or non-isolated [10, 23, 36, 37, 39, 41, 43, 44, 46, 48-50] topologies. Transformer based converters can easily achieve high voltage gain by adjusting the turns ratio and utilises low rated devices to reduce the conduction losses. However, the leakage inductor induces high voltage stress to the power device and traditionally requires a snubber. Either RCD snubber circuit or a clamp circuit must be used to handle the leakage energy. To address the demand for high step-up high powerdensityinDC-DCconverters,thepowerelectronicscommunityandindustrieshave been reacting in two different ways; developing semiconductor technology and or developing new converter topologies. This work addresses the later by proposing new converter topologies.

The high-frequency operation has been explored in the literature due to significant advantage of reducing the volume and weight of the converter. Miniaturization of power converter circuits is possible if they operate at a higher switching frequency. However, the switching losses are proportional to switching frequency. To design a compact converter, a way to minimise or eliminate the switching losses must be conceived. Resonant and soft switching techniques are applied to high step-up converters to mitigate the switching losses.

This chapter presents an overview of techniques of developing high step-up non-isolated DC-DC boost converters. The first section of this chapter describes the characteristics of conventional boost converter being the most popular topology and its major limitations in high step-up application. The subsequent section evaluates different techniques aimed at overcoming the limitations of the boost converter and improving the conversion ratio. The main advantages and drawback regarding each technique is highlighted, and the rationale for choosing the magnetically coupled converters and voltage gain extension cell in this work is explained clearly. Furthermore, some soft switching techniques and methods of alleviating the diode reverse recovery related losses are alsoreviewed.

3.2 DC-DC Boost Converter

3.2.1 General Structure of DC-DC BoostConverters

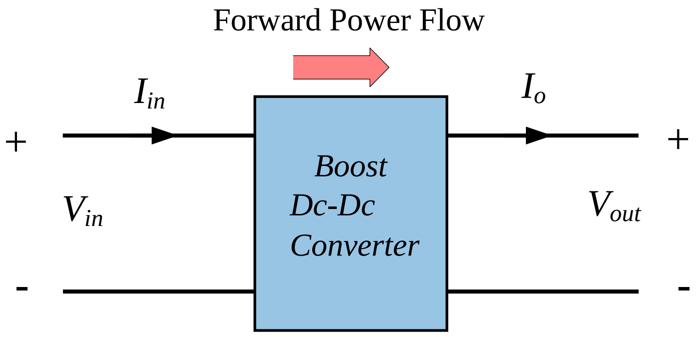


Figure 2.1 Boost converter unidirectional power flow

Figure 2.1 illustrate the generic structure of the DC-DC boost converter. Depending on the configuration, the input side can be current fed or voltage fed. The input voltage can be a battery, fuel cell or solar photovoltaic. The load is placed on the output side; this could be an inverter in stand-alone or grid-connected power system. The converter has a unidirectional power flow. The active switch is typically implemented with semiconductor devices such as MOSFET or IGBT. The term step-up and boost are used interchangeably to imply a converter whose output voltage is always higher in magnitude than the input voltage [14, 51]. In most cases, boost refers to converters without wide conversion ratio, whilst high step-up usually refers to converter with wide voltage gain. DC-DC converters are further classified as isolated or non-isolated

3.2.2 Isolated DC-DC BoostConverters

The high-frequency transformer based system is an attractive solution for providing galvanic isolation and impedance matching between the source and load. As an example, isolation is usually required by regulatory agencies in off-line power supply applications. Classical converters with galvanic isolation such as flyback, current-fed push-pull converters can easily achieve high voltage gain by adjusting the turns ratio. However from an efficiency standpoint, the high-frequency transformer implies additional cost, losses and inhibits developing a compact converter. Thus, the volume weight and losses are the main limitations of isolated converters in embedded applications. Isolated boost converters are either current-fed [26-28] or voltage-fed [34, 52]. Some typical examples of isolated DC-DC converters topologies include flyback [16, 53], forward [54], full bridge [26, 27], half bridge [28-30, 55], push-pull converters [31-33] or their variations.

A flyback converter is the most widely understood topology due to its relative simplicity. Theoretically, the transformer reduces the magnetic components count by providing energy storage and galvanic isolation. However, the semiconductor devices incur current and voltage stress which limit its use to low power applications. The interaction between the parasitic capacitor of the switch and transformer leakage inductance induces high voltage spike during turn off which necessitates the use of clamp circuit. The simplified circuit of flyback converter is shown in Figure 2.2. Note that a red colour is chosen for the power switch, load resistor, blue for the power diode and green for the capacitor. The colour convention is adopted throughout this thesis for easy recognition of one passive component from theother.

The full bridge DC-DC converter is considered one of the famous isolated topologies, with more component counts when compared with the half bridge converter. The operation of the circuits involves utilisation of the transformer leakage inductance for transferring energy from source to the load. Prominent advantages of full bridge converter include immunity from

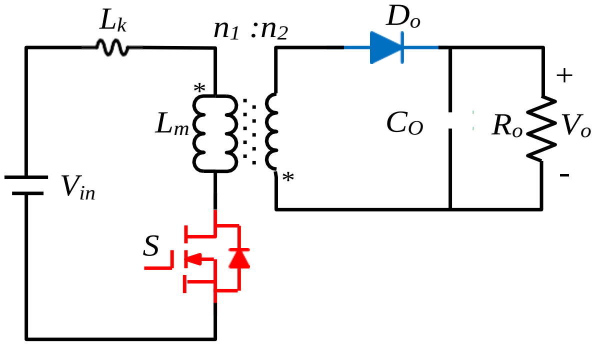


Figure 2.2 Flyback converter

transformer flux imbalance and absence of output inductor. A fundamental shortcoming of the voltage fed full bridge converter is the voltage spike across the output diode, due to the leakage inductance of the transformer. The voltage spikes are exacerbated by increasing the switching frequency [52]. Other problems include duty cycle loss and pulse current at the input which increases the filter size.

3.2.3 Non-isolated DC- DC BoostConverter

Rather than the isolated converters, non-isolated DC-DC converters can be used to improve the efficiency. Consequently, the volume, weight and losses associated with the high-frequency transformer are reduced. Furthermore, in the high power application where weight size is the main concern, the transformer-less structure is the most attractive [23]. It is becoming a more suitable solution to employ non-isolated converters to reduce the system cost and improve the efficiency. Since the passive components size and weight of non-isolated converters vary inversely with frequency, the components then operate at converter switching frequency in tens of kilohertz (KHz) range or higher. This high frequency leads to dramatic reduction in converter size and weight. In summary, for applications that require isolation between source and load based on safety measures, the isolated topologies are the right choices. However, in high power applications where volume weight is the main concern, the non-isolated topologies are the best option. The basic non-isolated DC-DC step-up topologies that produce an output voltage higher in magnitude than the input voltage are the boost and buck-boostconverters.

3.2.4 Conventional Non-isolated DC-DC BoostConverter

The conventional non-isolated DC-DC boost converter is shown in Figure 2.3. As the name implies the output voltage $V_O$is always higher in magnitude than the input voltage V_{in}. Higher output voltage can be accomplished by controlling the operation of the switch using the PWM signal. Accordingly, the states of the switch (ON/OFF) are changed periodically with the period equal to T_{sw}(switching period) and duty ratio equal to D. The level of the converted voltage depends on the magnitude of the applied input voltage and the duty ratio.

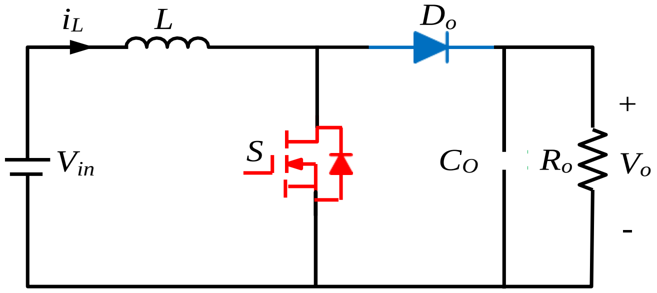


Figure 2.3 Conventional boost Converter

During the switch turn on instant, the diode $D_O$is reversed biased, and the input source charges the inductor L. When the switch turns off, the load receives energy from the input as well as the inductor. The capacitor $C_O$removes the switching harmonics from the applied input signal. Noticeably, the energy transfer in a step-up (boost) converter is between a voltage and current source. Since in a steady state, the capacitor or inductor can be represented by their instantaneous voltage or currents as an equivalent voltage and current sourcesrespectively.

The steady state operation described is known as continuous conduction mode (CCM), since the inductor passes a current continuously without a break. However, if the inductor current became zero for part of the cycle as duty ratio Dcomes out of conduction, then this operation is called discontinuous conduction mode (DCM).

3.2.5 Limitations of Conventional Converters in High step-upApplications

The boost and buck-boost converters are the simplest PWM controlled topologies for voltage step-up. However, these converters typically operate under extreme duty ratio to achieve high voltage gain. As a consequence, significant voltage and current stresses are incurred by the power converter devices and poor dynamic characteristics can result in the controlled output response. Besides, the power device rating is proportional to the output voltage and a high rated power device potentially increases the conduction losses which also degrade the efficiency. Furthermore, the output diodes often sustain short, but high amplitude, current pulses due to the narrow turn off time; which induces reverse recovery losses.

Chapter 4

Topology Evaluation

4.1 Topology Evaluation for High step-up DC-DC Boost Converter

The major obstacle of improving the efficiency of the basic DC-DC converters such as boost and buck-boost in a high step-up application is extreme PWM duty ratio, conduction losses emanating from high rated power devices and reverse recovery related loss of the output diode. In view of these limitations, several work have been carried out to explore numerous topologies with potentials of improving the limitations of basic topologies such as static gain, power devices voltage stress, power density and efficiency. The next section focuses on evaluating these topologies and stating their advantages ordisadvantages.

4.1.1 CascadeConverter

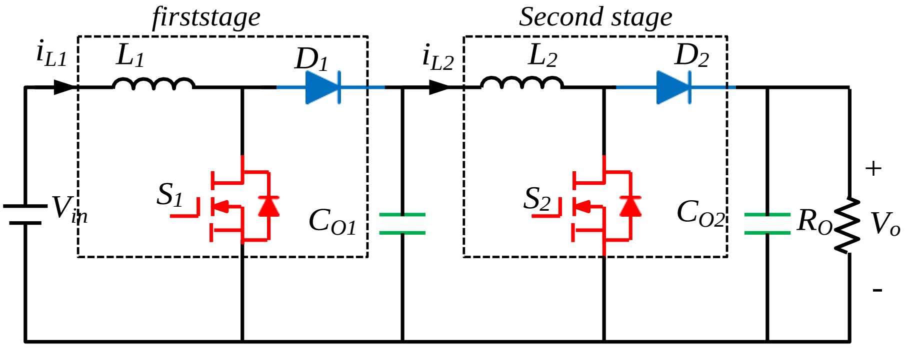


Figure 2.4 Cascade boost converter

The use of two DC-DC boost converters in cascade is an effective method of improving the static voltage gain [56]. It mainly involves connecting the output stage of a boost converter to the input of another boost converter, such that an intermediate bus voltage is developed around capacitor C_{O1}as illustrated in Figure 2.4. Effectively the cascade structure produces an output voltage which is a product of individual boost stages resulting in a higher static gain. By utilising the cascade structure each stage can achieve step-up function without extreme duty ratio operation, thus the conduction and switching losses are substantially reduced. The conduction loss of the first stage can be low, even though the input current is high. For the second stage, the input current is low due to the boost in voltage received from the intermediate bus voltage. However, the device voltage stress in the second stage is the same as the output voltage, and the reverse recovery loss of the output diode can be severe in high power applications. Another major drawback from the efficiency point of view is the energy is converted twice, which obviously has an impact on overall efficiency. Moreover, the interaction between the individually designed boost converters may cause instability inthe cascade converter from a small signal point of view [15].

Application of passive or active snubber cell to the cascade converter to implement (ZVS) for active switches as demonstrated in [36, 57], does not in any way improve the static gain of the original structure. The devices voltage stress usually remains the same with the original cascade structure despite (ZVS) soft switching performance.

4.1.2 Quadratic BoostConverter

In order to overcome the instability issue associated with the cascade connection of two individually designed boost converters, a quadratic converter is proposed in [37, 39, 58], by simply replacing switch S_1in Figure 2.4 with a diode D_3. The quadratic converter operates as two conventional boost converters in series utilising a single switch as shown in Figure 2.5. The quadratic boost converter can achieve wide conversion ratio and, therefore, operate without extreme duty ratio, since the overall voltage gain is the product of the gain of the multiple stages.

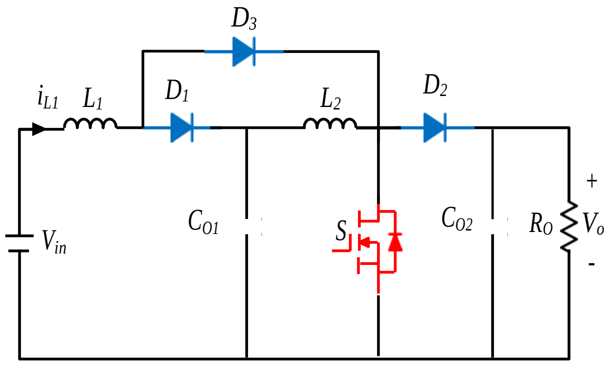


Figure 2.5 Quadratic boost converter

The main drawback of the quadratic boost converter is that the energy is converted twice similar to cascade converter. Furthermore, the power switch $S$and output diode D_2voltage stress is the same with the output voltage; thus high rated devices are necessary in the converter which lead to conduction losses. In high power application, the reverse recovery problem of the output diode is a major concern. The use of quasi resonant cell in the power stage to implement soft commutation can be found in [59].

4.1.3 Three Level BoostConverter

Figure 2.6 shows the three level converter [38, 60, 61], and the circuit has an advantage of voltage stress distribution among the power devices. The device voltage stress is half of the

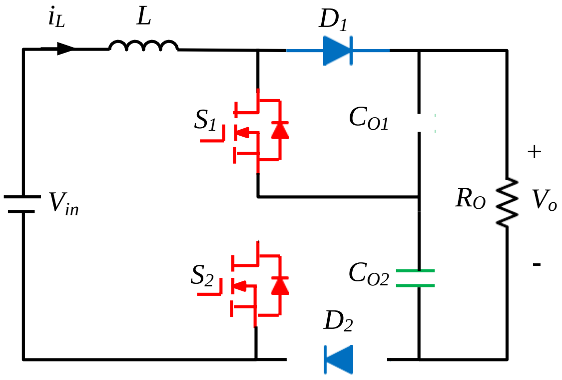


Figure 2.6 Three level boost converter

converter output voltage. Furthermore, the topology allows a significant reduction in inductor volume. These typical characteristics make it more suitable than the conventional boost converter in voltage step-up applications. With low voltage stress across the device, a high-performance MOSFET with low on state resistance can be employed to reduce the conduction loss. The switching loss is significantly reduced being a function of the voltage across the device and electro-magnetic interference (EMI) noise is suppressed.

The main drawback of this topology is that the voltage gain is the same as conventional boost converter as such it is not adequate in many modern applications that require higher conversion ratio of ten times or higher. For this reason, the converter must operate at extreme duty ratio to achieve higher conversion ratio and the diodes reverse recovery losses is another concern. Furthermore, the ripple current is large in high power applications.

4.1.4 Voltage MultiplierCell

An alternative technique to overcome the limitation of classical boost and buck-boost DC-DC converters for high performance and high conversion ratio applications is by use of voltage multiplier cells [23]. The use of voltage multiplier in both low and high frequency isolated DC-DC converters can be traced to Travelling Wave Tube Amplifiers (TWTA), mainly for high voltage gain [62]. The inclusion of the voltage multiplier cell is to reduce the problems of mass, volume and losses associated with the high voltage power transformers. Figure 2.7 shows the basic structure of voltage multipliercell.

The voltage multiplier cell is another classical use of capacitor charge transference which produces an output voltage higher in magnitude than the input voltage without the use of the magnetic element. The voltage multiplier cell can be inserted into classical converters such as buck, boost and buck-boost to implement high step down or high step-up converters [23]. The

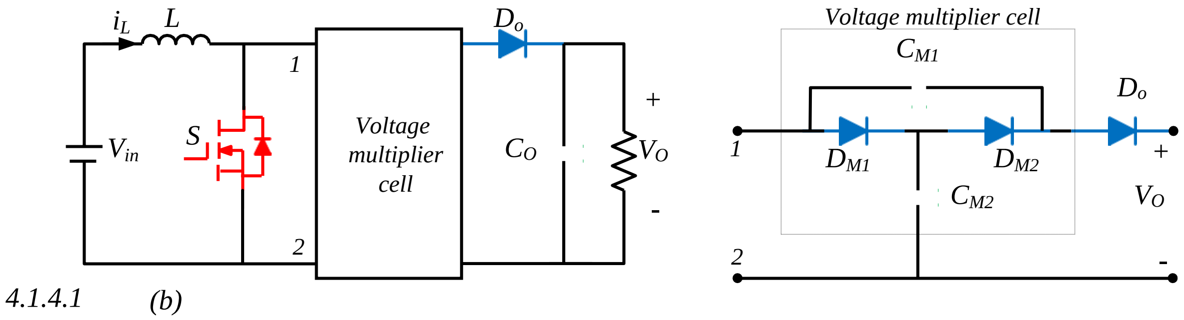


Figure 2.7 Boost converter with voltage multiplier cell
(a) Converter structure (b) voltage multiplier cell

new structure obtained is the same with all basic topologies. It is worth mentioning that insertion of the voltage multiplier cell in buck converter does not offer any practical advantage. When the power switch turns on, the input inductor stores energy and when the power switch turns off, the inductor releases its energy to the output via capacitor C_{M1}. Thus, $C_{M1}$and C_{M2}discharges in series to the output. The power switch voltage stress depends on the number of voltage multiplier cells and reduces as the number of the cells increases. The maximum voltage stress in the multiplier diodes and power switch is equal to half of the output voltage. Higher static gain is possible by employing more voltage multiplier cells at the expense of complexity, cost and a quite substantial amount of diode forward voltage drop. It is worth mentioning that insertion of the voltage multiplier cell in buck converter does not offer any practicaladvantage.

4.1.5 Switched Capacitor/Switched InductorTechniques

The switched capacitor/ switched inductor technique [40] allow achieving steep voltage gain in classical converters. The method uses capacitor/ inductor charge transference to step-up the input voltage. A switching cell formed by either two capacitors and two-three diodes, or two inductors and two-three diodes are combined with classical converters to get a steep function. Depending on the cell configuration, the structures can be of two types: step-up and step down, only step-up is considered here. When the converter primary switch is conducting, the two inductors in the switch inductor cell are charged in parallel, or the capacitors in the switch capacitor cell are discharged in series. When the converter primary switch turns-off, the two inductors are discharged in series or the two capacitors are charged inparallel.

Figure 2.8(a) shows the switched capacitor converter structure and the switched capacitor cell is shown in Figure 2.8(b). The switched capacitor circuit can provide a step-up function of the input voltage based on capacitor charge transference, when inserted in classical boost or buck-

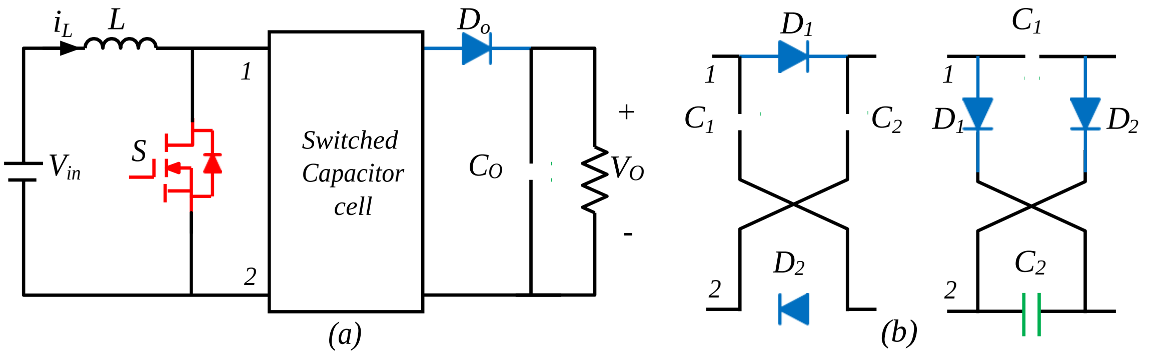
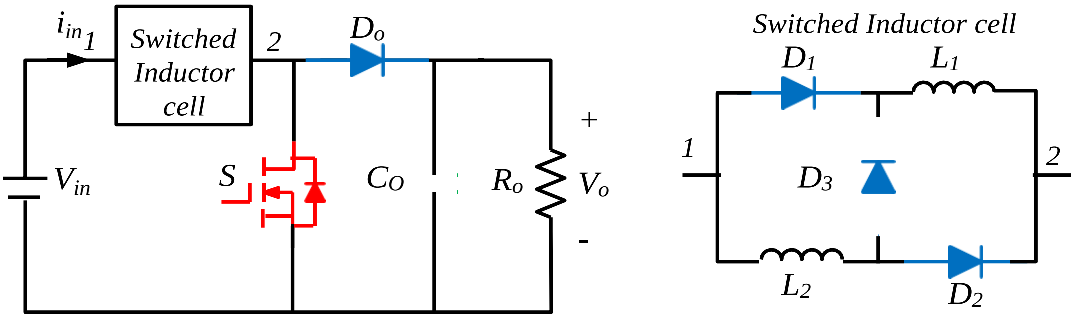


Figure 2.8 Switched capacitor structure
(a) Converter structure (b) Switched capacitor celltopologies

boost converters [40, 63]. The diodes in the cell are forward conducting when the converter switch is turned off, thus, the two capacitors in the switch cell are charged in parallel by the converter input voltage. During the switch turn on instant, the diodes are reverse blocking, and the capacitors are discharged in series. Switched capacitor cell can increase the voltage gain and reduced the device voltage stress[64].

Another famous circuit that utilises switched capacitor circuit is the charge pump and has been used in DC-DC power conversion for a long time especially in the management of integrated circuits. Charge pumps circuit operate based on capacitor charge transference and do not contain inductors [49, 64, 65]. The operation of the power switches in the converter is dictated by PWM duty ratio. Switched capacitor technique permit developing compact, lightweight converter, and the output voltage depends on the number of capacitors used. The efficiency of the converter is significantly reduced when a constant output voltage is required; due to a high pulse current which occurs at switching transient and raise the EMI labels [66]. In high step-up application, the circuit becomes complex with more diode forward voltage drops. Moreover, the number of active devices and their associated gate drives increases both the cost and complexity and the converter is limited to low powerapplication.

On the other hand, the switched inductor cell is formed by two inductors instead of capacitors and 2-3 diodes [40]. The switch inductor cell can as well provide step-up of the input voltage when combined with classical converters such as boost, buck-boost, zeta and sepic converters to create a new power supply. Figure 2.9(a) shows the structure of boost converter with switched inductor cell. Figure 2.9(b) illustrates a typical switched inductor cell. When the converter active switch is on, the diodes $D_1$and D_2became forward biased and the two inductors in the switch inductor cell are charged in parallel. During the switch turn off instant, the diodes $D_1$and D_2became reversed biased whilst D_3become forward biased. Thus, the two inductors discharged in series. Incorporation of switched inductor cell in theclassical



(a) (b)

Figure 2.9 Switched inductor structure
(a) Converter structure (b) switched inductorcell

converters provides a means of increasing the voltage gain, however, static gains of ten times or higher is not feasible without higher duty ratio. In addition, the device voltage stress is the same as the converter output voltage resulting in dominant conduction losses and severe reverse recovery problems limiting its use to low power applications.

4.1.6 Voltage LiftCircuit

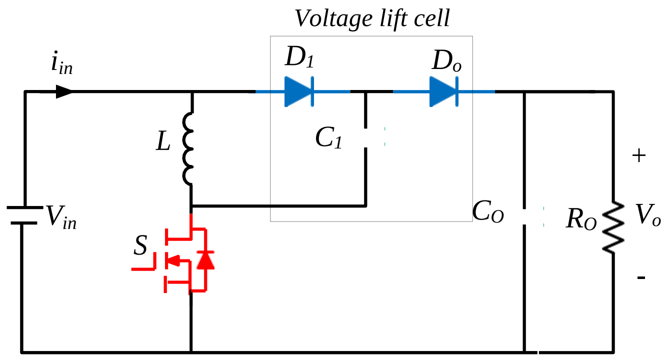


Figure 2.10 Voltage lift converter

Voltage lift technique has been successfully applied in DC-DC converters to implement a series of high voltage and wide conversion ratio [41, 42, 67-69]. The output voltage of a DC-DC converters employing voltage lift technique increases in stage by stage along arithmetic progression [42]. Figure 2.10 shows the voltage lift cell inserted in a conventional boost converter. Boost converter consisting of a single voltage lift cell has a simple structure and fewer components.

In simple term the inductor and the capacitor in the voltage lift cell are charged by the input voltage during the switch on period and both of the capacitors and inductor discharge their respective stored energy in series to the output when the converter switch turns off. The main drawbackisthattheconverter haslowerstaticgainandoperateswithhigher dutyratio operation. Although it is possible to combine multiple lift circuits to push up the static gain, however, the increase in the voltage transfer gain in all cases is obtainable with a significant increase in the number of passive components. Furthermore, the switch voltage stress is the difference between the output and input voltages.

Super lift [41, 67] is another technique of making the output voltage of DC-DC converter increasing in stages along geometric progression with either positive [41] or negative [67]. Effectively the voltage conversion ratio is achieved via power series. Further improvement in voltage gain along a power law is demonstrated in [68] by splitting a capacitor or an inductor. Similar work of improving the static gain in positive output super lift Luo converter by replacing the inductor with switched inductor is presented in [69]. This modification permits realising double increase in the line-to-output voltage ratio at the high values of the duty cycle. However, extreme duty cycle operation results in narrow turn off period of the switch. The output diode conducts a pulse current with high amplitude leading to severe reverse recovery related losses[14].

4.1.7 ActiveNetwork

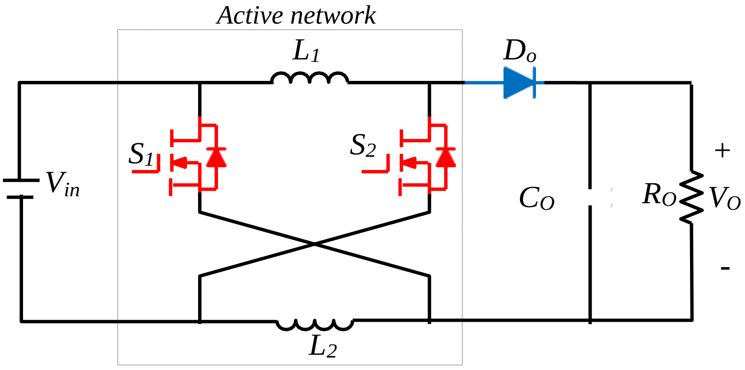


Figure 2.11 Active network converter

The operation of the active network converter is similar to the switch inductor cell [40]. The modification arose from eliminating diode $D_3$from the switched inductor cell in Figure 2.9 (switched inductor converter) and replacing the remaining diodes $D_1$and $D_2$with an active switch as shown in Figure 2.11. The active network converter makes use of two inductors which can be integrated on the same magnetic core resulting in simpler and compact topology. The two inductors are charged in parallel when the active switches turns-on and discharged in series during the switches turn-off period, hence the name active network. The two active switches operate with the same PWM duty ratio[42].

The main drawback of this technique is that the switched inductor converters left alone cannot provide wide conversion ratio. This is related to the fact that the two inductors stores energy similar in magnitude to the input voltage. Therefore, the active network converter provides an output voltage which is only three times higher than the input voltage [42]. This voltage gain is far less than the gain required by many applications. In addition, the output diode voltage stress is more than the output voltage, which can lead to reverse recovery losses in high power application. Besides, utilising active switches that are not connected to the same reference node makes the drive circuitrycomplex.

Extending the static gain of the converter is demonstrated in [42] by integrating the active network converter with a voltage lift cell [41]. Others include switched capacitor active network converter [70], substituting the conventional inductors with coupled inductors in an active network converter [71] and multi-cell switched-inductor/switched-capacitor combined active-network converters [72] mainly to extend the voltage gain.

4.1.8 Transformer Based DC-DCConverters

The transformer is widely used in electrical circuits to step-up or step-down voltage from one level to another and transfer energy between the source and the load with or without galvanic isolation. In the majority of applications, transformers provide an impedance matching between the source and the load. In many applications, it is desired to incorporate a transformer into the switching DC-DC converter to obtain a series of step-up wide range voltage conversion ratio. By adjusting the turns ratio of the magnetic element extreme duty ratio operation can be avoided. Another advantage is that the transformer based converter makes the power switch voltage stress far less than the output voltage. This feature allows low voltage rated power devices with low on state resistance to be employed in order to reduce the conduction loss. The inherent leakage inductance can be used to control the current falling rate of the diode, thus minimising the reverse recovery related loss. Adding multiple secondary winding provide a means of obtaining multiple DC outputs. In some DC-DC converters (such as flyback and forward) a transformer performs a dual function; one is energy storage and two is voltage step-up using the transformation ratio. Theoretically, reducing the magnetic components count. Nevertheless, a transformer provides means of enlarging the voltage gain in other topologies (such as full and half bridgeconverters).

Various high step-up topologies using magnetic means were reported in the literature [10, 43, 44, 48, 50, 73-75].High static gain (ten times or higher) can be achieved by adjusting the turns ratio. However, higher turns ratio implies winding losses and volume. Besides, the volume, weight and losses of the transformer are the limiting factors of producing compact and efficient converter. Furthermore, the leakage inductance of transformers induces high turn off voltage spike on the power device which increases the switching losses, EMI problems which consequently degrades the converter efficiency. The transformer primary current is large in high power application. In addition, the output diode voltage stress is very high leading to the use of high rated power diodes with low switching speed [10, 73,74]

4.1.9 Stacked DC-DCConverters

DC-DC converter stacking is the technique of arranging the capacitor voltages of a converter in series to obtain a higher output voltage which is the sum of nominal capacitor voltages connected in series. Many isolated converters such as current fed converter have been proved as suitable candidates for a high step-up application. A new non-isolated converter topology can be configured from the isolated converter to produce higher conversion ratio by stacking the secondary output side upon the primary output side [44, 76-81]. A high static gain is obtained because the output is in series. The advantages of this concept include distribution of the voltage stress on the semiconductor devices, direct leakage inductance energy recycling to the output side and high static gain. In addition, the secondary side voltage stress is also reduced significantly, since the power diodes voltage stress is the difference between the input voltage and the overall output voltage. This configuration allows part of the power to be directly transferred from the source to the output, leaving the rest of the power to be handled by the converter. The overall efficiency of the converter is improved when the converter manages the power.

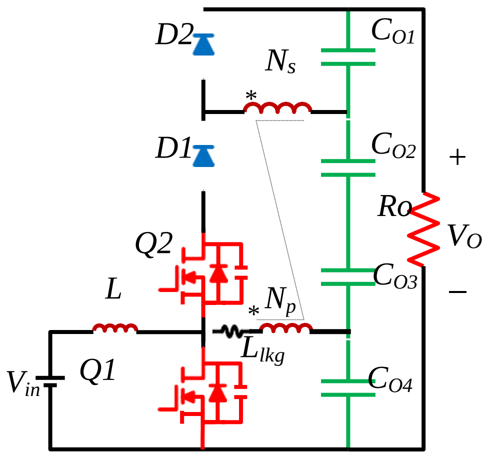


Figure 2.12 Non-isolated stacked converter structure [82]

Figure 2.12 illustrate the stacked converter structure.The simplest topology is the boost flyback converter proposed in [82], derived by combining the conventional boost converter with the flyback converter. Both converters use single a switch and the boost inductor, and the transformer of the flyback are replaced with a coupled inductor. The boost converter acts as clamp circuit to depress the leakage inductance energy. A similar approach of stacking boost converter with sepic converter is described in [78]. Sepic integrated boost converter provides an additional step-up gain with the help of an isolated sepic converter since both the boost and sepic converters share the filter inductor and single power switch.

Other solutions that supplement the insufficient static gain and distribute the voltage stress are demonstrated in [4, 46, 83]. A voltage multiplier cell is usually incorporated to enlarge the voltage gain.

The major drawback of this approach is when a higher static gain is required the voltage stress distribution in the secondary side is no longer the case since most of the voltage stress is impressed on the secondary side. Besides, the audio susceptibility is high due to the direct connection of the input source to the output. Another concern is voltage balance of the output capacitors due to series connection.

4.1.10 IntegratedConverters

At higher output voltage level, the CCM high step-up boost converter is the preferred topology for implementing a front-end converter. It has been mentioned in the preceding sections that high-efficiency is the most needed performance in all applications. It is worth noting that neither the capacitive nor the magnetic means can achieve higher conversion ratio without certain shortcomings. The former technique is based on capacitor charge transference and is successfully applied in voltage multiplier, voltage lift, switched capacitor, etc., mainly for increasing the voltage gain. Moreover, the increase in the voltage gain in all cases is obtainable with a significant increase in the number of passive components. Series connection of cells makes the whole circuit complex with additional current stresses. Whilst the latter (magnetic means) requires higher secondary turns ratio which implies volume, weight, losses which are inimical to achieving highly efficient converter. High-efficiency, high step-up converters have been the focus for many researchers, and a significant number of techniques/topologies have been proposed to this end. Majority of these topologies have been focused on integrating or combining the magnetic means and capacitive means to realise high staticgain.Thebenefitsofintegratingthetwotechniquescanbeexplainedinthreefold.First, lower turns ratio could be used to configure the gain extension cell with appropriate duty ratio since proper duty ratio operation can result in achieving desired operating point without incurring excessive current or voltage stresses. Second, the integration allow utilisation of low power rated devices with low on-state-resistance to reduce the conduction losses. Third, the inherent leakage inductance of the transformer could be used to control the current falling rate of the output diodes and achieve soft switching operation. It is well established in the literature that minimising the reverse recovery characteristics of the diode enhances the conversion efficiency and electromagnetic interference (EMI) significantly [13, 14]. The integrated converter would, therefore, result in simple, compact converter with low parts count. So far, many high step-up boost converters using magnetic and capacitive means have been proposed. They include high step-up boost converters with coupled inductor and voltage multiplier cells [47, 50, 84-86], coupled inductor and switched capacitor techniques [76, 87-89], integrating three-state switching cell and auto transformer [90], three-state switching cell and voltage multiplier cell [91].

The main caharcteristics of the integrated topologies are:

1. Proper duty ratio operation is made possible using the transformation ratio of the magnetic elements, and the output voltage can be further step-up by adjusting the turnsratio.
2. The converter passive components including the transformer operate at the converter switching frequency which permits a reduction in weight andvolume.
3. By proper choice of the turns ratio, voltage stress across the devices is far less than the output voltage, allowing low rated power devices with low on-state resistance to reduce the conduction losses. Likewise the current stress imposed on the power devices is also minimized, leading to improvedefficiency.
4. The turn off voltage spike caused by the leakage inductance energy interaction with parasitic capacitance of the primary switch conventionally required asnubber.
5. The current falling rate of the diode can be controlled using inherentleakage inductance of the magneticelement.

Literature shows that the active and passive clamp solutions are the most widely employed approach for recycling the transformer leakage energy in DC-DC converters. Note that the main advantage of active clamp circuits is recycling the leakage inductance energy and also provides a mecahnism of achieving (ZVS) of the main and clamp switch [48, 50, 73, 74]. Sometimes, zero voltage transition (ZVT) of all the active devices can be achieved [50]. The passive clamp circuits are effective in depressing the power device voltage excursion due to leakage energy. Nevertheless, the passive circuits [43, 70, 75, 76] do not offer (ZVS) of the main switch. However, this does not in any way compromise the conversion efficiency. The downside of the transformer/coupled inductor based converters is large input current ripple in high power applications due to the operation of the coupled inductor.

To increase the power density of the state of the art high step-up boost DC-DC converters, multiphase current interleaving technique has been reported [4, 23, 45, 46, 83, 92-103]. It has been demonstrated that interleaved converters have the advantage of lower device current stress and better efficiency. Interleaved structure is an effective solution of reducing the current ripple, miniaturising the passive components and improving the transient response of a converter. The interleaved structure can only share the converter input current so as to increase the power density, but not to enlarge the voltage gain. High static gain is possible in interleaved DC-DC converters by utilising switched capacitor cell, voltage multiplier cell, transformer turns ratio or their combinations [23,46].

4.2 High Step-up DC-DC Converters Platforms

This section outlines the general platform for developing high step-up converters with wide conversion ratio. The platform consists of voltage gain extension cell that integrates capacitor charge transference and magnetic means. For example, a switched capacitor and coupled inductor can be integrated to configure the voltage gain extension cell. This cell can be inserted between the power switch and diodes of the conventional boost converter to realize high step-up boost converter platform. The typical platform is shown in Figure 2.13.

Due to this voltage extension cell, the main limitations of a basic converter in a high step-up application such as extreme duty ratio operation can be overcome. By proper choice of the turns ratio, the current or voltage stresses imposed on power devices can be dramatically reduced. Consequently, low rated MOSFET with low on-state-resistance can be employed to reduce the conduction losses. In order to increase the power density of high step-up converter, the voltage gain extension cell can as well be inserted in an interleaved structure as shown in Figure 2.14. This platform for the high step-up converter is deduced from proposed concepts introduced in [47, 50, 76, 84-89] and [4, 23, 45-47, 83, 92-103] for single phase and interleaved converters respectively. Also, this platform can be utilised to drive the future high step-up boost converters.

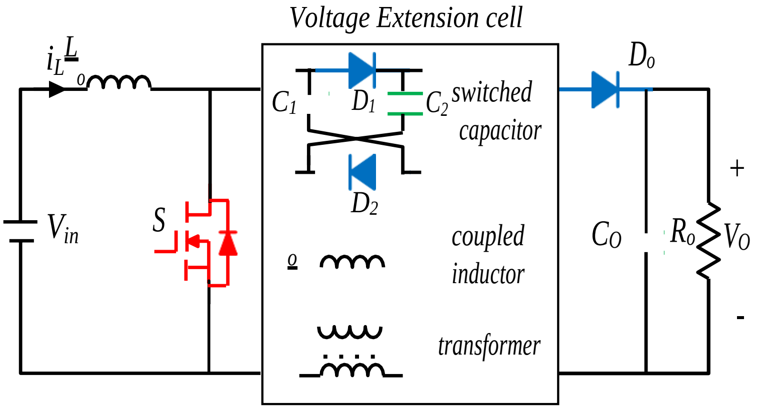


Figure 2.13 Typical circuit for high step-up dc-dc conversion

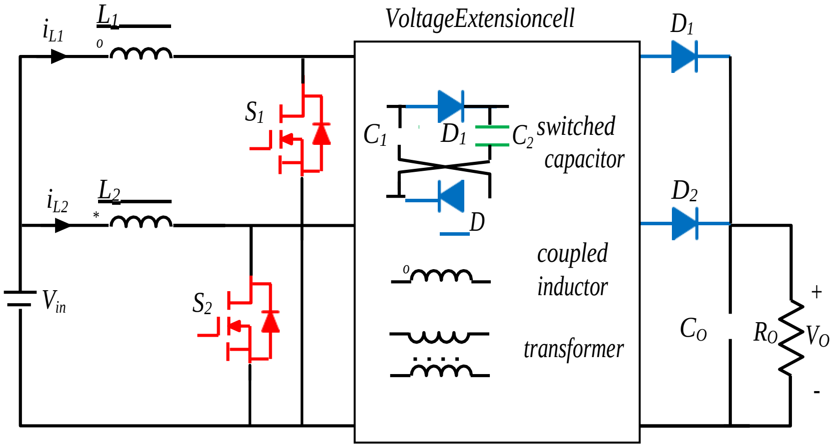


Figure 2.14 Typical circuit for interleaved high step-up dc-dcconversion

Chapter 5

Non-isolated DC-DC Boost Converters

5.1 Classification of Non-isolated DC-DC Boost Converters

Several high step-up DC-DC converters have been proposed in the literature for the purpose of improving key issues associated with conventional topologies, such as efficiency, static gain and power handling capability. State of the art techniques include interleaving, magnetic/capacitor charge transference and their variations. Coveters can be further classified as those with or without wide voltage conversionratio.

5.1.1 Step-up Converters without Wide Voltagegain

Basic boost and buck boost converters are the typical topologies without wide conversion ratio. They have only one degree of freedom (duty cycle) to enlarge the voltage gain. Other topologies without wide conversion ratio includes conventional interleaved, three level boost converters. Figure 2.15 shows the classification of the converters without wide voltage gain.

5.1.2 Step-up Converters with Wide Voltagegain

Wide conversion ratio non-isolated boost converters possess bi-degree of freedom to enlarge the voltage gain. DC-DC converters with wide conversion ratio usually employ magnetic or capacitive means. Integrating magnetic and capacitor charge transference is another technique of realising topologies with wide conversion ratio. Figure 2.15illustrates the family tree of high step-up converters with wide conversion ratio.

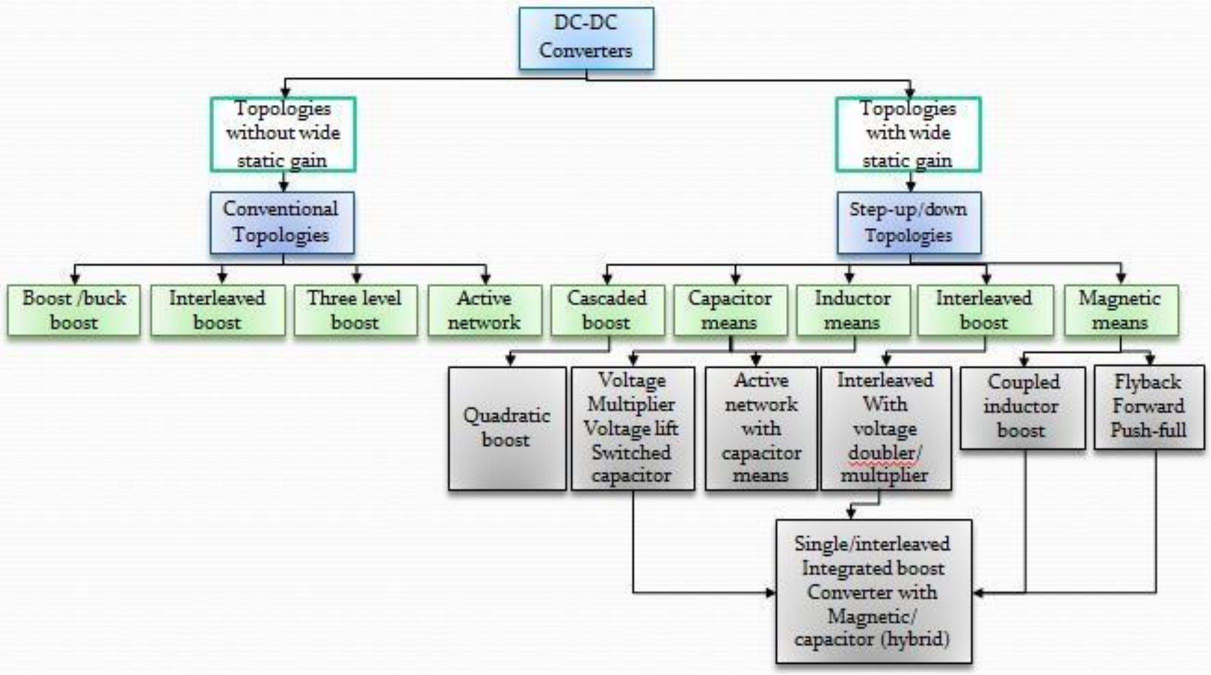


Figure 2.15 Classification of step-up converters

5.2 High Switching Frequency Operation

To accommodate the ever-increasing demand for compact and high efficient power supply, there is need to push the operating frequency of the switch-mode power supply. Since the volume and weight of all the passive components are function of switching frequency. High-frequency operation ultimately reduces the passive components size such as transformer, inductor and capacitor drastically. Increased speed, higher voltage or current ratings and a relatively low cost of these devices are the other factors that have contributed to the emergence of switch mode power supply. However, these benefits of switch-mode power converter come at the cost of higher complexity, hard switching operation which involves higher switching losses and EMI noise. These problems are the major factors that inhibit PWM converters from operating at higher operating frequency. Any attempt to push the operatingfrequencytodesigncompact,high-performancesystem,theswitchinglosesare further aggravated which ultimately compromises the converter efficiency. Although the power devices are capable of being operated at a higher frequency, these problems pose a practical upper limit on the operatingfrequency.

However, reducing the operating frequency is not a good solution regarding power density and cost. As the operating frequency increases so does the switching losses. The switching losses are mainly caused by abrupt turn-on of the switch which causes the energy store in the parasitic capacitance of the device to dissipate within the device. In practice, when a power device makes an instantaneous switching transition (from on to off and vice versa), an overlap exist between current and voltage waveforms [13, 51]. A typical switching trajectory of hard switching power device is shown in Figure2.16.

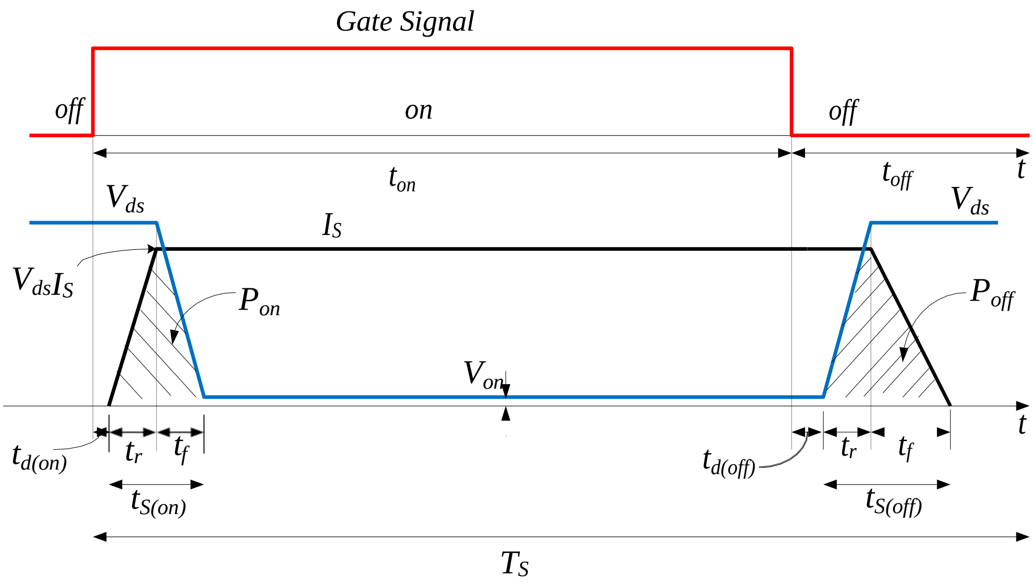


Figure 2.16 Typical linearized switching trajectory of power device

By applying a positive gate signal to the switch; during turn on instant the current build up consist of a short delay $t_{d(on)}$followed by the rise time t_r. After a finite time duration the current flow through the switch and the switch voltage drop to a small on state value $V_{on}$with a fall time t_f. The shaded area indicates an overlap of switch voltage and current during switching transition $t_{(on)}$, $t_{S(off)}$, which denotes power loss during each period. Since power loss depends on the product of voltage and current. The energy dissipated within the device during the switching transition is denoted by $P_{on}$and P_{off}respectively. These losses are referred to as switching losses and are proportional to the switchingfrequency.

Since the efficiency of the power converter is the most needed performance and to achieve higher efficiency, a way to reduce or eliminate the switching losses must be conceived.

Passive turn-on and turn-off snubbers are used to control the rate of rising of voltage or current during switching transitions, clamp voltage overshoot and minimize switching losses. However, snubbers only transfer the losses from switch to the snubber capacitor, and, therefore, do not result in overall reduction of the losses [10, 16]. Switching condition of semiconductor devices in switch mode power supply can be further improved by incorporating certain resonant circuit in PWM converter [59, 104-106]. This modification reduces the switching loss and allows the converter to operate with higher switching frequency. But at the expense of increased circulating current which further increases conduction losses. Another major drawback of the resonant converters is variable frequency operation which makes the design of the passive components difficult[105].

Soft switching is a compromise between the PWM and resonant converter and is targeted towards minimizing the switching losses without a significant increase in circulating current. Soft switching combines the resonant and PWM technique to soften the switching transition and reduce circulating current with fixed switching frequency operation [16, 57, 73, 107]. Soft switching performance is realized with energy recovery snubbers, in which the energy stored in the snubber capacitor or inductor is transferred to the source or load, instead of being dissipated. At any instant the switch is made to change its state (from off to on and vice versa) when either voltage across it or current through it is zero, which minimizes the power loss in the device; such switching action is termed as the soft switching. In zero-voltage-switching (ZVS), the switch changes its state when the voltage across it is zero, whereas in zero-current-switching (ZCS), the switch changes its state when current through it is zero. The (ZVS) or (ZCS), are collectively referred to as soft switching, and can be realized in different ways, which are further described in the subsequent section.

5.3 Soft Switching Performance in High Step-up Converters

In switch mode power converters, the power semiconductors turn-on and turn-off under hard switching condition resulting in switching losses and stress. The switching loss is proportional to the switching frequency, overcoming the problem of switching loss allows higher switching frequency operation in power converters. Various techniques such as passive snubbers, resonant and soft switching techniques can be implemented in the power stages to improve the efficiency of the converters. The concept of soft switching is built around combining the advantages of conventional PWM technique and resonant technique. The soft-switched converter utilizes the resonance in a controlled manner, such that theresonance occurs prior to the turn-on and turn-off instances so as to create (ZVS) and (ZCS) conditions. At all other instances, the converter behaves like a conventional PWM converter. A soft switching technique provides an effective solution of suppressing EMI and has been successfully applied to converters, inverters and rectifiers. (ZVS), (ZCS) and voltage clamping are the emphasis of the next sections [108, 109].

5.3.1 Zero Voltage Switching (ZVS)Technique

The objective of the technique is to use resonance to force the voltage across the device to zero prior to its turn-on or turn-off. A (ZVS) turn-on is implemented by discharging the parasitic capacitor and subsequently forcing the antiparallel diode of the device to conduct prior to the application of the gate signal. Therefore, the switch turns-on with only antiparallel diode voltage drop. A (ZVS) turn-off is achieved sometimes by adding a capacitor across the switch to limits the overlap between the voltage and current during turn-off. If the switch voltage waveform is shaped during turn-on and turn-off period (i.e. switching transition) to create a (ZVS) condition, such phenomenon is called zero voltage transition(ZVT).

MOSFET is used in a medium power, suitable for high switching frequency applications and have significant drain source capacitance; they are mostly used in (ZVS) circuits. An external snubber capacitor is often added to drain-source capacitance to ensure (ZVS) turn-off. To ensure (ZVS) turn-on of the device a negative current usually discharges the snubber capacitor and makes the antiparallel diode conduct so that the device can turn-on with (ZVS) condition.

5.3.2 Zero Current Switching (ZCS)Technique

(ZCS) is another technique similar to (ZVS) that uses resonance to force the current following through the switch to zero during turn-on or off. A (ZCS) turn-on is implemented by including a small inductor in series with the switch that controls the rise of the current when the switch turn-on. During turn-on, the switch current increases linearly from zero. Finally, the switch can be commutated at the next zero current duration. Likewise, if the switch current waveform is shaped during turn-on and turn-off period (i.e. switching transition) to create a (ZCS) condition, such phenomenon is called zero current transition (ZCT). The major drawback of MOSFET when used to implement (ZCS) is the capacitive turn-on losses and high current stress. IGBT is a minority carrier device, have large tail current in the turn-off process. Thus, (ZCS) are useful particularly in minimizing the switching loss forpower devices such as IGBT.

5.3.3 VoltageClamping

In a transformer based DC-DC converter, the interaction between leakage inductance and the parasitic capacitor of the switch induces high voltage stress to the primary switch and traditionally requires a snubber. RCD snubber can be used to limit to switch voltage excursion, however, the energy recovered is dissipated as heat within the snubber. To overcome the limitation of the RCD snubber, a clamp circuit can be incorporated in the power stage to limit the turn-off voltage spike of the switch and recycle the leakage energy. This approach makes use of either passive clamp circuit (composed of a diode and a capacitor) [10, 55] or the active clamp circuit (composed of a switch and a capacitor) [46, 48, 50, 73, 110]. The leakage inductance energy is transferred to the clamp capacitor during the primary switch turn-off period and subsequently recycled to the output. The clamp circuit is always off during boost mode and in series with the primary converter switch. The active clamp circuit not only resets the leakage energy but also realizes (ZVS) for all the active switches [46, 48, 50, 73, 110]. The downside of this method is a significant amount of conduction loss due to circulating current flowing through the clamp switch or its antiparalleldiode.

5.4 Reverse Recovery Characteristic of Output Diode

The CCM of operation is the preferred method of operating boost converter. However, if a boost converter operates under CCM, the reverse recovery current of the output diode has a detrimental effect on the performance of the converter. This is related to fact that once a diode is conducting, and suddenly its forward current reduces to zero (as a result of application of reverse voltage), the diode continues to conducts due to the minority carriers that remain stored within the p-n junction (depletion region of the junction) and bulk semiconductor material. This phenomenon requires a certain time for the minority carriers to recombine with the opposite charges and become neutralized [13]. The reverse recovery time induces more turn on loss to the power switch, which consequently, increases the switching losses and compromises the converter efficiency.

Significant efforts have been made in recent years to improve the efficiency of the high step-up boost converters. One of the key focuses is on alleviating the adverse effect of output diode reverse recovery problem on the conversion efficiency and electromagnetic interference EMI.

The efficiency of CCM boost converter can be significantly improved if the output diodes could be turned off softly [111]. The recent state of the art solutions involve turning the diode off softly by controlling the current falling rate of the diode during turn off with the aid of additional components to form active snubber [104, 112, 113] or passive snubber [114, 115]. The active snubber employs an active auxiliary switch and passive components such as capacitors, inductors, and diodes whilst the passive snubber uses only the passive components.

Besides soft switching turn off of the diode, the active snubber has another advantage of implementing (ZVS) of the main switch. However, adding a snubber circuit with active switch increases the complexity of the converter. Also the active snubber exhibit voltage and current stresses on the devices. The passive snubber behaves in a similar way with the active counterpart with exception of (ZVS) soft switching performance. The main drawback of the snubber circuits is significant current and voltage stresses are incurred by the primary switch which necessitates the use of higher rated components [114,115].

Another approach involves shifting the output diode current to another branch with additional switch and passive component to form an active snubber [111]. The snubber uses only three components to offer soft switching of both the output diode and the added switch at no extra current or voltage stress. This technique produces higher efficiency, because the power loss in the branch is less. The main drawback of this approach is the circulating current in the auxiliary switch increases the conduction loss. Also overlapping between the driver signal of the main switch and auxiliary switch usually leads to short circuit and the overall failure of thecircuit.

A simple and effective method to control the current falling rate of the output diode in CCM boost converter is proposed in [116]. The technique suggests shifting the diode current to a new branch. The new branch consists of a diode and secondary winding of a coupled inductor. Literature shows that a boost converter can achieve current steering using the leakage inductance of the coupled inductor. The current falling rate of both diodes is controlled with no additional current or voltage stresses.

Chapter 6

Conclusion and Further Work

6.1 Introduction

It is likely that significant amount of global future energy requirement could come from RESs; such as solar photovoltaic and ESS such as Li-ion batteries. From this viewpoint, research and development in alternative energy sources has been given utmost importance. This is related to the fact that these RESs and ESS are among the cleanest methods of generating and storing energy. However, the growing use of RESs and ESS brings other challenges to the energy conversion technology; because devices that store or produce electrical energy are often realized using multiple low voltage storage cells, which are usually connected in series to produce sufficient voltages for the intended applications. These challenges make RESs very expensive and inhibit their widespread application. Literature studies have revealed that the major areas of research in energy conversion are improvement of the system efficiency and lowering the system cost. A target area of reducing the power system cost is to eliminate, combine or simplify as many conversion steps as possible. Therefore, the aim of the research in this thesis is to contribute towards lowering the cost, raising the conversion ratio and improving the efficiency of high step-up converter system. Four areas have been highlighted where performance improvements can be made which include:

i) Avoiding extreme duty ratiooperation,
ii) Minimizing the voltage or current stress imposed on powersemiconductors,
iii) Lowering the current falling rate of thediodes
iv) Soft switchingperformance.

A single phase and interleaved high step-up boost converter has been proposed to address the above issues. The proposed innovative solutions have achieved significant performance improvements and higher conversion ratio over the state of the art topologies.

Firstly, higher conversion ratio is realised in all the proposed converter topologies by integrating coupled inductor and switched capacitor to configure a voltage gain extension cell. This integration permits achieving higher voltage gain with lower turns ratio, thus reducing the volume and copper loss associated with the coupled inductor. Furthermore, the coupled inductor turns ratio provides another degree of freedom to enlarge the converter static gain in conjunction with the duty ratio. The extreme duty ratio operation is simply avoided by proper choice of coupled inductor transformation ratio. In addition, the voltage stresses imposed on power devices are minimized. As a result, low voltage rated power devices with low on-state resistance are employed to reduce the conduction loss; leading to improvedefficiency.

Secondly, the turn-off voltage spike seen by the primary switch due to leakage inductance energy traditionally requires a snubber. Literature shows that the active and passive clamp circuits are the most widely employed approach for recycling the transformer leakage energy in a transformer based DC-DC converters. However, a true performance evaluation of the clamp circuits when applied to the same power converter is rarely discussed. This thesis presents the theoretical analysis and clamp schemes performance comparison on the proposed high step-up DC-DC converter. The experimental results, obtained via two prototype circuits, validate both the theory and operational characteristics of each power converter. It is shown that the active clamp converter has the advantage of achieving (ZVS) of all the active switches and achieves 1% higher efficiency than its passive clamp counterpart. On the other hand, the passive clamp converter offers low cost, simple structure, low level of circulating current and higher reliability; thus increasing the lifetime of the converter. Importantly, unlike many power converters presented in literature, both of the proposed topologies in this thesis exhibit low devices voltage stress. The diodes voltage stress is significantly less than the converter output voltage and the low-voltage diodes typically recover faster. The diodes turn off softly with (ZCS) by utilizing the inherent leakage inductance of the coupled inductor to control their current fallingrate.

Interleaving is usually adopted as an effective solution in high power applications to reduce the passive component size, increase the power level, minimize the current ripple, improve the transient response, and realize thermal distribution. In this work, a new (ZVS) interleaved, non-isolated, high step-up DC-DC boost converter with active clamping circuit is proposed. The converter uses two coupled inductors in both forward and flyback mode and a switched capacitor to achieve high conversion ratio. Interleaving is adopted on the primary side to share the input current and cancel the current ripple of the coupled inductors and increase thepower level. The secondary windings of the coupled inductor are connected in series to achieve winding coupled configuration and sustain the high voltage at the output. Importantly, unity turns ratio is utilised to achieve ten times (10X) voltage gain; which reduces the copper loss and leakage inductance of the coupled inductor. Furthermore, the voltage stress of the active switches and diodes are reduced. By adopting active clamping, (ZVS) is achieved for all the switches. The diode reverse recovery problem is alleviated for all the diodes, hence switching losses are further reduced yielding an efficient green power supply solution.

In many DC-DC boost converters, deriving a state space average model of the system is a key step towards predicting the (RHP) zero and consequent design of feedback control system having wide bandwidth and adequate (PM). The derived model must be able to respond to the characteristic of the system. In this work, a fifth-order state space average model of the high step-up interleaved boost converter is derived. A reduced third-order model is later developed from the fifth-order to represents a dynamics model of the current in one phase, voltage on one of the clamping capacitors and the output voltage. This is achieved with the assumption that the other phase of the converter behaves symmetrically. In addition to the symmetry of the phases, the coupled inductors and the clamping capacitors in each phase are considered to be the same. Hence the duty cycle is assumed to be the same in the converter primary switches. A Matlab simulation is used to validate the models; the switching model and the averaged model show a good agreement. After linearizing the model, the control-to-output transfer function is once again verified in simulation using Matlab systemidentification method. The control-to-output transfer function estimated from the measured data after perturbing duty cycle set point with sinusoids of different frequencies, agrees closely with the calculated control-to-output transfer function. A dual loop controller is designed based on the derived power stage model to control the powerflow.

Each concept have been analysed designed and tested by constructing appropriate hardware. The experimental results obtained are presented in this thesis. In this chapter, a conclusion of the work carried out so far is presented and relevant areas that require further investigation are described.

6.2 Single Phase High Step-up Converter

Utilising a coupled inductor is a simple solution of avoiding extreme PWM ratio in high step-up converters. However, the leakage inductance of the coupled inductor induces high voltages stress to the power switch and traditionally requires a snubber. The use of RCD snubbers can reduce the voltage stress, but the recovered leakage inductance is dissipated as heat within the snubber. The limitation of RCD snubbers is largely overcome by either active clamp circuit or passive clamp. The clamp circuits have been explored with the benefit of recycling the leakage inductance energy of the coupled inductor whilst minimising the turn- off voltage spike of the power switch. In this thesis, the non-isolated coupled inductor with active clamping is first introduced. The active clamp circuit is then replaced with the passive clamp consisting of only a diode and clamp capacitor. The passive clamp circuit achieves a level of operation similar to the active clampcircuit.

Theoretical analysis and clamp circuits performance comparison of a new set of high step-up DC-DC boost converters are presented in this thesis. The experimental results, obtained via two prototype circuits, validate both the theory and operational characteristics of each power converter. It is shown that the active clamp converter has the advantage of achieving (ZVS) of all the active switches and achieves 1% higher efficiency than its passive clamp counterpart. On the other hand, the passive clamp converter offers low cost, simple structure, low level of circulating current and higher reliability; thus increasing the lifetime of the converter. Importantly, unlike many of power converters presented in literature, both of the proposed topologies in this thesis exhibit low devices voltage stress. The diodes voltage stress is significantly less than the converter output voltage and the low-voltage rated diodes typically recover faster. The diodes turn off softly with (ZCS) by utilizing the inherent leakage inductance of the coupled inductor to control their current falling rate.

6.3 Interleaved High Step-up Converter

In high step-up interleaved boost converter system, each converter phase is synchronised to the common input voltage source. Consequently, reducing the large current ripple produced by each converter due to coupled inductor operation. The phase shift between the interleaved converter phases is straight forward to implement in software and does not in any way affect the processor execution time. Increasing the number of phases, provides more opportunity for input current ripples reduction. However, it is also reasonable to predict that a point is reached whereby employing the multiple phases in interleaved form can no longer reduce the current ripple in the system. Further study would be required to investigate the limit of increasing the converter phases and extent of the benefit of reducing the current ripple.

The addition of phases in an interleaved form does not in any way increase the static gain of a converter rather than sharing the input current and increasing the power level. Interleaving provides a mechanism of minimizing the input current ripple; improve thermal distribution and reduces the passive component size.

In a single phase high step-up converter system, there is no opportunity for current ripple minimization. Any attempt to push the power level further amounts to relatively high current stress incurred by the switching device (a major detriment of increasing the power density). The winding couple configuration of the secondary side permits achieving ten times (10X) voltage gain even with a unity turns ratio. Unlike the single phase converter and many interleaved converters which require some transformation ratio to realise similar voltage gain.

The coupled inductor of the interleaved high step-up converter serves a dual purpose, energy storage and means of enlarging the voltage gain. The primary windings behave like a conventional inductor at the input and therefore, serve as a constant current source. Theoretically, reduces the number of magnetic component in the converter. The (ZVS) performance of the entire active switches, as well as reverse recovery alleviation of the output diodes, depends on the leakage inductance. Meaning that, the leakage inductance should be design carefully, since higher leakage inductance value degrades the conversion efficiency. It is also worth mentioning that careful attention to the design of the coupling inductor is key to achieving optimum circuit performance; higher efficiency and excellent coupling between the windings is essential to reduce the duty cycle loss cause by the leakage inductance which degrade theefficiency.

6.4 FurtherWork

Literature shows that many works have been carried out in identifying suitable, often novel high step-up converters topologies covering a broad range of applications with improved efficiency. However, further investigation is required in high power density, high step-up DC-DC converters. The future trend is high power density low cost and low profile power electronic converters. The development of miniaturised converter provides the possibility of pushing further the switching frequency to increase the power density. Increasing the switching frequency makes the passive components smaller, but the limit of the switching frequency and extent of the benefits needs further investigation. Increasing the switching frequency exacerbate the switching loss. Another thought is magnetic element integration could, of course, produce a compact converter. Further study of the coupled inductor interleaved power converters and performance improvement via design optimisation, as well as comparison with the current state of the art topologies, would be an interesting research topic.

Literatures have further revealed that current state of the art topologies for high step-up applications employ capacitor charge transference or magnetic elements. Nevertheless, integrating capacitive and magnetic means mainly for voltage gain is another popular method. However, further research on gain extension cells could lead to new topologies with the potential of improving the efficiency.

The control structure of the proposed converters utilises a classical current mode PI controller and has a smooth regulation. But for all other applications, a certain control scheme needs to be developed and investigated. For example, in particular, battery charging application requires the controller to switch at one point from a voltage controlled to the current controlled mode depending on the state of the charge (SOC) of the battery. In essence, the transition between current mode to voltage mode battery charging and mode transition between voltage mode battery charging and battery voltagedischarging.

The traditional averaging method has been used in this thesis to obtain information about the stability of the high step-up interleaved boost converter and its dynamic behaviour. However, literature has shown that averaging method itself is accurate up to about one tenth of switching frequency. Furthermore, whilst the averaging technique can capture the instabilities that occur on a slow time scale, it did not account for all phenomena that occur at switching frequency. At switching frequency, the fast scale instabilities that may develop in the converter waveforms can lead to subharmonic oscillation and chaos. Further study of analysing and prediction of such instabilities would be another interesting researchtopic.

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