ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ

ΠΟΛΥΤΕΧΝΙΚΗ ΣΧΟΛΗ

ΤΜΗΜΑ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ ΚΑΙ ΜΗΧΑΝΙΚΩΝ ΥΠΟΛΟΓΙΣΤΩΝ

Σχεδιασμός επαγωγικών DC/DC μετατροπέων

Διπλωματική Εργασία

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Βόλος 2020

UNIVERSITY OF THESSALY

SCHOOL OF ENGINEERING

DEPARTMENT OF ELECTICAL AND COMPUTER ENGINEERING

DESIGN OF INDUCTIVE DC/DC CONVERTERS

Diploma Thesis

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Volos 2020

ACKNOWLEDGMENTS

To everyone who contributed to this project.

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List of Abbreviations

AC	Alternative current
AEA	All electric aircraft
BJT	Bipolar junction transistor
CCM	continuous conduction mode
CP	charge pump
CT	center tap
CW	Cockcroft Walton
D	duty cycle
DAB	dual active bridge
DC	Direct current
DC/DC	direct current to direct current
DCM	discontinuous conduction mode
DPS	dual phase shift
e.g.	for example
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EPS	extended phase shift
eV	electronvolt
FC	fuel cell
FET	Field effect transistor
Fig	Figure
GaAs	gallium arsenide
GaN	gallium nitride
HBC	Hybrid boost converter
HV	high voltage
HVDC	High voltage direct current
IGBT	Insulated gate bipolar transistor
ISG	Intergrated starter generator
k	voltage conversion ratio
kWh	kilowatt-hour
LDO	Low dropout regulator
LV	low voltage
MEA	More Electric Aircraft
MOS	Metal Oxide Semiconductor
MOSFET	Metal oxide semiconductor field effect transistor
MW	megawatts
mW	milliwatts
NiCd	Nickel-cadmium
NMP	non minimum phase
PIPO	paraller input parallel output
Pout	output power
PS	phase shift
PV	photovoltaic
PWM	pulse width modulation

QBC	Quadratic boost converter
RDS	the total resistance between the drain and the source of the MOSFET
RHP	right half plane
rms	root mean square
SC	switched capacitor
Si	silicon
SiC	silicon carbide
SOA	safe operating area
SPS	single phase shift
TPVD	two phase voltage doubler
VGS	voltage gate source
VL	voltage lift
VMC	voltage multiplier cell
VMR	voltage multiplier rectifier
WBG	wide bandgap
ZCS	zero current switching
ZVS	zero voltage switching
η	efficiency

List of symbols

Περίληψη

Η αύξηση της κατανάλωσης και της ζήτησης της ηλεκτρικής ενέργειας στα σύγχρονα αεροσκάφη, ενθαρρύνει τους κατασκευαστές να ενσωματώσουν ηλεκτρικούς ενεργοποιητές για την ρύθμιση των επιφανειών ελέγχου πτήσης και άλλα μεταβατικά φορτία υψηλής ισχύος σε μελλοντικά αεροσκάφη. Προκείμενου να επιτευχθεί κάτι τέτοιο, απαιτείται η χρήση DC/DC μετατροπέων ισχύος. Στην παρούσα διπλωματική εργασία, αναλύεται και σχεδιάζεται ένας μετατροπέας DC/DC για μετατροπή ισχύος μεταξύ των επιπέδων τάσης 28V/270V, κατάλληλος για εφαρμογές αεροδιαστημικής.

Αρχικά, δίνονται βασικές πληροφορίες σχετικά με τα χαρακτηριστικά των DC/DC μετατροπέων. Οι μετατροπείς DC/DC υψηλού επιπέδου αποτελούν βασικό στοιχείο σε φορητές ηλεκτρικές συσκευές και σε άλλες εφαρμογές. Παρουσιάζονται οι διάφορες κατηγορίες μετατροπέων, με βάση τα χαρακτηριστικά τους, και εισάγονται οι πιο κοινές τεχνικές ενίσχυσης τάσης. Απεικονίζονται θεμελιώδεις τοπολογίες DC/DC μετατροπέων ισχύος, κατάλληλες για πολλές εφαρμογές.

Επιπλέον, παρουσιάζεται μια γρήγορη ανάλυση των εξισώσεων που περιγράφουν και χαρακτηρίζουν ένα κύκλωμα μετατροπέα σε λειτουργία σταθερής κατάστασης. Εξηγούνται οι δύο τρόποι λειτουργίας ενός συμβατικού μετατροπέα ώθησης, ο τρόπος συνεχούς αγωγιμότητας (CCM) και ο τρόπος ασυνεχούς αγωγής (DCM).

Στη συνέχεια, ένας αμφίδρομος απομονωμένος μετατροπέας διπλής ενεργούς γέφυρας (DAB) DC/DC επιλέγεται ως ο καταλληλότερος για αεροδιαστημικές εφαρμογές, καθώς διαθέτει πολλά πλεονεκτήματα. Εξηγείται και αναλύεται θεωρητική και μαθηματική ανάλυση σταθερής κατάστασης του DAB για λειτουργά υποβιβασμού και ανύψωσης τάσης. Τέλος, ένα πρωτότυπο σχέδιο μετατροπέα σχεδιάζεται και κατασκευάζεται μέσω του λογισμικού MathWorks MATLAB / Simulink, με σκοπό την επαλήθευση της λειτουργίας του.

Abstract

The increase of electrical energy consumption and demand in modern aircraft, stimulates manufacturers to employ electrically powered actuators for adjusting flight control surfaces, and other high power transient loads in future aircrafts. To achieve this, DC/DC power converters are mandatory. In this thesis a DC/DC converter for power conversion between 28V/270V voltages levels, suitable for aerospace applications, is analyzed and designed.

Firstly, basic information about the characteristic of the DC/DC converters is given. High step-up DC/DC converters are for major concern in portable electronic devices and in other applications. Several categories of step-up DC/DC converters, based on their characteristics, are presented and the most common used voltage boosting techniques are introduced. Many fundamental power converter topologies suitable for many applications are illustrated.

Additionally, a quick analysis of the equations that describe and characterize a converter circuit in steady state operation are proposed. The two operating modes of a conventional boost DC/DC converter, the continuous conduction mode (CCM) and the discontinuous conduction mode (DCM), are explained.

Moreover, a bidirectional isolated dual active bridge (DAB) DC/DC converter is chosen as the most suitable for aerospace applications, as it features many advantages. A theoretical and a mathematical steady state analysis of the DAB in both buck and boost mode are explained and proposed. Finally, a converter prototype is designed and built through MathWorks MATLAB/Simulink software, for the purpose of verifying its operation.

Chapter 1 Introduction

The worldwide airline industry has carried 4.5 billion passengers in 2019 with a passenger growth of 5% from last year. The industry contributes almost 900 million tons of carbon dioxide emissions, which is around 2% of all CO2 emissions produced by human activity. It is absolutely recognized that emission of carbon, nitrogen oxides, halogens and other products, coming from the burning of aviation fuel have serious effects on the climate change. Additionally, the industry faces increasing problems on rising fuel costs. To reduce its impact on mankind, governments are encouraging technological innovation towards reducing heat-trapping gases and preventing further deterioration of the environment and safeguarding the health and well-being of current and future. Currently, air transport focuses on reducing future gas emissions in the transport sector and making environmentally-friendly flights to facilitate local and global transport. The solutions of these issues, is improving fuel efficiency by using pure electric technologies in aircraft airframes. A study completed by NASA demonstrated that using more electrical technologies for a typical 200 seat aircraft could result in a 10% reduction in aircraft empty weight, a 13% reduction in required engine thrust and a 9% reduction in aircraft fuel burn, which are significant improvements both economically and environmentally. The development of more efficient aircraft designs with reduced cost, emissions, noise and fuel burn is the motivation of More Electric Aircraft (MEA). [3]- [7].

1.1 Moving towards More Electric Aircraft

Conventional aircraft architectures used for civil aircraft embody a combination of systems dependent on mechanical, hydraulic, pneumatic, and electrical sources. In a conventional architecture, as shown the basic schematic in figure 1.1, fuel is converted into power by the engines. Each system has become more and more complex, and interactions between different pieces of equipment reduce the efficiency of the whole system. As a result, aerospace industry is promoting the use of more electrical technologies. The "all-electric" aircraft is not a new concept. Since the early 1990s advances have been made with the aim of reducing or eliminating centralized hydraulics aboard aircraft and replacing them with electrical power.

Aeronautical distribution technology and the More Electric Aircraft (MEA) concept have gained an increased importance. The development of more-electric and an all-electric aircraft (MEA and AEA) is a step in the evolution of more efficient aircraft. New ways of generating, distributing, and using power onboard are examined at the aircraft level. "More Electric Engines" (MEEs), fuel cells, variable frequency generators, complex embedded digital systems and distributed system architectures are just a few of the technologies suitable aircraft, known as the concept is known as "More Electric Aircraft" (MEA) presented in figure 1.2. In fact, hydraulic, mechanical, or pneumatic power sources are replaced by electric systems, in a wide range of aerospace applications. Some of the key benefits of replacing non-electrical system with electrical system are:

- The enhancement of the performance and increase the reliability of aircraft systems and subsystems.
- The reduction in total weight (of about 50%) and operating costs of the aircraft.
- The more efficient energy conversion.
- The improved reliability and safety.
- The reduction of noise.
- The easier maintenance.
- The low pollution and a significant reduction in the fuel burn.

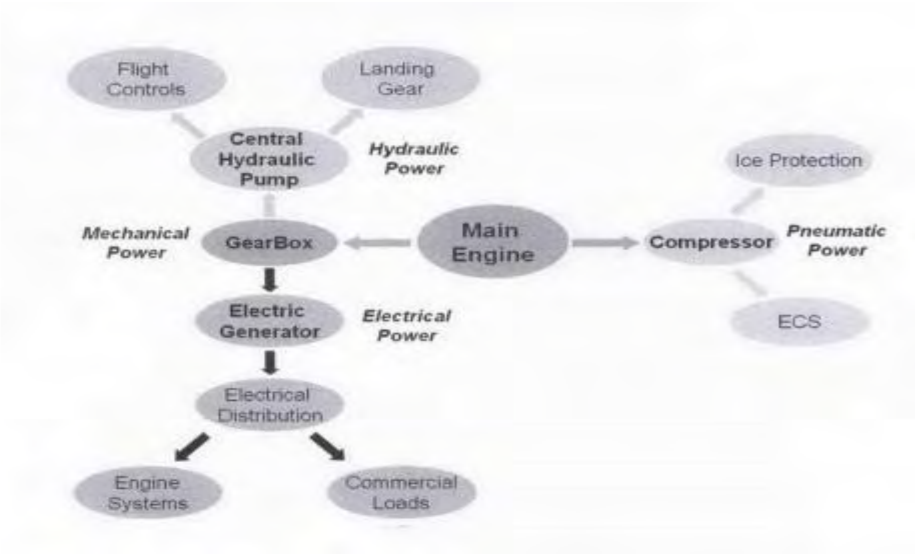


Figure 1. 1 Schematic of conventional power distribution [4]

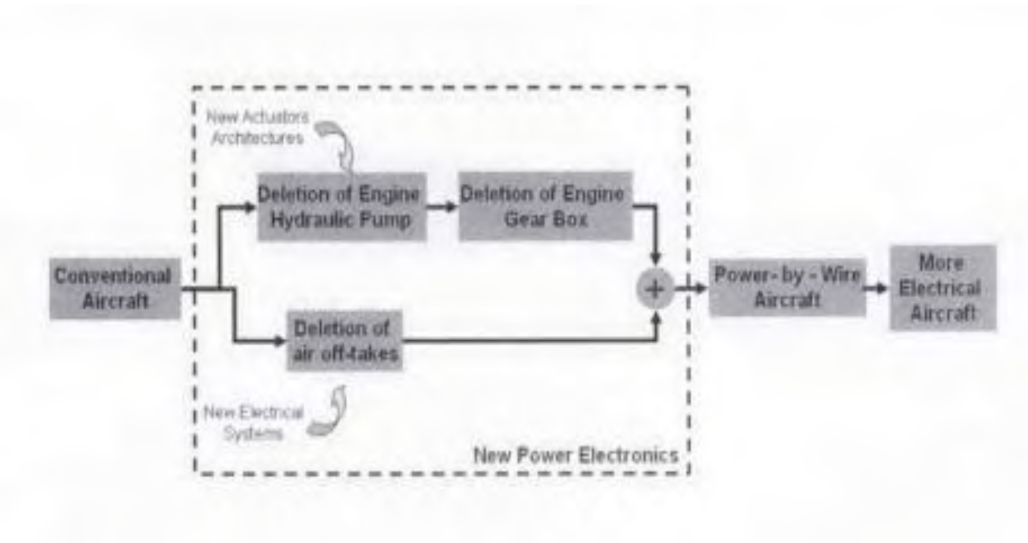


Figure 1. 2 Concept of More Electric Aircraft (MEA) [4]

1.2 Motivation

This increase, in electrical energy demand, has led to a rapid technology development. Not only more suitable energy storage systems are required, but also more suitable power electronics for integrating the storage devices into the supply network are mandatory. More electric technology revolution in aerospace applications has put forward several challenges to design engineers to ensure that aircraft systems and subsystems are ultra-reliable, compact, easy to maintain, low cost and of high performance.

Hence, the increase in energy density of storage devices and the state-of-art converter types, has led the conventional methods of energy transfer in aircrafts to be replaced by power electronics converters.

The focus of this project is on electrical technologies that can feed power at the right output voltage and power level with all desired features and specifications to each electrical and electronic subsystem. Such a power system within the aircraft will require electrical power generation with high speed generators, HVDC power transmission and DC power storage. Thus, DC-DC power converters have an important role to interface the transmission and storage subsystems.

1.3 Aircraft Electrical System Overview

The electrical system for a commercial aircraft is a complex mix of AC and DC components intended to form a reliable and redundant system. The electrical system can be divided into four sections: power sources, power distribution, power conversion, and electrical loads. Power comes from the generators and battery. The generators take power from the engines through a gearbox. Power is then distributed by the AC and DC buses. Power is converted by the transformers, inverters, and rectifiers and is consumed by the electrical loads to do work or provide other functions. DC/DC power converters convert the power they take from buses and deliver it to other buses so as to be delivered to the loads. In order to design an efficient aircraft system, there are 4 design paths that have to be followed: [5], [6].

- The power rating, depends on the type, capacity, range, speed of aircraft and the type of electrical system that is used.
- The power density. The volume of the aircraft body is designed based on structural efficiency and to support aerodynamic shape and reduce drag. To minimize operation costs, the economic incentive for airline carriers is to maximize the passenger or cargo volume inside the aircraft
- The fault management. Any fault management strategy consists of both system design as well as individual components that can reliably isolate parts of the electrical network during a fault.
- The reliability. There are some tests that measure the reliability of individual semiconductor switching components.

1.4 Organization of the Thesis

This chapter gives background information about the research area, the main goal of the research and describes the structure of the thesis.

In the second chapter, a general overview of DC/DC converters is proposed. The two types of voltage conversion; linear and switched are presented and discussed. Chapter 3 focuses on the categories of high step up DC/DC converters, based on their characteristics and the voltage boosting techniques that are used.

Chapter 4 gives general information about the steady state and the operation modes of a conventional boost DC/DC converter, while chapter 5 illustrates the semiconductor devices and the materials that are used in a high step-up converter, suitable for high efficiency applications.

The sixth chapter proposes a DAB DC/DC converter topology, suitable for the aircraft system. The converter must be designed to provide high power density and high efficiency, to be integrated in the aircraft structure with minimum impact on volume, weight and heat management, in order to improve the performance of the aircraft system. Such type of converter will be used to interface between the aircraft power distribution bus and adjusts its input voltage to the voltage at the specific loads. After a theoretical operating and steady state analysis of the converter, chapter 7 focuses on the design and construction of the DAB. It includes the selection information of power semiconductor devices, coupling inductor, transformer, input and output filter capacitors, battery and snubber capacitors.

In chapter 8, simulation results through MATLAB Simulink software verify the operating performance of the DAB for both forward and reverse operating modes under single phase shift modulation. Finally, conclusions and contributions in the research are summarized.

Chapter 2 Background Information of DC/DC converters

Modern AC/DC and DC/DC converters have been extensively studied and implemented, to provide efficient power conversion so as to deliver a controlled, safe and well-regulated DC power supply for a variety of electronic instruments, devices and systems. The design and use of converters is becoming increasingly widespread. Reasons for that, include the growing mobile consumer market, such as cell phones, notebooks and digital cameras, the spread of automotive electronics, as well as the need of handling with ever-higher voltages and transforming the power grid. DC/DC converters can interconnect grids with different voltage levels, technology and architectures.

2.1 DC/DC Voltage conversion

The Direct-Current to Direct-Current (DC/DC) converter is an electronic circuit which can convert a DC voltage into another DC voltage. It has been widely used in current portable electronic devices for regulation of supply voltages. They can be used either to step-up or step-down the supply voltage. The two basic types of voltage conversion, linear and switched mode, are discussed. Several methods exist to achieve DC/DC voltage conversion, since the last decades, but before choosing the best method for the appropriate application, there are specific parameters that we have to take into account such as: [2]

- Power conversion efficiency η, which is the percentage of output power and input power as defined by the equation 2.1. It is the primary conversion specification for any given energy converter, since it is fundamental goal for every DC/DC converter to maximize the power efficiency and to minimize the dissipated power, that transferred into heat.

$$\eta = \frac{Pout}{Pin} \quad (2.1)$$

- The voltage conversion ratio range k, which is the ratio of the output voltage (Vout) over input voltage (Vin), as defined by 2.2.

$$k = \frac{Vout}{Vin} \quad (2.2)$$

- The maximal output power, Pout.
- The number of components and elements in the circuit.
- The power density.
- Galvanic separation of input and output.
- Output ripple: Output voltage fluctuation amplitude when the output voltage ripple is in steady state.
- Current ripple.
- Transient load response: After the load current changes, the time to regain the referenced output voltage represent the transient load response capability.

2.2 Linear DC/DC converter

The first and oldest method of performing DC-DC voltage conversion is by means of linear voltage converters. Linear converters achieve DC-DC voltage conversion by dissipating the excess power into a resistor, making them resistive dividers. This kind of DC-DC converter is also named low-dropout regulator (LDO). There is a control circuit, which adjusts the value of the variable resistor so as to regulate the output voltage to the desired value. They are simple to implement as they do not need large and space consuming inductors and capacitors. However, they function only as step-down converters as their output voltage is generated by a division of the input voltage. Another drawback of this method is the poor power conversion efficiency (n_{lin}). Since the excess power is dissipated on the resistor, this method is inefficient. There are two basic categories of Linear DC/DC converters the series DC/DC converter and the shunt DC/DC converter.

2.2.1 Series converter

Figure 2.1 shows a typical circuit or a linear series DC/DC converter. R_{series} is placed in series with R_L, lowering V_{in} to V_{out} . R_{series} is controlled by the control system, which keeps V_{out} constant under varying values of R_L and V_{in}. The control system uses V_{in} as supply voltage and consume, however, power which is illustrated by I_{cs}. The power conversion efficiency (n_{lin}) of a linear series DC/DC converter can be calculated by (2.3), when I_{cs} is neglected and assumed to be zero. It is clear that n_{lin} is independent of R_L and it tends to decrease when Pout decreases.

$$n_{lin} = \frac{Pout}{Pin} = \frac{VoutIout}{Vin(Iout+Ics)} = k_{lin} \quad (2.3)$$

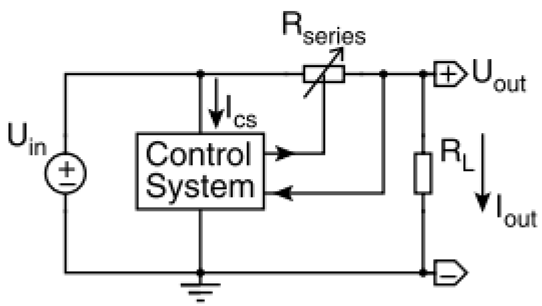


Figure 2. 1 A typical circuit of a linear series DC/DC converter [2]

This type of converter is characterized by simple nature and lack of large passives. However, as the excess power is dissipated as a Joule-loss in R_{series} , the maximal Pout is limited by the allowed on-chip power dissipation.

2.2.2 Shunt converter

A typical circuit of a linear shunt DC/DC converter can be seen in figure 2.2. V_{in} is lowered to V_{out} by means of the resistive division between the fixed R_{in} and both R_L and R_{shunt} .The output voltage is calculated by the equation (2.4). The control system adapts the value of R_{shunt} so as V_{out} to be kept constant under varying R_L and V_{in} . Shunt linear converter has a self-start circuit, so V_{out} can be used as supply voltage to control the system. The power conversion efficiency (n_{lin}) can be obtained by the equation (2.5), when I_{cs} is neglected and assumed to be zero.

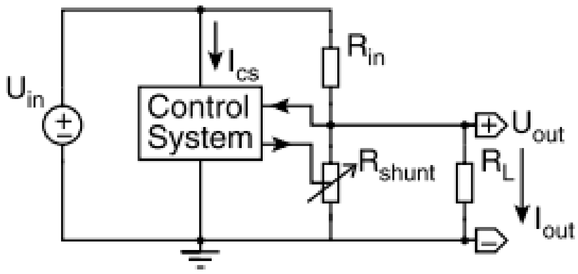


Figure 2. 2 A typical circuit of a linear shunt DC/DC converter [2]

$$V_{out} = V_{in} \frac{\frac{R_L}{R_{shunt}}}{R_{in}+\frac{R_L}{R_{shunt}}} \qquad (2.4)$$

$$n_{lin} = \frac{Pout}{Pin} = \frac{\frac{Vout^2}{RL}}{\frac{Vin^2}{Rin+\frac{RL}{Rshunt}}} = \frac{Vout^2}{RL} \times \frac{Rin}{Vin^2 - ViVout} \quad (2.5)$$

It is clear, that n_{lin} is linear dependent on Pout. This makes a linear shunt converter inferior compared to a series converter, in terms of n_{lin}. However, its simple practical implementation makes it suitable for applications that require a small and quasi constant Pout. Furthermore, a linear shunt converter can prove to be more practical than a linear series converter in applications that have a low value for klin and Pout, and is useful in many designs due to its self-start feature.

2.3 Switched mode DC/DC converters

Except for the elementary linear voltage converters, which can only be used for stepping-down applications, DC/DC voltage conversion can be achieved by switched-mode DC-DC converters. These types of converters originated with the development of pulse width modulated (PWM) boost converter, which is a fundamental DC/DC voltage step-up circuit. PWM converter is suitable for various simple and low cost applications, has a low number of components but it characterized by low efficiency and hard switching. The key principle in switching voltage converters is energy conservation.

A power source firstly stores some energy in a single or coupled inductor, transformer, or capacitor through the use of various active or passive switching elements (power switches and diodes), in one phase, and then the same amount of energy will be transferred from those energy reservoir components to the output in the other phase. Thus, allowing for generating a different higher voltage from the power source.

The switch is realized using semiconductor devices, such as transistors and diodes, which are controlled to turn ON and OFF as required to perform the function of the ideal switch. Switching power converters have the potential to achieve a desired voltage conversion ratio with high efficiency. Switching can be ideally lossless and therefore can achieve higher power conversion efficiency than do linear voltage converters. That's the reason why they are widely accepted in power source management. There are three fundamental conversion methods:

2.3.1 Capacitive or Charge-pump DC/DC converters

In order to implement a DC-DC converter is using a switched-mode charge-pump circuit to realize the step-up or step-down voltage conversion.

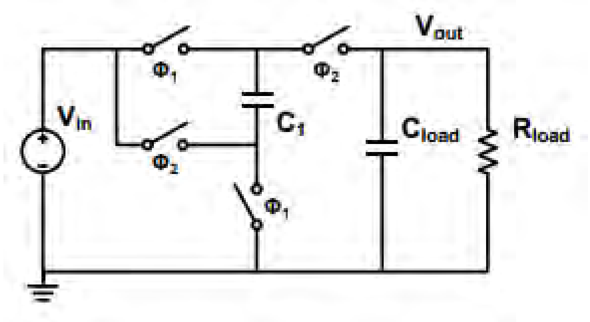
This kind of DC-DC converters only uses capacitors as energy-storing elements and power switches. By periodically turning on and off the power switches, the topology of the circuit is changed, thus achieving the voltage conversion.

Figure 2.3 shows the circuit and the operating principle of a step-up charge-pump DC-DC converter. In the first phase ($\Phi 1$), the capacitor $C1$ is connected to the input voltage source and energy coming from the input is stored in $C1$. In the second phase ($\Phi 2$), the capacitor $C1$ is connected to the load capacitor $C2$ and the energy stored in $C1$ is delivered to the load capacitor $C2$. The output voltage of this DC-DC converter can be obtained by Equation (2.6).

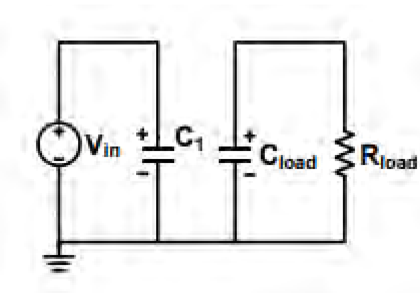
$$V_{out} = \frac{2R_L f_s C_1}{1+R_L f_s C_1} V_{in} \quad (2.6)$$

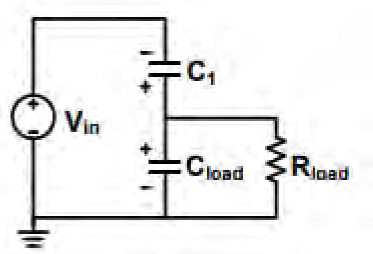
An ideal DC/DC converter can achieve 100% efficiency. However, in reality due to non-negligible static and dynamic power losses of the power switches and the complex control circuit, the efficiency can't be as perfect as expected.

The energy charging efficiency Nc_charge is higher when the steady state region is more closely approximated, or when the Vc(0) is being charged as close as possible to Vin.



(a)





(b) (c)

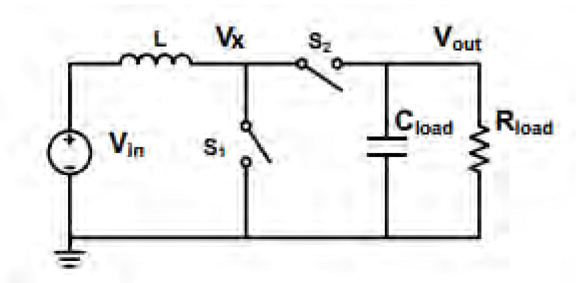
Figure 2. 3 (a) schematic of a charge-pump DC-DC converter, (b) schematic of a charge-pump DC-DC converter during first phase Φ1, (c) schematic of a charge-pump DC-DC converter during second phase Φ2 [2]

2.3.2 Inductive boost DC/DC converters

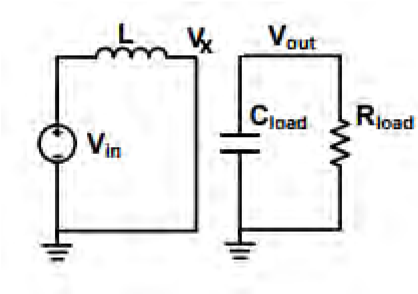
Voltage conversion can also be achieved by inductor-based DC/DC converters. This type of switched-mode DC/DC converters is a combination of an inductor and a capacitor. Figure 2.4(a) shows the circuit and the working phases of an inductive step-up DC/DC converter, where he output voltage is higher than the input voltage ($V_{out} > V_{in}$).

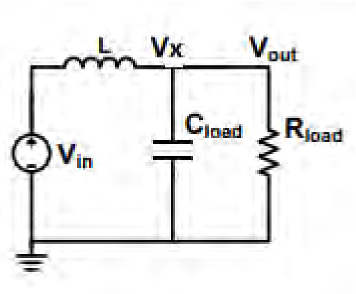
In the first phase, fig. 2.4(b), when the active switch S1 is closed and S2 is opened, Vx is grounded providing a charging path from the input power source through the inductor L to the ground. The inductor current level increases in this phase storing energy in L. In the second phase, fig. 2.4(c), when the switch S1 is opened and the switch S2 is closed, the inductor charges Vx to be equal to V_{out} , as currents flows through the diode to the output capacitor C. Multiple switching cycles build the output capacitor voltage due to charge it stores from the inductor current. This results in an output voltage that's higher than the input.

The charging of inductors by means of a voltage source is ideally lossless, unless a finite non-zero series resistance is assumed. Similar to charge-pump circuit an ideal inductor-based step-up circuit can reach 100% efficiency. However, since the number of the power switches in an inductor-based DC/DC converter is generally half of that in a charge-pump DC/DC converter, the power losses caused by the power switches and the control circuit, are less. Therefore, the power conversion efficiency of the inductive converters is better.



(a)





(b) (c)

Figure 2. 4 (a) An ideal boost switched inductor-based DC/DC converter, (b) An ideal boost switched inductor-based DC/DC converter during first phase φ1, (c) An ideal boost switched inductor-based DC/DC converter during second phase φ2 [2]

Chapter 3 Literature review on Step-up DC/DC converters

The recent emphasis on energy efficiency and renewable energy development has intensified research on step-up converters in both academia and industry. The overall technological advancement is leading to increasing levels of power demand from a number of applications and systems. There are voltage and power requirements of DC/DC converters employed in relevant applications.

In ultralow-power applications, conventional boost DC/DC converters are being used to step up the voltage level of micro energy sources with low voltages and low currents, using solar, thermoelectric, motion or vibration energy. Usually Pulse Width Modulated (PWM) or other fundamental step-up DC/DC converters are used in such applications. They have small size and low weight, they are simple to implement with low cost as they consist of a low number of components (an inductor, a switch and a diode). They can operate either in CCM or DCM. However they are hard-switched types with severe reverse recovery in the output diode and they are characterized by low efficiency.

In this chapter, we are going to analyze, discuss and categorize step-up (boost) DC/DC converters. They have the ability to convert a lower input voltage into a higher output voltage. DC–DC converters with voltage boost capability are widely used in a large number of power conversion applications, from fraction-of-volt to tens of thousands of volts at power levels from milliwatts (mW) to megawatts (MW). [8]-[14].

A general categorization of DC/DC converters based on their characteristics is illustrated. Figure 3.1 indicates the step-up DC/DC converter classification.

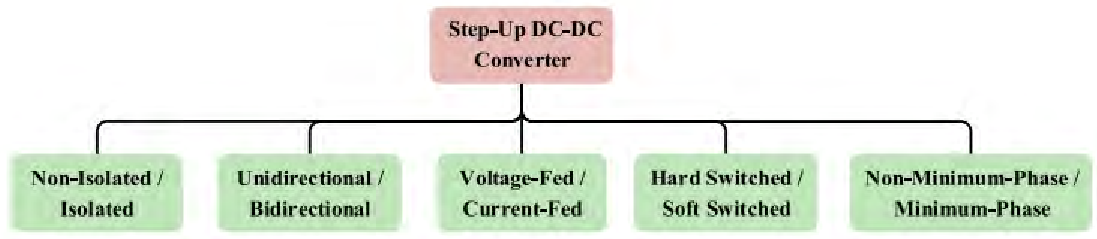


Figure 3. 1 Categories on step-up DC/DC converter [1]

3.1 Non-isolated/isolated topologies

Figure 3.2(a) and 3.2(b) presents the structure of non-isolated and isolated converters respectively. The non-isolated converters have broad applicability and simplicity of implementation and design. They are often characterized by simple structure, light weight and low manufacturing cost. These circuits can be used with shared ground between the input and output or with a floated output. Non-isolated converters can be built with or without magnetic coupling and there is an electrical connection between input and output. They are suitable for low or medium power level and for applications where high voltage step up is not considered and efficiency is not a major concern. In fact, without the transformer and its turn ratio, these topologies become impractical for big voltage differences.

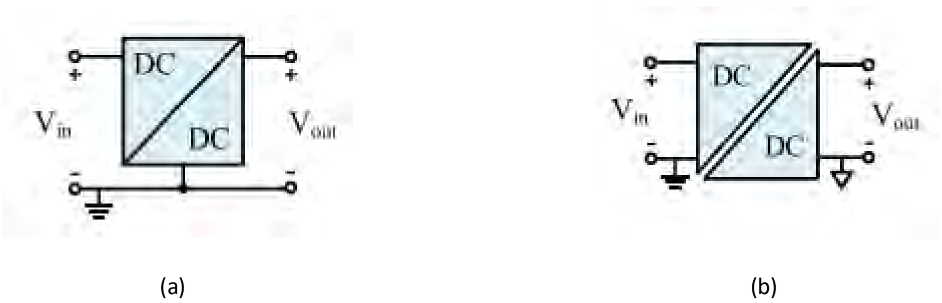


Figure 3. 2 (a) Structure of non-isolated DC/DC converter, (b) Structure of isolated DC/DC converter [1]

A basic method for stepping-up a DC voltage is to use a conventional PWM boost converter (fig. 3.3), which comprises only three components (an inductor, a switch, and a diode). A PWM boost converter is a simple, low cost, and efficient non-isolated step-up converter suitable for many dc applications. Other basic non-isolated topologies of a DC/DC converter were studied as a result of the interconnection of both of the simple topologies, such as the two-stage inverting buck-boost converter, known as Cuk converter (fig. 3.4(a)) or the two-stage non-inverting buck-boost SEPIC or ZETA converter, (fig. 3.4(b)).

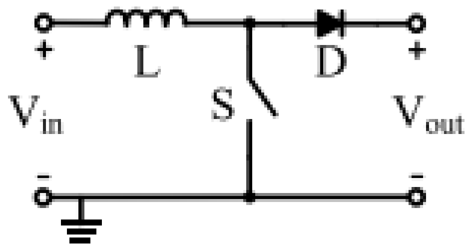
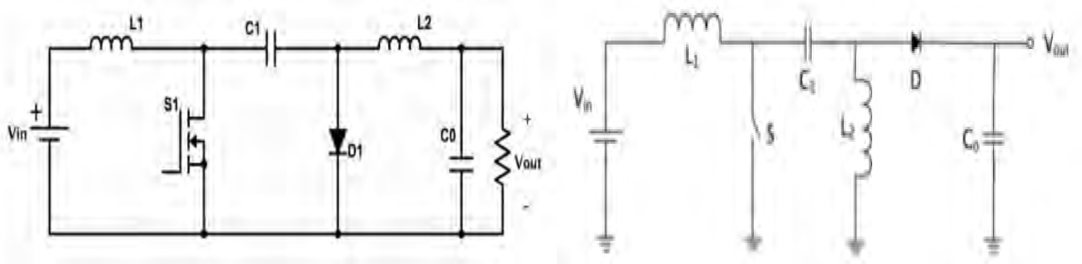


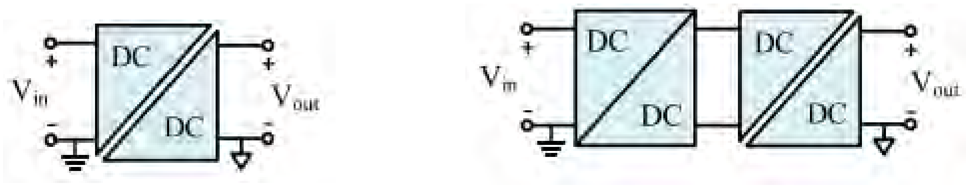
Figure 3. 3 Circuit of a conventional PWM boost [1]



(a) (b)

Figure 3. 4(a) Circuit of a Cuk converter [1], (b) circuit of a SEPIC converter [8]

Isolated DC/DC converters are single or double stage structures (fig. 3.5), which have a separation between the input and output terminal, allowing them to have high isolation voltage properties. This isolation can be achieved by either a transformer or a coupled inductor. Isolation is an important feature for grid-tied DC/DC converters and other applications that require reliable power transfer with low noise and reduced EMI problems. Especially for some sensitive loads, such as those used in medicine, military and avionics applications, which are vulnerable to faults and noise, electrical isolation is necessary. Isolated converters are suitable for high power levels, have easy implementation of multiple output topologies and are advantageous for negative or positive grounds, as for floating ground. However they need precise coupled magnetic design for high voltage gain. When designing an isolated DC/DC power converter, the first and most critical choice is the selection of the topology. This selection is basically based on many factors such as desired output power level, cost, size, electrical stress, output noise and input voltage range. The switching concept varies by topology.



(a) (b)

Figure 3. 5 (a) 1-stage isolated DC/DC converter, (b) 2-stage isolated DC/DC converter [1]

3.1.1 Basic isolated topologies of DC/DC converter

Isolated DC/DC converters can be categorized based on the symmetry of the magnetic cycle of the isolation device. The basic topologies with an asymmetrical magnetic cycle, where the magnetic operating point of the isolation device remains in the same quadrant, are flyback and forward converters. Converters with symmetrical magnetic cycles, include the half-bridge converter, dual active bridge converter, full-bridge converter, and push-pull converter.

There are two basic types of single-ended isolated converters: the Flyback and the forward converter, (in both types a high frequency transformer provides the isolation between the input and the output). [8], [9], [11].

3.1.1.1 Flyback

A flyback converter is developed from the buck-boost topology to realize high voltage conversion ratio by utilizing large-turns-ratio transformers. It is found in low cost and low power applications. In Flyback topology, as shown in figure 3.6, energy is stored in the magnetic field of the transformer during the first half of the switching cycle and then released to the secondary winding(s) connected to the load in the second half of the cycle. The transformer is forced to have a big size, as it stores energy, in the air gap of the transformer's core, when the main switch turns ON and when the main switch turns off, the energy is delivered to the load. Flyback transformers are also known as coupled inductors, because they have a gapped core construction and store energy in the core.

The main advantages of this topology are:

- Smaller number of passive and active components.
- Smaller size when it is used in discontinuous conduction mode (DCM).

However, the basic drawbacks of this topology are:

- High losses on transformer and poor transformer utilization.
- There is a need for an extra output or input capacitor due to the high input and output ripple currents.
- Higher switch voltage stress.

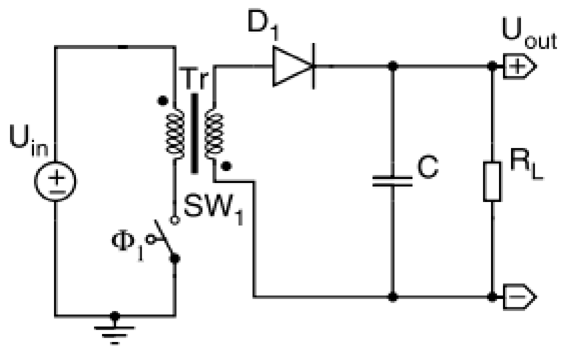


Figure 3. 6 Structure of flyback DC/DC converter

3.1.1.2 Forward and active clamp forward

These topologies are often employed in medium power applications. A typical Forward converter consists of a transformer, which is capable of transfer electric energy to magnetic energy and then back to electric energy to the load, a transistor such as a MOSFET which acts as the switching device, diodes, capacitors and an inductor. Galvanic isolation provides protection from any possible fault and transient, between the source and the primary end of the converter. Energy is passed directly from primary to secondary during the transistor's conduction phase, in contrast to Flyback converter. The output voltage is determined by the input voltage, the transformer turns ratio $\frac{Ns}{Np}$ and the duty cycle D, equation (3.1). The structure of a single-switch forward converter is shown in fig. 3.7.

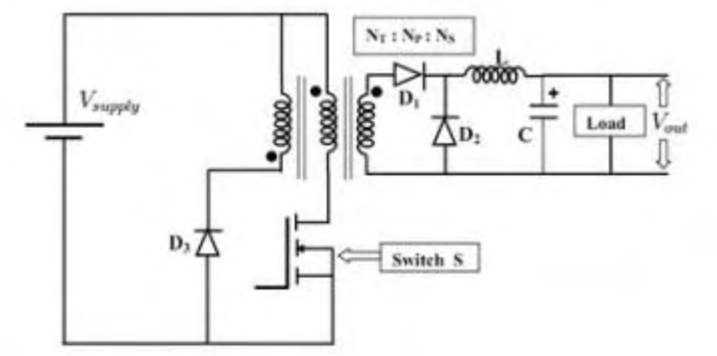


Figure 3. 7 Structure of single-switch forward converter [8]

$$\frac{Vout}{Vin} = D\frac{Ns}{Np} \quad (3.1)$$

The variation between the forward and the active clamp forward converter is that the last uses an active clamp (FET) to reset the transformer instead of a separate winding.
There are other double-ended topologies such as the push-pull, the half-bridge and the full-bridge topology, derived from the above mentioned forward converter. In these topologies a direct energy transfer from the primary to the secondary side during the ON time of the switches is achieved. In contrast to flyback operation, no magnetic energy storage in the transformer is needed.

3.1.1.3 Push-pull

Push-pull topology is suitable for low input voltage. The push-pull converter requires a split-winding transformer to function. This circuit adopts two parameters of the same power, a BJT or a MOSFET. When the system is operating, only one of the two symmetrical power switches conducts at a time, the conduction losses reduced, resulting in an increase in efficiency. In general, this circuit is characterized by simple structure, high utilization of the magnetic core, and low conduction loss. It is suitable for low voltage and high current applications. However, high voltage stress on the transistor, high input current ripple, center tap (CT) in the transformer and high voltage spike on the transistor when switching are major drawbacks. Figure 3.8 shows the simplified circuit of the push pull converter.

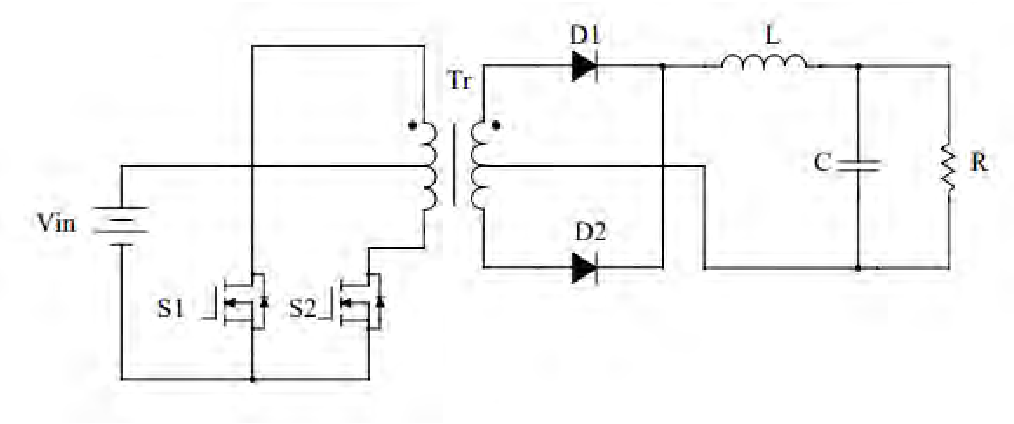


Figure 3. 8 Structure of push-pull DC/DC converter

3.1.1.4 Full-bridge/half-bridge

A similar topology to the push-pull converter is the half bridge and full bridge converters, which use two or four switches to steer the current through the transformer primary winding, which no longer needs the primary center-tap connection as with the push-pull converter (but still uses a center-tap secondary).

The half-bridge topology is used for low and medium power level converters. As shown in fig. 3.9, the two switches connect the single transformer primary across the two capacitors alternately. Since two capacitors (C1, C2) share the input voltage evenly, the voltage stress for the MOSFET is half of the input voltage compared with the case in full-bridge topology. As a result, lower voltage rated MOSFET is qualified for half-bridge topology application. Two half-bridge topologies are widely used in DC-DC converters; the symmetric half-bridge topology and the asymmetric half-bridge topology.

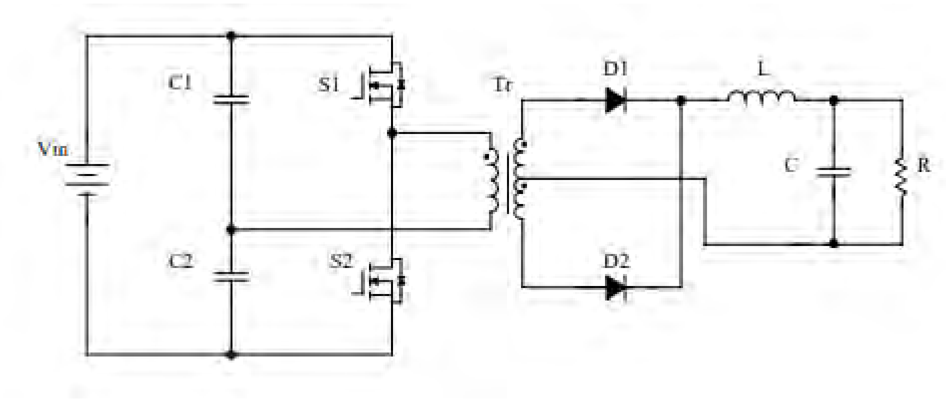


Figure 3. 9 Half bridge topology

The full-bridge topology is typically used at power levels greater or equal to 750 W, while topologies as the forward converter are ideal for lower power levels. As shown in fig. 3.10, it consists of four switches, two in each leg alternatively to deliver the power to the load. When S2 and S3 conduct at the same time, Vin is applied to transformer primary winding. The polarity of the voltage applied on primary side winding reverses when S1 and S4 conduct. As a result, transformer core is fully utilized and no core resetting circuit required. The size of the transformer is smaller and consequently losses on the transformer are lower.

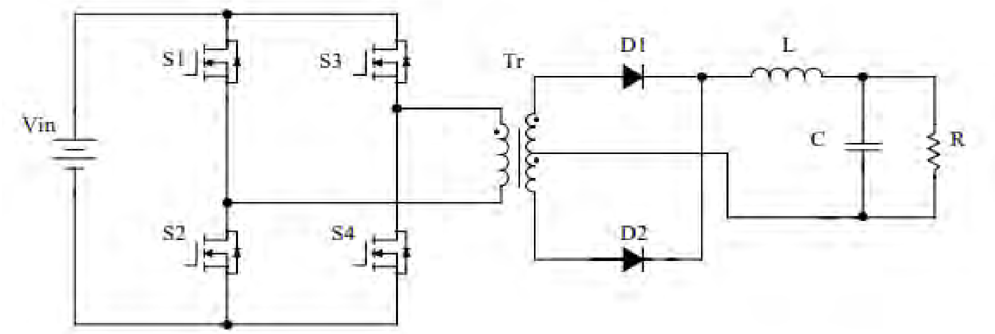


Figure 3. 10 Full-bridge topology

Manufacturers and researchers have made efforts to implement the full-bridge topology, so as to be more suitable in many different and more challenging applications and to lower the cost and the complexity. In literature many different possibilities of the full bridge topology are proposed [11], [23], [46].

3.2 Unidirectional/Bidirectional

Unidirectional step-up DC/DC converters only allow one direction power flow. The input source should only supply the load or absorb the energy. Unidirectional converters are usable for on board loads, such as sensors, battery-based household application, utilities or safety equipment. Figure 3.11 shows a typical layout of such type of converter, and figures 3.12 and 3.13 depict the basic type of a non-isolated and an isolated unidirectional boost DC/DC converter respectively, which consist of inductors, active switching devices (IGBT or MOSFET), diodes and capacitors. The power flow is unidirectional because single-quadrant switches are used. There is no path for the current to be conducted in the reverse direction due to the present of the diode. Unidirectional converters are preferred owing to their lower number of controllable switches and simple control implementation. Dissimilar to high power step down applications, diodes in unidirectional boost converters can sometimes have minimized effects on the circuit power efficiency. When the output voltage is much higher than the rectifying diode voltage drop, designers decide to retain a diode instead of replacing it with a synchronous rectifier.

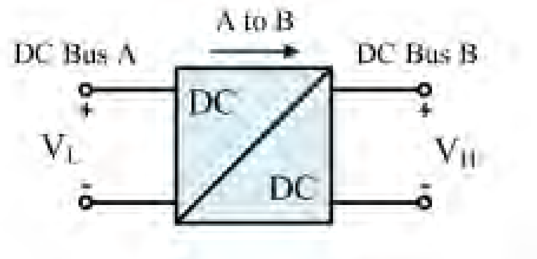


Figure 3. 11 Typical layout of a unidirectional DC/DC converter [1]

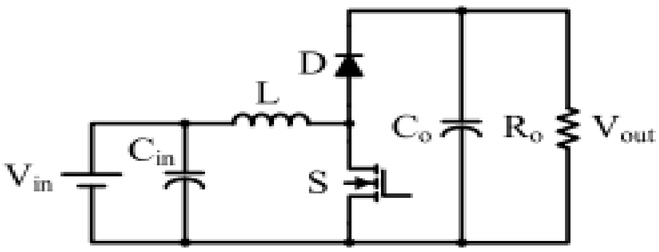


Figure 3. 12 Unidirectional non-isolated boost DC/DC converter [1]

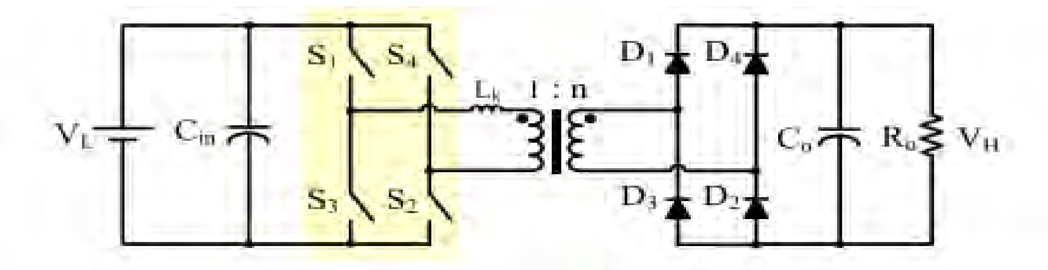


Figure 3. 13 Unidirectional isolated boost converter [1]

A slight modulation of the unidirectional DC/DC converter, by using switches such as MOSFETs instead of diodes, enables the power to circulate in both directions, providing the bidirectional type (fig. 3.14). Bidirectional DC/DC converters allow straight and reverse power flow due to the two-quadrant switches. Figure 3.15 shows a basic circuit of a non-isolated bidirectional step-up DC/DC converter, consisting of two semiconductors (IGBTs or MOSFETs) and one inductor, whereas figure 3.16 indicates a bidirectional isolated DC/DC converter type. Bidirectional converters are suitable for applications with storage system and bidirectional energy capability, such as in renewable energy systems, in railway transportation, in automotive transportation, in smart grid or in aerospace. They are more complicated and costly than unidirectional converters and they need FET complex driver and control units.

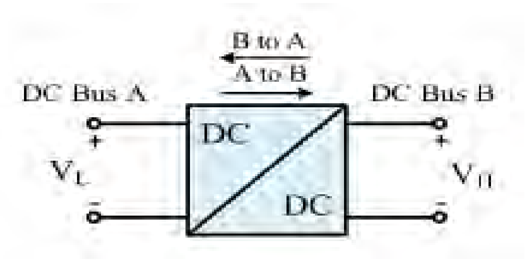


Figure 3. 14 Typical layout of bidirectional DC/DC converter [1]

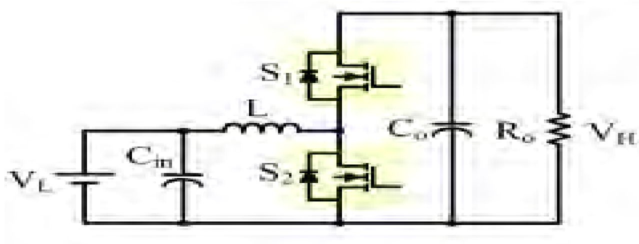


Figure 3. 15 Bidirectional non-isolated boost DC/DC converter [1]

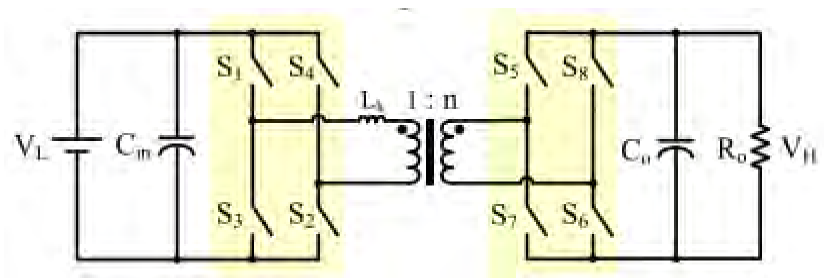


Figure 3. 16 Bidirectional isolated boost DC/DC converter [1]

DAB (dual active bridge) converters are one of the most promising types of isolated bidirectional DC/DC converter, derived from unidirectional full-bridge DC/DC converter topology. They are suitable in high voltage power level applications.

3.3 Voltage-Fed/Current-Fed

Depending on their input circuitry DC/DC converters can be categorized as either voltage-Fed or current-Fed.

Voltage-Fed DC/DC converters have inherent buck characteristics, as they have a capacitive input filter C_{in} and normally can convert input voltage to a lower output voltage. They have large input current ripple which is often discontinuous. Such converters usually have fast dynamic response and are suitable for low-power applications. Figure 3.17 shows a voltage-fed full-bridge converter suitable for high-power applications. It consists of an input capacitor and a low-pass filter at its output.

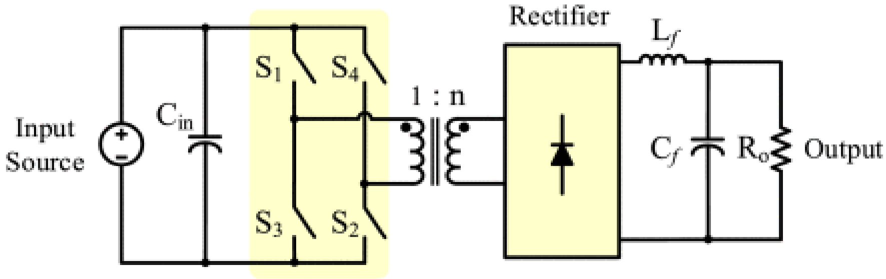


Figure 3. 17 Voltage-Fed full-bridge DC/DC converter [1]

On the other hand current-Fed DC/DC converters present inherent boost characteristics as they have an inductor at the input circuit and can convert input voltage to a higher output voltage. They are very popular for low voltage renewable energy applications, such as photovoltaic (PV) and fuel cells (FCs), because their input inductor can provide a continuous input current with low ripple. Unlike to voltage-Fed converters, current-Fed topologies have slow dynamic due to input inductor and zero RHP. Current-fed converters usually can achieve a large range of soft switching and provide high efficiency over a large range of power rating in applications with wide input voltage variation. Figure 3.18 is an example of a current-fed full-bridge converter, which consists of an input inductor and a capacitive output filter.

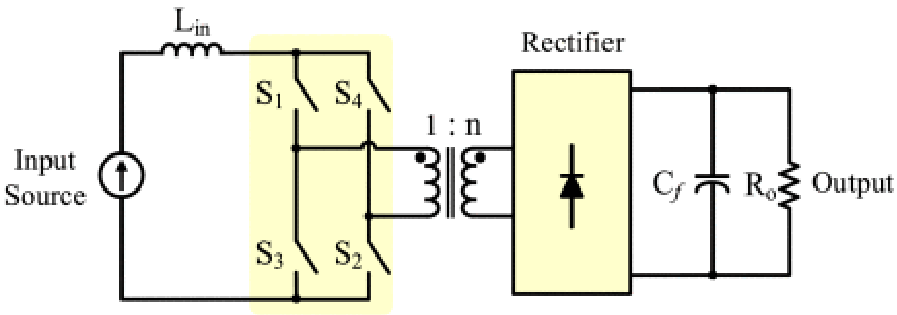


Figure 3. 18 Current-Fed Full-bridge DC/DC converter [1]

3.4 Hard-Switched/Soft-Switched

Hard-switched DC/DC converters have high switching power losses and they suffer from high EMI due to high $\frac{dv}{dt}$ and $\frac{di}{dt}$ at switching transitions. Switching losses increase with the increase of the switching frequency and as a consequence, limited switching frequency occurs. They present a low power density and often a low efficiency. The basic idea of hard switching is that, we usually consider that voltage and current are in steady state and generally speaking are constant at that moment. Then, at commutation, both of them, voltage and current, start increasing and decreasing respectively at turn-off. This results in switching losses. The waveforms of that case are shown in fig. 3.19.

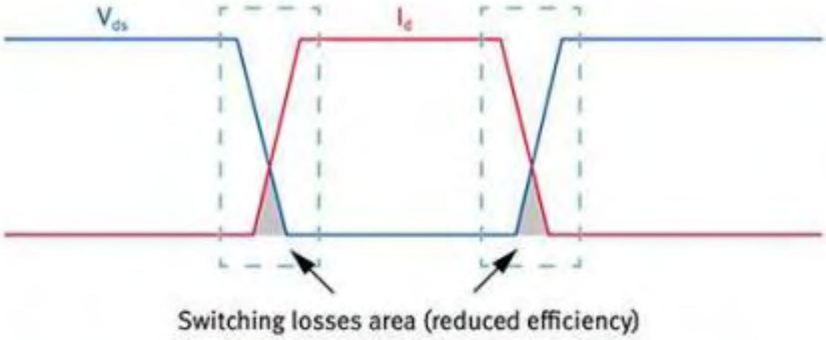
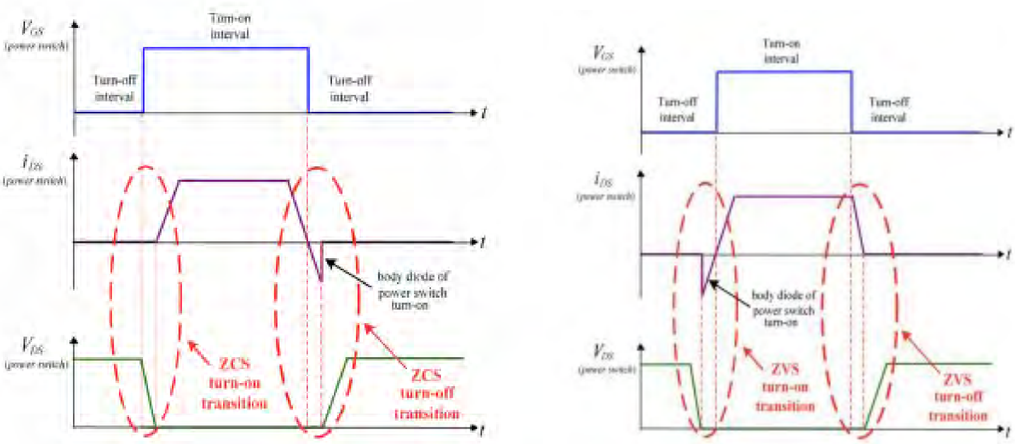


Figure 3. 19 Hard switching current and voltage waveforms [1]

As efficiency is becoming more and more important nowadays, soft switching techniques are included in many designs of DC/DC converter, with the main object to minimize the losses related to the switching of devices that change states interrupting current and voltage. The main advantages of incorporating soft switching in our designs are:

- Reduction in switching losses in the semiconductors.
- Reduction in size and weight. Lower losses means less dissipated heat in the devices, making them consequently smaller as there is no need for big heat sinks. Additionally, the total value of their impedance can remain constant by switching at higher frequencies.
- Reduction in cost. As size and weight is reduced the whole amount of material is reduced.
- Reduction in electro-magnetic Interference (EMI).
- Utilization of parasitic elements such as leakage inductances of transformers.

Soft-switched DC/DC converters can achieve near zero-voltage (ZVS) and zero-current switching losses (ZCS). ZCS is s type of soft switching that is functioning on bringing the current to zero before changing the switch state, that is, either from on to off or vice-versa. Correspondingly, a ZVS indicates that the voltage becomes zero before the turning on and off. The waveforms of the ZCS and the ZVS are depicted in figure 3.20(a) and 3.20(b) respectively.



(a) (b)

Figure 3. 20 (a) Schematic of ZCS waveforms, (b) Schematic of ZVS waveforms [1]

Soft-switching converters can be classified as load resonant converters, which operate at high-frequency without conversion efficiency degradation and allow low reductions in the size or weight of the converter.

3.5 Non-Minimum phase/Minimum phase

A non-minimum phase system is identified if its transfer function has at least one right half-plane (RHP) zero, or a RHP pole, or a time delay. Among others, systems with RHP zero(s) constitute a very important category of NMP systems, both from theoretical and practical point of view. An interesting aspect of NMP systems is that their closed loop transfer functions can maintain the same RHP zeros as their open-loop transfer functions. This symmetry leads to the so-called inverse response to the step input change. However, controllers for these NMP systems are more difficult to design because, as the gain increases in a conventional controller, the closed-loop poles will be attracted the RHP. Various techniques can be employed to alleviate the effect of the RHP zero in boost converters. Furthermore, various control techniques have been introduced to overcome the problems caused by the RHP zero. Obtaining an acceptable stability margin in such converters is a concern for controller designers Active switches or magnetic coupling are two basic ways to eliminate RHP zero.

3.6 Voltage boosting techniques

High step-up DC/DC converters are popular in portable electronic devices and in applications where battery storage systems or renewable sources are typically employed as input sources to supply DC bus for electronic devices. The limitations of the conventional boost DC–DC converter such as low boost ability and low power density have led to the utilization of several voltage boosting techniques. For this reason, many topologies have been proposed to achieve high voltage gain in past decades.

Literature [1], [12] has reported on various voltage boosting techniques in which fundamental energy storing elements (inductors and capacitors) and/or transformers in conjunction with switch(es) and diode(s) are utilized in the circuit. Figure 3.21 shows the classification of voltage boosting categorization that can be found in the literature [1]. In this chapter five major voltage boosting techniques are analyzed: switched capacitor, voltage multiplier, switched inductor, magnetic multistage/-level.

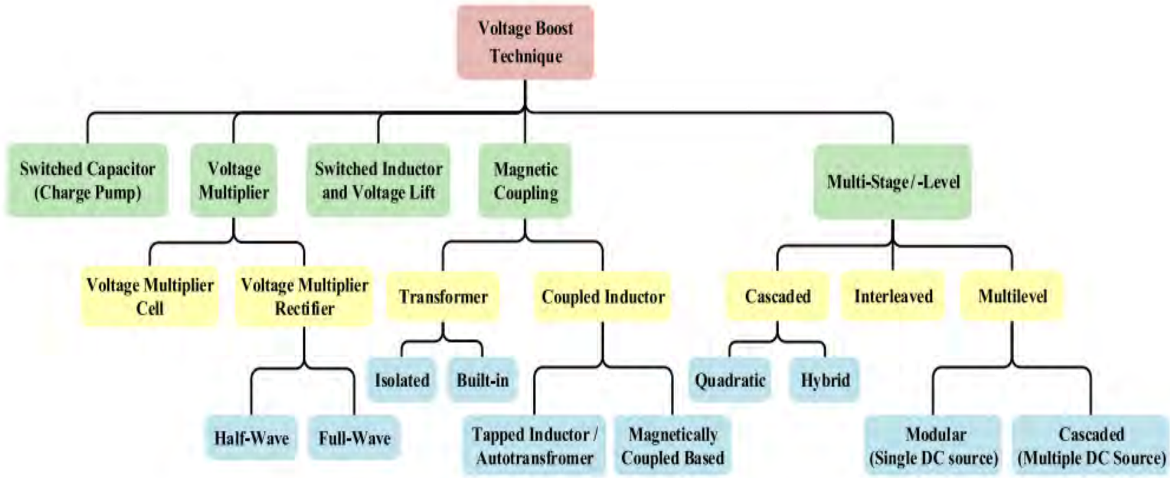
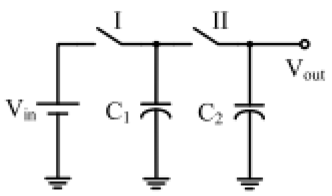


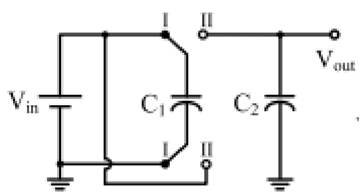
Figure 3. 21 Diagram of voltage boosting techniques [1]

3.6.1 Switched capacitor

The switched capacitor (SC) is one of the most popular voltage boosting techniques and one of the most common implementations of the charge pump (CP) circuit, used in numerous applications. [13] This technique comes solely from capacitive energy transfer and doesn't involve magnetic energy transfer. Figure 3.22(a) shows the basic concept of CP circuit, called pumping the energy from one capacitor to another. When switch I is turned ON, capacitor C1 is charged to the input voltage level, and when switch II is turned ON, the stored energy in C1 is transferred to capacitor C2, and after several cycles, the output voltage reaches the desired voltage level. The idea of switched capacitor includes also the charging and discharging process of the capacitor as the charge pump structure. A two-phase SC voltage doubler (TPVD) is shown in fig. 3.22(b). In the first phase, capacitor C1 is charged to the input voltage. In the second phase, capacitor C1 is placed in series with the input source, so as the capacitor is discharging, transferring energy to the load. The voltage of the load would be N times of the input source (N is the number of switched capacitor stages in the converter. For higher voltage gains, fig. 3.22(c) shows a TPVD series connection, called doubler SC, and fig. 3.22(d) shows a series-parallel connection.



(a)



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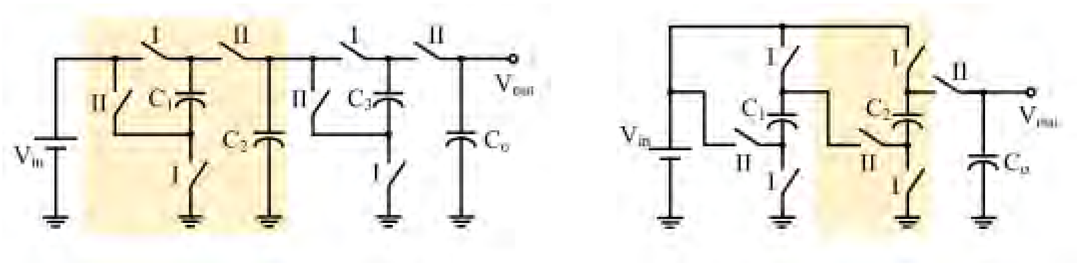
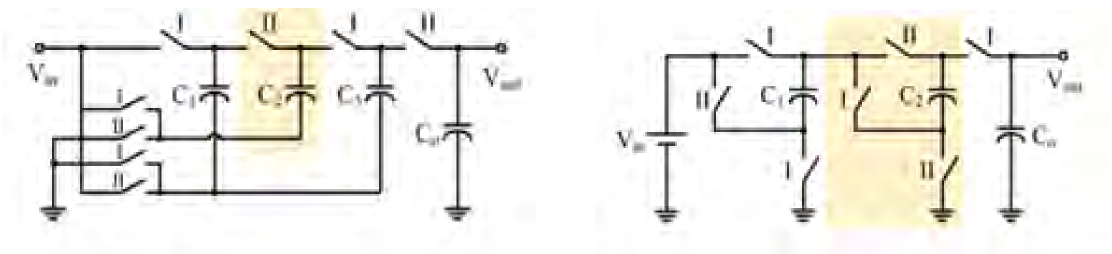


(c) (d)

Figure 3. 22 (a) Basic charge pump circuit, (b) two-phase SC voltage circuit, (c) Doubler SC (d) Series parallel connection of SC [1]

In order to reduce the number of switches and increase the efficiency, different types of topologies have been introduced. Fig. 3.23(a) shows the Dickson SC, which can be used as voltage multiplier. In the Dickson CP, diodes are used instead of active switches. The Makowski SC , illustrated in Fig. 3.23(b), can provide high-voltage boosting with low-device requirement. This SC circuit type is also known as a Fibonacci design owing to the fact that its voltage gain characteristic increases according to the Fibonacci number sequence {1, 1, 2, 3, 5, 8, 13, . . .}.



(a) (b)

Figure 3. 23 (a) Dickson circuit, (b) Makowski or Fibonacci circuit [1]

3.6.2 Voltage multiplier

Voltage multiplier is an efficient, low cost and simple topology circuit. It consists of a set of diodes and capacitors to obtain high DC output voltage. It can be divided into two categories based on its structure:

3.6.2.1 The non-isolated voltage multiplier cell (VMC)

The non-isolated VMC can be implemented in the middle of a circuit usually after the main switch, as illustrated in fig. 3.24(a), in order to reduce voltage stress. They are popular for high boost applications due to their simple structure and easy implementation. Figures 3.24(b-g) depict some fundamental configurations known as VMC that can be found in DC/DC converters. Some consist only of diodes and capacitors, while other more complicated structures have active switches or inductors to increase voltage-boosting ratio.

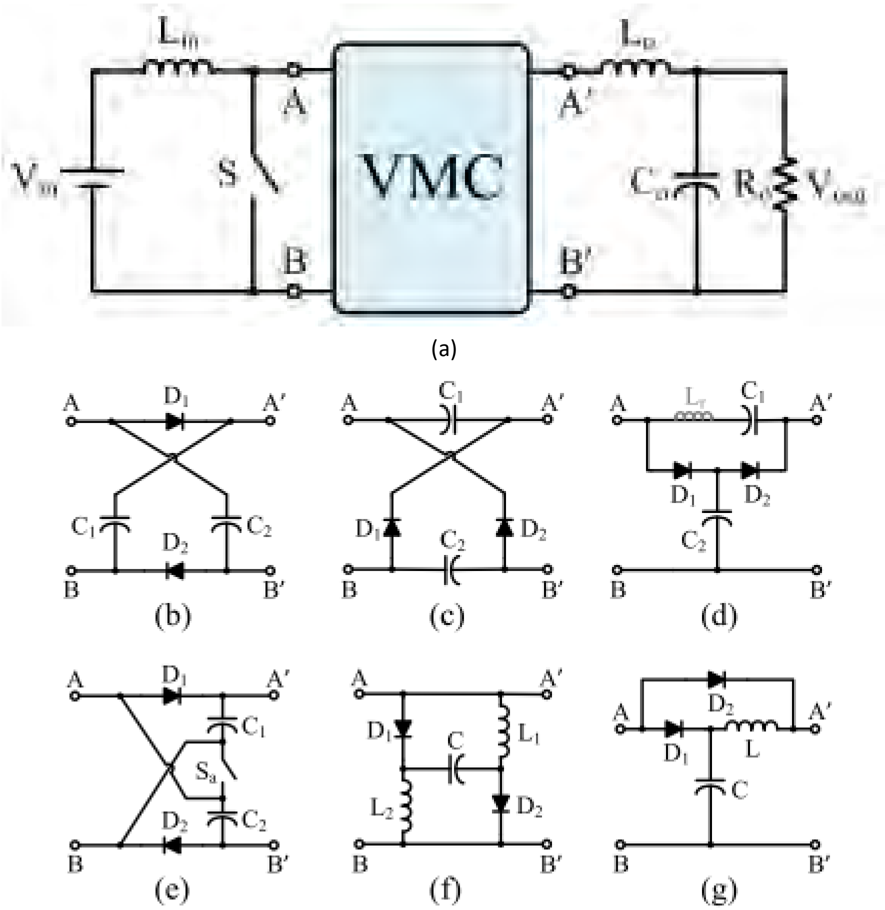


Figure 3. 24 (a) General topological view of the placement of non-isolated voltage multiplier cells (VMCs) in step-up converters, (b)–(g) various voltage multiplier cells. [8]

3.6.2.2 *The isolated voltage multiplier rectifier (VMR)*

The VMR is placed at the output end of the transformer or coupled inductor based structures (fig. 3.25), in order to rectify AC or pulsating DC voltage into different capacitors and multiple the voltages together to achieve higher voltage gain. VMRs consist of different configurations of diodes and capacitors and they have two subsections:

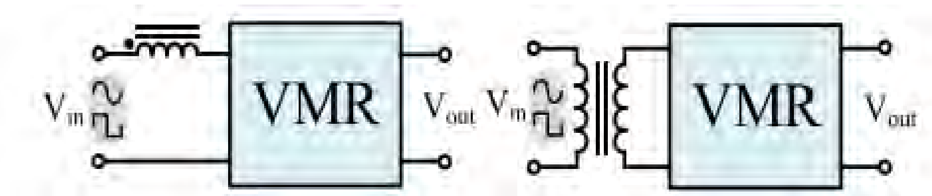
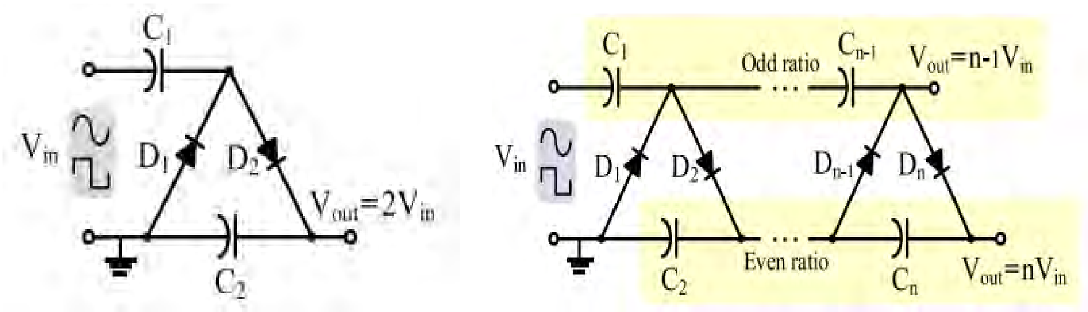


Figure 3. 25 General topological view of the placement of VMRs [1]

Half-wave

These circuits are not only placed on the secondary side of isolated transformers and coupled inductors, but they can also be used in converters with built-in transformers and coupled inductors. Figure 3.26(a) presents a half-wave voltage multiplier circuit known as Cockcroft–Walton (CW) voltage multiplier, where the input voltage would charge C1 in its negative period, and, together with C1, charge C2 in its positive period. Thus, the output voltage is 2 times of the input. CW VMR can provide high voltage levels. Fig. 3.26(b) is an extended version of the CW voltage multiplier, where the up and down capacitors are used for odd and even multiplication, respectively. The disadvantage of half-wave VRMs is the high voltage stress on diodes and output capacitor, identical to high output voltage.

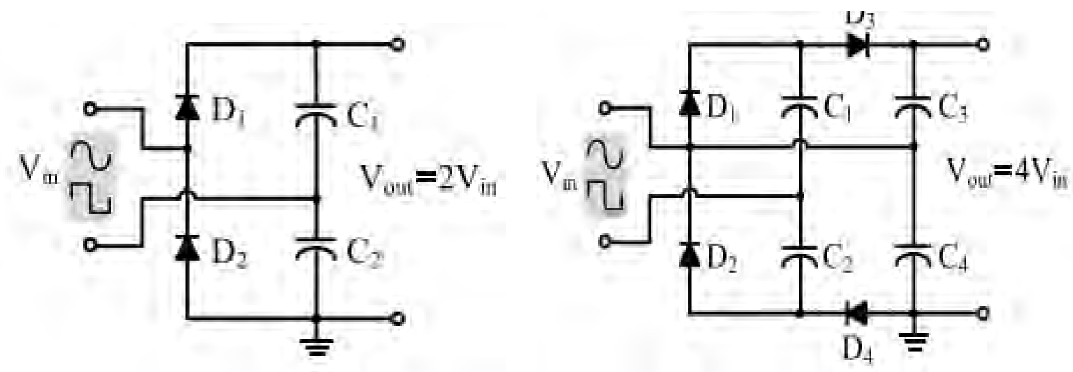


(a) (b)

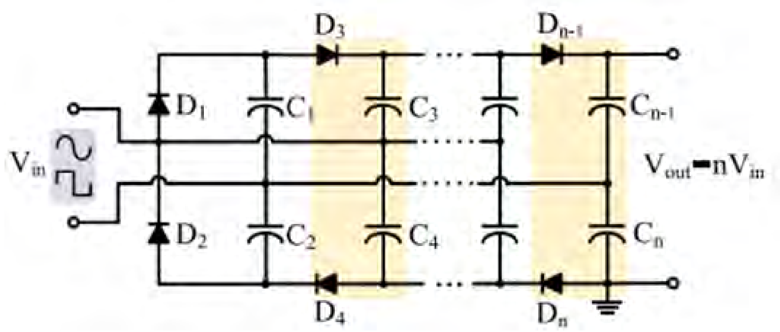
Figure 3. 26 (a) Cockcroft-Walton (CW) voltage multiplier (b) an extended version of Cockcroft-Walton (CW) voltage multiplier [1]

Full-wave

Full-wave VMRs are commonly employed at the output stage of transformer-based converters. The VMR in fig. 3.27(a) is a full-bridge voltage doubler rectifier, where the positive and negative periods of the input voltage, charge C1 and C2 respectively, and the voltages of C1 and C2 represent the output voltage directly. The VMR in fig. 3.27(b) is a quadrupler voltage rectifier, useful for boosting stage in modern DC/DC converters. Fig. 3.27(c) illustrates a multistage structure consisting of the VMRs in figures 3.27(a) and 3.27(b). It is a voltage tripler rectifier that is used in many Ultra step-up DC/DC converters. This VMR can be found in isolated or in multilevel output series structures. Owing to its reduced voltage stress on output capacitors (it reduces the output voltage by one-half), is commonly used in various dc–dc converters.



(a) (b)



(c)

Figure 3. 27 (a) voltage doubler rectifier, (b) voltage quadrupler rectifier, (c) voltage multiplier rectifier [1]

3.6.3 Switched inductor and voltage lift (VL)

This method, in order to increase the output voltage of the DC/DC converter, charges a capacitor to a certain voltage (e.g., input voltage), and then stepping up the output voltage (lifting voltage) with the voltage level of the charged capacitor. The output voltage can be further increased by repeating this operation with additional capacitors, to create the so-called relift, triple-lift, and quadruple-lift circuits. Figure 3.28 shows the general frame of voltage lift boost DC/DC converter.

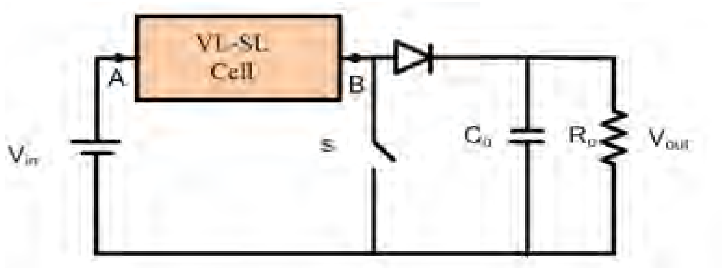


Figure 3. 28 Schematic of voltage lift (VL) step-up DC/DC converter [8]

3.6.4 Magnetic coupling

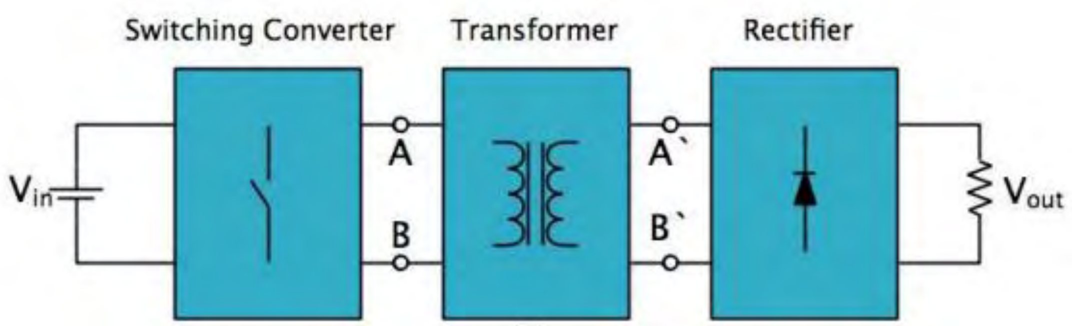
Magnetic coupling is another popular voltage boosting method used in many non-isolated and isolated DC/DC converters. This technique can be achieved by either a transformer or a coupled inductor. The transformer and coupled inductor are almost identical, apart from some differences which are presented in the following section.

3.6.4.1 Transformer

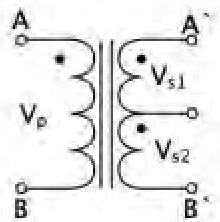
Topologies of transformer-based converters is one of the most popular in the research industry, as the can be suitable for high step-up applications, due to the transformers turns ration along with the duty cycle. The transformers deliver energy from one winding to another, without any energy storing process. Transformer-based converters can be divided into two types: isolated transformer-based converters, which provide electrical isolation; and non-isolated transformer-based converters, known in the literature [1], [8], as built-in transformers.

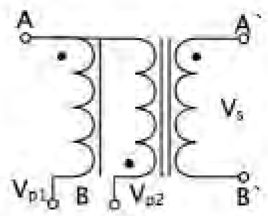
Isolated transformer-based DC-DC converter

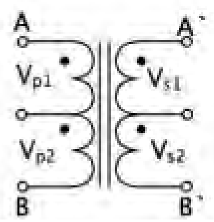
Figure 3.29(a) shows the basic layout of isolated transformer-based converter with an input DC source followed by a network of switches, diodes, and transformer that is then rectified and connected to an output filter. There are several common types that are includes in many applications such as full and half bridge structure, forward structure, and push-pull structure. For the purpose of enhancing boost ability, researchers have developed several new types of DC/DC converters, including source-based isolated DC/DC converters, such as half or full bridge structures, forward or push pull topologies (figures 3.29 (b-d)), or dual active bridge structures.



(a)







(b) (c) (d)

Figure 3. 29 (a) Basic layout of isolated transformer-based DC/DC converter, (b) Full-half bridge structure, (c) Forward structure, (d) Push-pull structure [8]

Non-isolated transformer-based DC-DC converter

Non-isolated transformer-based DC/DC converter or also known build-in transformers, have more flexible topology than isolated transformers. Figure 3.30 shows the general layout of non-isolated transformer-based converters. These circuits derived from isolated circuits, using direct energy transfer. One part of the energy transfer is directly delivered from the input source and the other is transferred through the magnetic coupling using voltage multipliers. There is a balance of magnetic flux in the core.

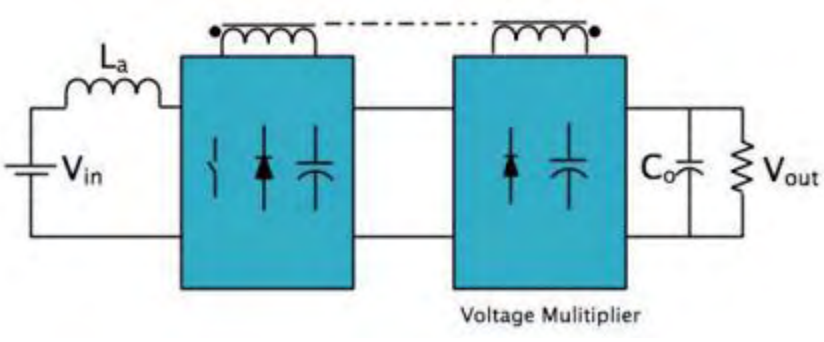


Figure 3. 30 Basic layout of non-isolated transformer-based converters [8]

3.6.4.2 Coupled inductor based converters

Applications that do not require electrical isolation can use coupled inductors. Voltage boosting technique in these types of converters is achieved by storing energy in one cycle and power the load in the other cycles. In contrast to transformers, coupled inductors have air gaps to increase the energy storing capacity, which can be useful in the converter that magnetic energy storage is necessary, i.e., flyback converter. Figure 3.31 shows the basic structure of coupled inductor DC/DC boost converter.

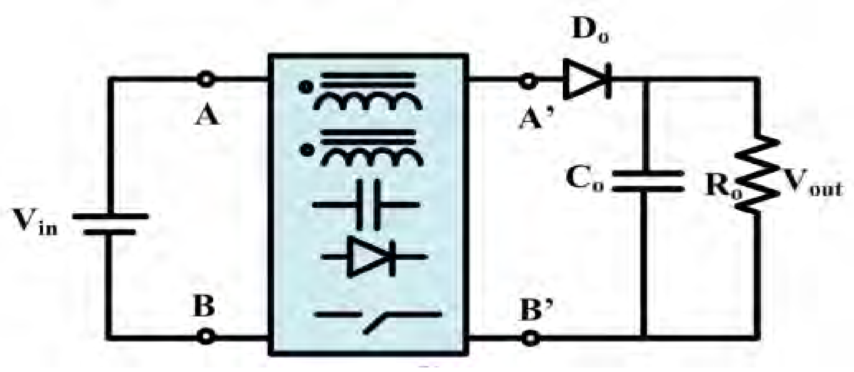


Figure 3. 31 Basic layout of coupled inductor DC/DC step-up converter

3.6.5 Multi-Stage level

Another one of the most well-known voltage boosting methods, to increase voltage gain, is the connection of various identical or similar DC/DC converter modules connected in diverse ways. The voltage gain in multistage level structures increases linearly or exponentially (often multiplicatively by number of stages) as a function of the topology used. In this section, sub-groups of multi-Stage level, such as interleaved, cascaded and multilevel converter topologies are presented.

3.6.5.1 Interleaved converter

Interleaved converter topology is characterized by efficient power distribution, fast transient response, voltage and inductor current ripple cancellation and passive component size reduction. Especially, when the converter work near 50% duty cycle for two phase interleaved boost converter, input current ripple will be more reduced. Fig. 3.32 depicts the general circuit of interleaved boost dc-dc converter with voltage multiplier modules. Parallel input series and output boost converter are combined to increase the high voltage gain.

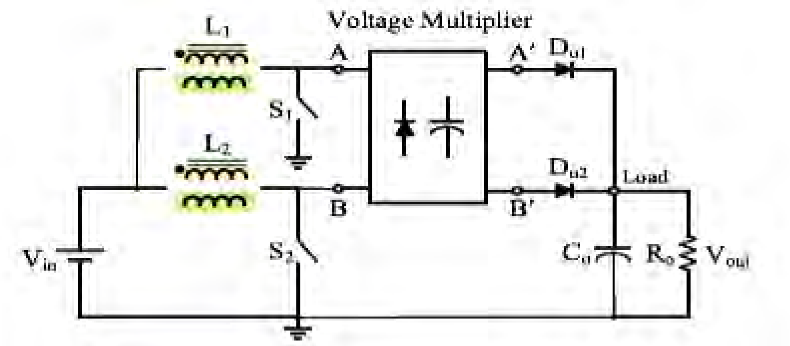


Figure 3. 32 Interleaved boost DC/DC converter with coupled inductor

3.6.5.2 Cascaded converter

Cascaded converters are a simple connection of two or more boost converters in a convenient and straight forward approach, in order to increase voltage gain. As shown in the schematic of a cascaded converter in figure 3.33, DC/DC converters are connecting in a queue. There are two categories, quadratic boost converters, where the structure consists of identical converters and hybrid boost converters, where the structure is comprised of different converters.

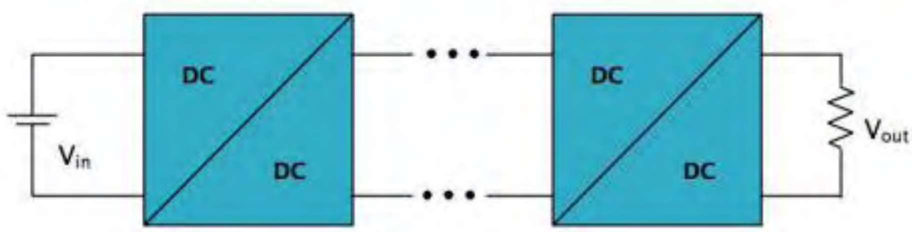


Figure 3. 33 General layout of the cascaded converter [8]

Quadratic boost DC/DC converter (QBC)

Figure 3.34(a) shows a basic circuit of a cascaded quadratic boost converter consisting of two identical converters. There are two stages; on the first stage the voltage stress is relatively low and it operates at high frequency, where on the second stage it operates in lower frequency in order to reduce the switching losses. Structure in figure 3.34(b) is a less complex circuit of quadratic converter, where the switches are integrated into one switch and an extra diode is used. A three-level quadratic boost DC-DC converter shown in figure 3.34(c), is suitable for high voltage gain applications as it is able to reduce the voltage stress on the semiconductors. The basic quadratic converter has been implemented with several modifications. In general, these types of converters may have four switches and contain a single inductor and capacitor for each stage of the converter.

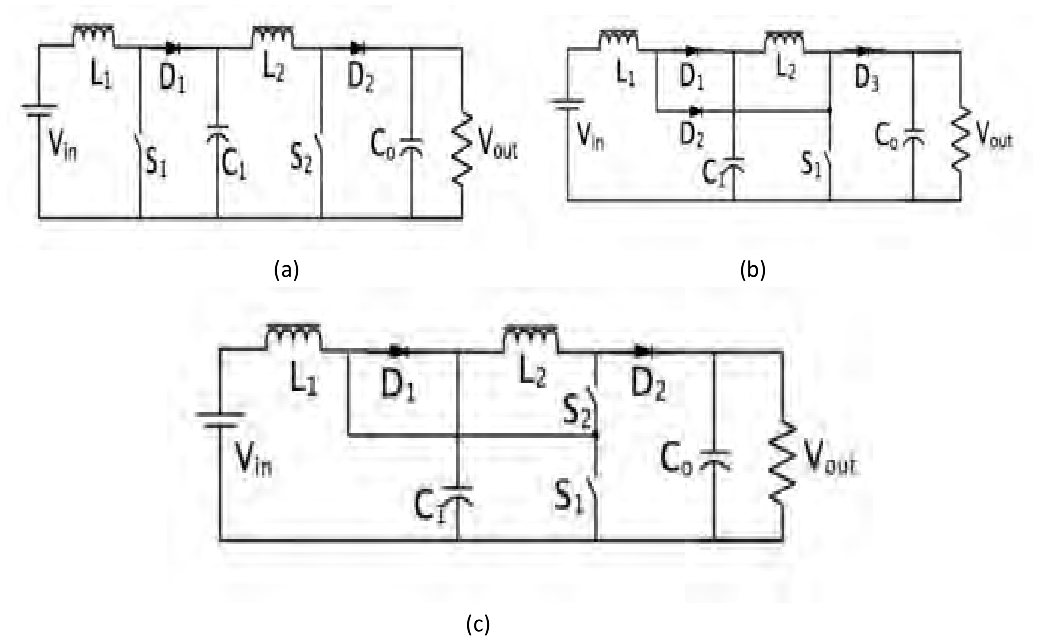


Figure 3. 34 (a) A typical circuit of a cascaded quadratic boost converter consisting of two identical converters, (b) A simplified quadratic boost converter, (c) Three-level quadratic boost converter [1]

Hybrid boost DC/DC converter (HBC)

Figure 3.35(a) shows a general structure of a hybrid cascaded converter, which is a connection of a quadratic boost and other voltage boosting techniques. Fig. 3.35(b) is an example of hybrid converter, where the first stage is considered as a quadratic boost converter and in the second stage, a coupled inductor module is included with a series connection of output capacitors.

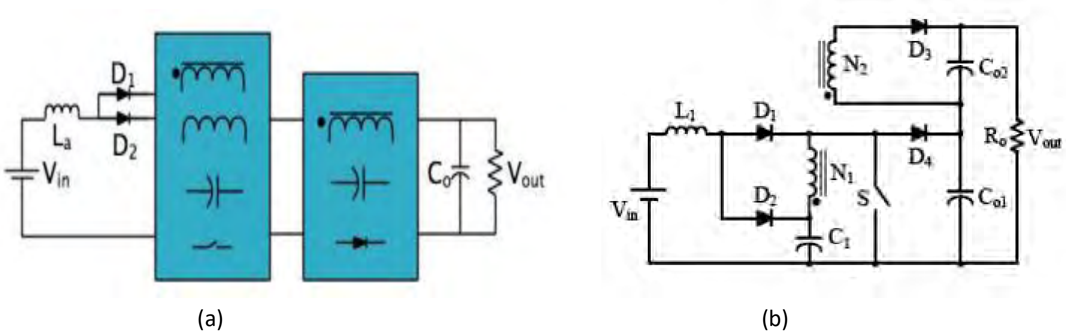


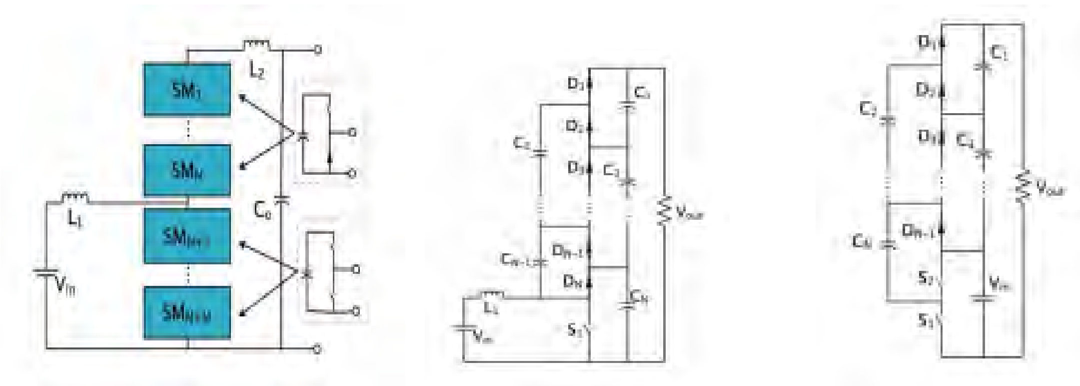
Figure 3. 35 (a) General structure of a Hybrid cascaded converter, (b) an example or a quadratic based hybrid cascaded converter [1]

3.6.5.3 Multilevel

Multilevel technique has the aim of decreasing or eliminating the magnetic components, which results in converters with lower size and weight. From the point of input voltage, multilevel DC/DC converters are divided into two types: multilevel converters with a single dc source and multiple dc sources.

Single-source multilevel (modular)

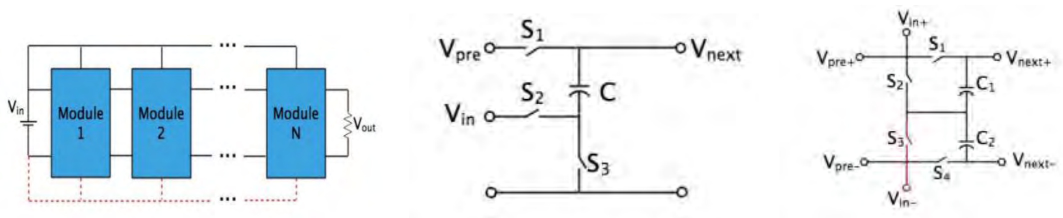
Single source multilevel types of converters, known in the literature as modular, basically consist of semiconductors and capacitors. Figure 3.36(a) shows the general structure of this kind of multilevel converters with several submodels. Two basic circuits of this type without any active switches at the output stage are presented in figures 3.36(b) and 3.36(c). Both of them are flexible and simple structures and have low voltage stress at the output device. The difference between them is that, in structure 3.36(c), there is no inductive component.



(a) (b) (c)

Figure 3. 36 (a) General structure of single source multilevel converter with voltage multipliers, (b), (c)Two examples of the modular type of converter [1]

Figure shows another type of single-source multilevel converters, which consist of SC (switch capacitor) structures. Fig. 3.37(a) shows the basic structure of this topology, which only consists of transistors and capacitors, thus, there is no magnetic component in the entire circuit. Fig. 3.37(b) illustrates a three-switch module with one capacitor circuit for boosting the dc voltage level and fig. 3.37(c) presents another DC/DC module that uses two capacitors and four switches to double the dc input voltage.

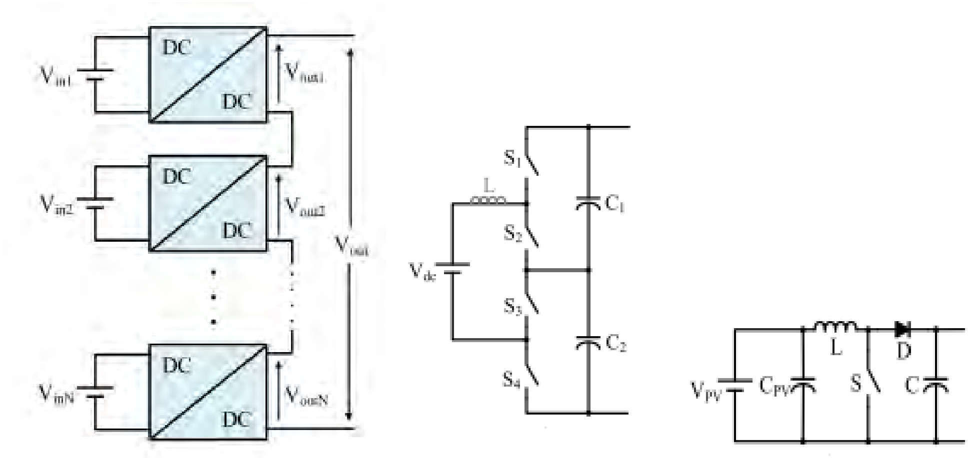


(a) (b) (c)

Figure 3. 37 (a) General structure of single-source multilevel SC converters, (b), (c)Two examples of DC/DC single-source multilevel SC modules [1]

Multiple-source multilevel

Several single DC sources, which mentioned above, can be connected in series in order to increase their string voltage with the aim of increasing the output voltage level of the converter. Additionally, these sources can be connected in cascaded multilevel form (shown in figure 3.38(a)), which is more reliable, safer and costs less. Figures 3.38(b) and 3.38(c) illustrates two examples of this type of converter.



(a) (b) (c)

Figure 3. 38 (a) General structure of multilevel cascaded DC/DC converters, (b), (c) two examples of converter modules [1]

Chapter 4 Analysis and operation of a DC/DC converter

DC-DC converters, namely, switching converters, consist of semiconductor power devices, inductors and capacitors in the form of an electric network to transform electric energy. In this section, DC/DC topology mechanisms and analysis methods of voltage conversion are explained. [2].

4.1 Steady state performance

Steady state performance is a combination of criteria that determine the quality of the system. The 4 most important criteria are:

- Average current and average voltage.
- Conversion ratio
- Output ripple
- Power efficiency

Based on different waveforms of the inductor current, there are two conduction modes for the boost converter, which are the continuous conduction mode (CCM) and the discontinuous conduction mode (DCM).

4.2 Continuous Conduction Mode (CCM)

The principle of operation of the DC/DC converter is explained by its ideal waveforms of the current and the voltage.

In continuous conduction mode (CCM), the current in the inductor, has a finite, positive non zero value for each switching cycle ($I_L(t) = 0$). In the ideal case of CCM, one of the power switches is immediately turned open when the other one is turned closed, which means, there is not a moment (dead time) when two power switches are simultaneously open. Figure shows the basic circuit diagram of an inductor-based boost DC-DC converter. The boost DC/DC converter depicted in fig.4.1 is used for analyzing the operation in CCM, for voltage conversion. In the boost converter, two power switches are alternatively opened and closed, which periodically switches the inductor between the input terminal and output terminal, with the aim of achieving the function of boosting the voltage. The operation of voltage boosting includes two phases:

- Phase 1: the switch S1 is closed and the switch S2 is opened. During this period t_{on} , the inductor L is connected with the input source and is charged by Vin. The current which flows through the inductor increases linearly to I_{Lmax} and expressed by the relationship 4.1:

$$\frac{di_L}{dt} = \frac{Vin}{L} \quad (4.1), \qquad I_L(t) = I_{Lmax}\, when\, t = t_{on}$$

Simultaneously, the output capacitor C is discharged through the load R.

- Phase 2: the switch S1 is opened and the switch S2 is closed. During this period, $t_{off,}$ the inductor L is discharged into the capacitor C and the load R causing the current to decrease linearly from I_{Lmax} to I_{Lmin}, as expressed by the relationship 4.2:

$$\frac{di_L}{dt} = \frac{Vout-Vin}{L} \quad (4.2), \qquad I_L(t) = I_{Lmin} \; when \; t = t_{off}$$

Due to the fact that the inductor L is discharged in series with the input voltage, it can be assumed that the output voltage Vout would always be higher than the input voltage. As analyzed and explained in the literature [2], it can be proven from the equation (4.3), that the voltage conversion boosting ratio ($\frac{Vout}{Vin}$) depends only on the duty cycle D and not on the load R.

$$\frac{Vout}{Vin} = \frac{1}{1-D} \quad (4.3),$$ where the duty cycle D is defined by (4.4)

$$D = \frac{ton}{ton+toff} = \frac{ton}{T} \quad (4.4),$$ T =t_{on}+ $t_{off,}$ is a time of a period.

The working principle of a CCM boost DC-DC converter can be illustrated by the timing diagram of the main signals in the converter, which is shown in figure 4.2.

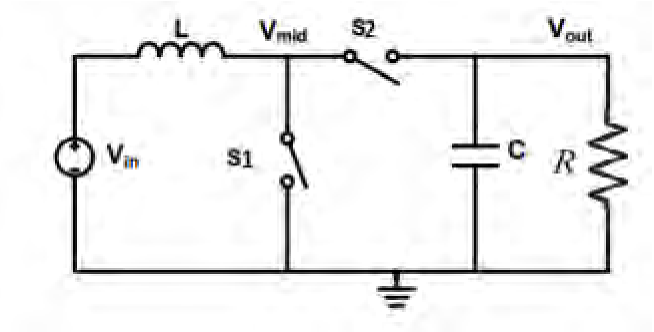


Figure 4. 1 Structure of an ideal boost DC/DC converter

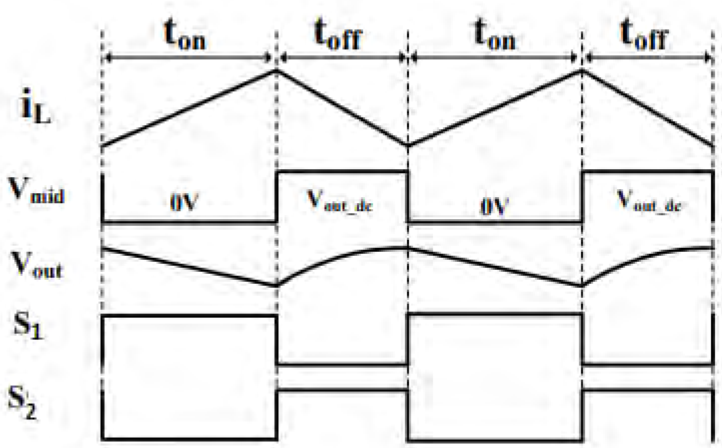


Figure 4. 2Timing diagram of main signals in a CCM boost converter.

4.3 Discontinuous Conduction Mode (DCM)

In Discontinuous conduction mode (DCM), the current flowing through the inductor will go down to zero and stay in zero ($I_L(t) = 0$) for some while, which means there is a period of time, called dead time, (t_{dead},) when the two power switches, S1 and S2, will be both open. As a result, in DCM, except for the two phases that were referred in CCM, there is also a third phase, called "dead phase". There is no current through the inductor L, as it is not be charged by Vin. However, the load is charged through the capacitor C, as explained in CCM in phase during t_{on}. Analyzes and calculations explained in the literature [2] have concluded to the equation (4.5), where can be observed that the voltage conversion boosting ratio ($\frac{Vout}{Vin}$) , is dependent on the value of the load R, the inductor L and the period T.

$$\frac{Vout}{Vin} = \frac{1+\sqrt{1+\frac{2R}{L(ton+toff)}ton^2}}{2} = \frac{1+\sqrt{1+\frac{4D^2}{\frac{2L}{RT}}}}{2} \quad (4.5)$$

The structure of the boost converter during dead time is shown in figure 4.3. Since both switches are open, the voltage of the middle point (Vmid) is equal to the input voltage, which means the voltage across the inductor and the current through the inductor are both zero. The output of the converter is in the same condition as during in the on-time phase. The timing diagram of the main signals in a DCM is shown in fig. 4.4.

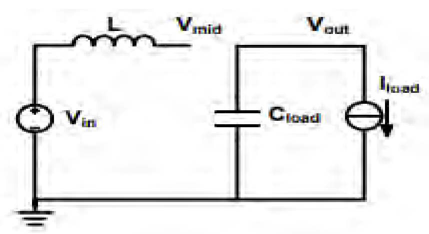


Figure 4. 3 Boost DC/DC converter during dead time

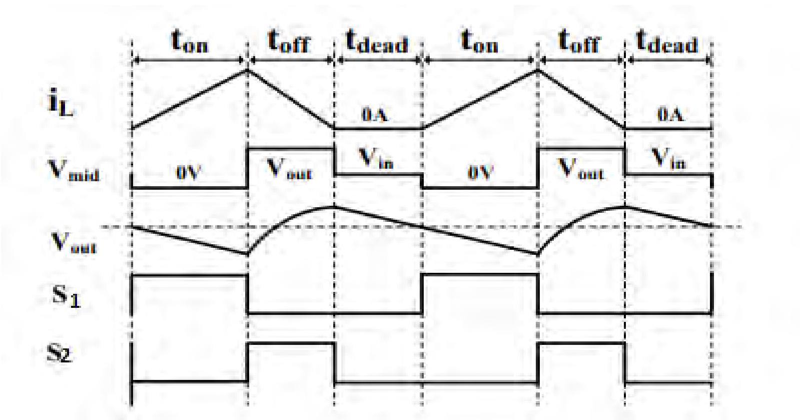


Figure 4. 4 Timing diagram of the main signals in a DCM boost converter.

4.4 Comparison between CCM and DCM in converter circuits

The choice of the operating technique that is going to be used, (either the CCM or the DCM), in order to achieve voltage boosting, depends on the application and on the features of the input voltage.

In applications where the input source can provide high power levels (P), for example if the energy source is a photovoltaic panel, it is preferred the CCM, in order to reduce high inductor currents and energy losses. On the other hand, in applications where the input source provides low power levels (P), it is preferred the DCM, in order to reduce conductive losses.

Chapter 5 Materials and technologies

The DC/DC switched mode DC/DC converters, analyzed in chapters 2 and 3, are implemented with solid state semiconductors, like insulated gate bipolar transistors (IGBTs), power metal-oxide-semiconductor field effect transistors (MOSFETs), thyristors, or another power-controlled semiconductor devices as well as diodes and LC circuits.
A transistor is basically a silicon or germanium semiconductor device, used to amplify or switch electronic signals and electrical power. It is similar to the diode, but their operation and performance differ. A diode is a two terminal device, which allows current in one direction only from the anode to the cathode, in contrast to the transistor, which consists of three layers of semiconductor and allows current to flow from high resistance region to low resistance region. [8], [11], [28]

5.1 MOSFET

MOSFETs have been used as the basis of today's integrated circuits. MOS transistors, which are specifically designed for high current, low on-resistance and high blocking voltage applications, are called power MOSFETs to distinguish them from their low-power, or small-signal transistor counterparts. Power MOSFETs usually operate as switches. [11], [47].
A MOSFET is a metal oxide semiconductor field-effect transistor, whose Gate input is electrically insulated from the main current carrying channel and is therefore called an Insulated Gate Field Effect Transistor (IGFET). It's the most common type of insulated FET transistors, even more common than BJTs (bipolar junction transistors), used in digital and analog circuits, for many different kinds of applications, designed for coping with high voltage power levels. MOSFET is a four-terminal device with source (S), gate (G), drain (Dr) and body (B) terminals, the structure of which is illustrated in figure 5.1. Often the body (or substrate) of the MOSFET is connected to the source terminal, making it a three terminal device like other field effect transistors. In a MOSFET a

drain is controlled by the voltage of the gate terminal, thus a MOSFET is a voltage controlled device. The voltage that is applied across the gate controls how much current flow into the drain.
The voltage at gate controls the operation of the MOSFET. In this case it can function in two modes:

- Enhancement mode: The transistor requires a Gate source voltage (VGS) to switch the device "ON". The enhancement mode MOSFET is equivalent to a "Normally Open" switch.
- Depletion mode: The transistor requires the Gate-Source voltage (VGS) to switch the device "OFF". The depletion mode MOSFET is equivalent to a "Normally Closed" switch.

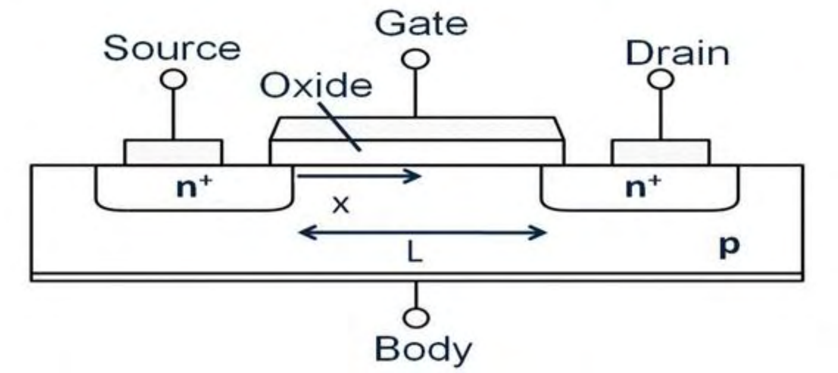


Figure 5. 1 Structure of power MOSFET [2]

5.1.1 Working Principle of MOSFET

The aim of the MOSFET is to be able to control the voltage and current flow between the source and drain. It operates as a switch. The main part of the MOSFET is the MOS capacitor. Between the source and the drain is located a semiconductor oxide layer surface, which can be inverter from p-type to n-type by applying positive or negative gate voltages respectively. Both of these types can either be in enhancement or depletion mode.
The P- Channel MOSFET has a P-Channel region between the source and the drain terminals. The drain and the source is a p-type semiconductor and the body or substrate is a n-type. On the other hand, the N-Channel MOSFET has a N-channel region between the source and the drain terminals. The drain and the source are n-type semiconductor and the substrate or body is P-type. The gate terminal itself is made from metal and is detached from the source and drain terminals using a metal oxide. This level of insulation offers low power consumption and is the fundamental benefit of this type or transistor. Power MOSFETs have diverse intrinsic components as essential parts of their structure:

- Parasitic capacitance: This capacitance can be divided into gate capacitance caused by the channel charge, and into diffusion capacitance which formed by the source region due to the structure of the transistor.
- Body diode: An intrinsic diode is formed between the drain and the source. It is appropriate for circuits where a path is required for reverse drain current, known as "free-wheeling current".

The main characteristics of Power MOSFETS are:

- The static behavior, which is determined by the circuit, the on-resistance and its own conductance. There are three different regions of working; Ohmic, where the device acts as a resistance, current-saturated, where the drain current is defined by a function of the gate-source voltage, and cut-off, where the device is an open circuit.

- The on-resistance settles the conduction power dissipation and increases with raising temperature.
- The dynamic behavior, which is defined by the switching features of power MOSFET.
- The intrinsic resistance, which forms an RC circuit that defines constant times of voltage change at the MORFET, and consequently its switching time.
- The heat which generated within the chip is dissipated by means of a heat sink comprised of thermal resistances and thermal capacitances. This, making the power MOSFET to has junction temperature limitation.

5.2 Materials

Materials of chips inside power electronic devices have been evolving the last years. Integrated circuits and power devices have been almost exclusively based on silicon (Si) technology. In fact, Silicon, Gallium Arsenide (GaAs), and Gallium Nitride (GaN) were the primary semiconductors used in power electronics for many years. The next big change in power electronics would be the use of Silicon Carbide (SiC). [11], [8], [45], [46].

5.2.1 Silicon

Silicon is still the main used material, power electronics and power system applications are designed from Silicon.

Since high conduction losses of Silicon in MOSFET are usually occurred, manufacturers developed new Silicon-based materials and technologies. Silicon can't satisfy the demanding properties of new applications, such as faster response, higher voltage or temperatures without expensive cooling systems or large number of series or parallel devices. Although the advances in technology, Silicon devices have led power electronic industries and they are still not a bad option.

5.2.2 Silicon Carbide (SiC)

In recent years there has been increasing demand to investigate and monitor ever more hostile environments including those containing high temperatures and/or extreme radiation flux. The introduction of Silicon Carbide, also known as SiC, as a semiconductor has significantly impacted power electronics, including higher voltages, higher switching frequencies, a wider bandgap, extreme temperature tolerance, and low resistance; all of which are fundamental parameters to the continued development of effective power electronics and the designs that depend on them. Silicon carbide (SiC) boasts a much higher band gap than conventional silicon and is therefore more chemically stable allowing electronic circuits made from this material to be deployed in environments where conventional silicon based electronics cannot function.

In general, SiC is a semiconductor base material that is comprised of pure silicon and pure carbon. It is a popular material used in many high power and high voltage operations, due to its durability and low cost. It has been exploited in the high performance power MOSFETs and diodes that are commercially available. It’s very suitable in certain applications in More Electric Aircraft (MEA).

The global silicon carbide market is expected to grow from 2019 to 2025. Regardless of its advantages over Silicon, Silicon Carbide needs to be improved in terms of costs and production process. [3], [50].

5.2.3 Gallium Nitride (GaN)

Gallium nitride (GaN) is replacing silicon as the material of choice for power transistors in industrial automation, motor drivers, high-frequency dc-dc conversion, and similar applications. It’s one of a class of wide-bandgap (WBG) semiconductors that have superior performance to silicon in power applications. GaN’s bandgap energy is 3.4 eV, compared to 1.1 eV for silicon. Gallium Nitride power transistors provide a number of advantages such as: [30].

- Their inherent low gate capacitance and output capacitance, enables higher switching frequency, in the range of MHz, with lower switching losses.
- Higher efficiency, resulting in lower conduction and switching losses, and low or zero reverse recovery losses and EMI.
- A smaller footprint for higher-power-density designs.
- Lower RDS(on) for higher current operation.

All these characteristics make them suitable for applications in the range of 30V and higher DC/DC voltage conversion. They provide significant efficiency benefits across a wide load range

Chapter 6 Proposed a DC/DC converter suitable for aerospace applications

As already discussed in chapter 1, in recent years, electrical systems are replacing hydraulic, mechanical, or pneumatic power sources in a wide range of aerospace applications. This increase in electrical energy demand has led to a rapid technology development, particularly in power electronics.

Nowadays in most planes it is integrated as input voltage 28V, which comes from the rectifier and as output voltage 270V. Typically, bidirectional DC/DC converters are employed in the battery back-up systems of aircraft in order to convert low voltage inputs to a high voltage DC bus in the boost mode, or high-voltage inputs to lower output voltage in the buck mode. This implementation is useful for regenerative applications. The battery based energy storage system is required for storage and dissipation of the returned energy to maintain the DC bus voltage. In such systems, the battery storage can be used at the 28V DC bus and the bidirectional converter should supply the 270V DC bus.

Figure 6.1 presents the block diagram of the system needed for Integrated Starter/Generator (ISG) power processing. The DC/DC converter is necessary for boosting or stepping down the battery voltage and the inverter converts the boosted or stepped voltage in to AC. The bidirectional power flow capability of the DC/DC converter allows the low voltage at the terminal of the battery to be converted into high voltage at the terminal of the inverter. When the power transfer is from the battery to the ISG (which is defined as motor mode or discharging mode), the inverter changes the stepped-up voltage in to a three phase AC voltage required by the ISG. On the other hand, during the power flow from the ISG to the battery (which is called Generator mode or charging mode), the inverter changes the AC voltage from the terminal of the ISG to DC voltage at the terminal of the DC/Converter and the battery is charged from the stepped down voltage by DC/DC converter. [19]-[27]

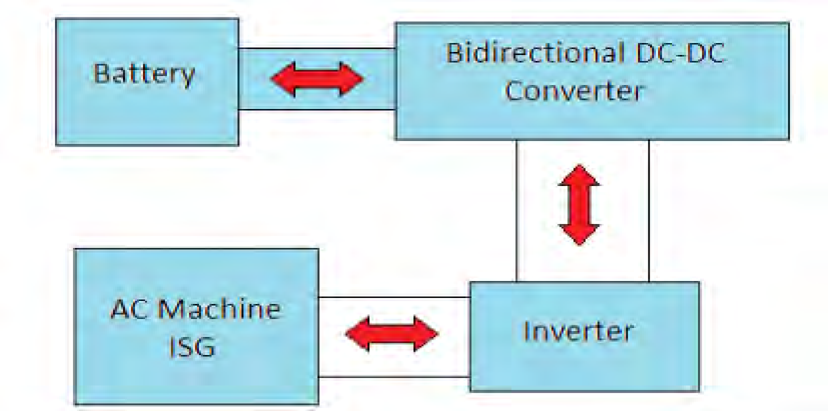


Figure 6. 1 DC-DC converter in Integrated Starter/Generator system [26]

This converter is formed by active elements (switches and control) and by passive elements (transformer and bridges). The DC/DC converter comprises of a high voltage (HV) port with the terminal voltage, Vout(270V maximum value) and a low voltage (LV) port with the terminal voltage , Vin(13V ≤ Vin ≤ 28V). A nominal output power, Pout, of 100W is required within the specified voltage range in generator mode.

6.1 Characteristics of a suitable DC/DC converter for avionics

Future aircraft will employ high power transient loads such as electrically powered actuators for adjusting flight control surfaces. Ultra capacitors or conventional batteries are possible forms of energy storage devices that may be used to meet these high transient power demands and smooth the load on the generators. Although Ultra capacitors could conceivably be beneficial in aircraft energy storage applications due to their fast response time and high current and power handling capability over a wide range of operating temperatures, batteries are selected for this implementation, due to their less complexity.

As discussed in chapter 1, the practical interest of the aviation industry to make airplanes either more electric or even all electric has increased. As a result, power electronics are playing a major role. In order to reduce fuel consumption on the plane, operating costs and to increase the efficiency, the conventional methods of energy transfer in aircrafts are being replaced by power electronics converters. Hence, researchers focus on the design of an efficient and lightweight DC/DC converter, with high power density and high efficiency, to be integrated in the aircraft structure with minimum impact on volume, weight and heat management.

There is a wide range of DC/DC converter types. Before selecting the most appropriate for this application there are some important characteristics that we have to consider about: [11], [54-56].

- Bidirectionality. Bidirectional converters are a better solution for cost-critical applications with limited installation space.
- High efficiency for the whole power conversion process.
- Wide variations of input voltage versus fixed output voltage.
- Necessity of low dimensions and weight for better system integration and cost reduction.
- High reliability during emergency operations. The converter should also provide safety in fault conditions.
- Isolation. As safety is a major concern, isolation is needed.
- Fulfill thermal and electrical stress and immunity to conducted noise.

Subject of this project is a cellular converter, where all the cells are connected to each other in PIPO mode (Parallel Input Parallel Output). The interleaving technique is used to reduce components size, in particular the size of the inductor L, current ripple, and EMI and to improve the reliability. For high-power applications, such as aircraft applications, boost full bridge converter is a good choice which reduces voltage stress of switches, removes the necessity of reset circuits for the transformer, and, finally, is bidirectional. Additionally, transformer in full bridges topologies is simpler than in half-bridges, which is also an advantage in the selection. Thus, each cell is a boost full bridge converter. The selected topology that will be discussed in the following paragraphs is the dual active bridge (DAB) DC/DC converter topology.

6.2 DAB DC/DC converter topology

A dual active bridge (DAB) topology for DC-DC conversion, shown in figure 6.2, originally proposed and published in 1991 by Doncker Etal and has been selected for the integration of the proposed battery configuration in the MEA power system architecture. In literature many other bidirectional isolated DC-DC converter are given, but DAB has been popular among researchers over other bidirectional DC-DC converters, the past two decades, due to its number of advantages: [30-33].

- High performance and low cost.
- High efficiency.
- High power density.
- Galvanic isolation. Isolation would minimize any electricity related accident, which at least concerning human safety.
- Inherent soft-switching property.
- Different possible kinds of modulation techniques.
- Bidirectional power flow capability, which permits flexible interfacing to energy storage devices.
- A symmetrical structure.
- Simple control mechanism.
- Low number of passive components.

Additionally, it has to be mentioned that, DAB presents lower loss switching loss due to their natural capability of achieving ZVS commutation when the devices are turned on, in a wide operating range and without drastically increase the control system complexity. Because of the extra power switching devices, the pressure and flow capacity of the power switching are strong, so a larger power can be transmitted. All these features make this topology of DC/DC converter suitable for high power density aerospace applications.

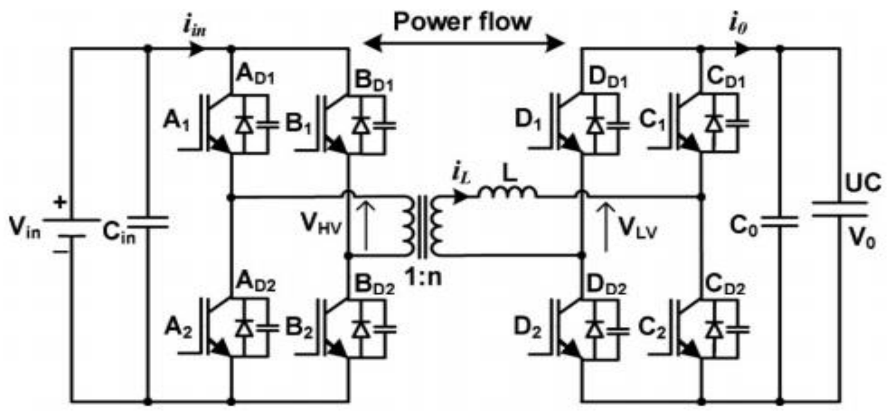


Figure 6. 2 The DAB DC/DC converter

In this section the operation and characteristics of the DAB DC/DC converter are discussed, in order to meet aviation requirements. In literature, researchers have shown different modulations of the DAB. Among them there is three classical forms named phase-shift, triangle and trapezoidal modulations. Many efforts have been made to improve the performance of the DAB converter, which presented and analyzed in high quality and detailed in [29-34].

6.3 Modulation techniques

There are different types of DAB DC/DC converter, varying on their modulation techniques, interleaving methodologies and soft switching capabilities. Depending on the specification of the DAB, a zero voltage switching mechanism can be implemented effectively. The type of the switching mechanism depends on voltage ratios of the input and output, and the variation of the load. In literature [29], [34], [40], [41] researchers have shown the different modulations which are able to control the DAB. Among them there are three classical forms, depicted in diagram 6.3.

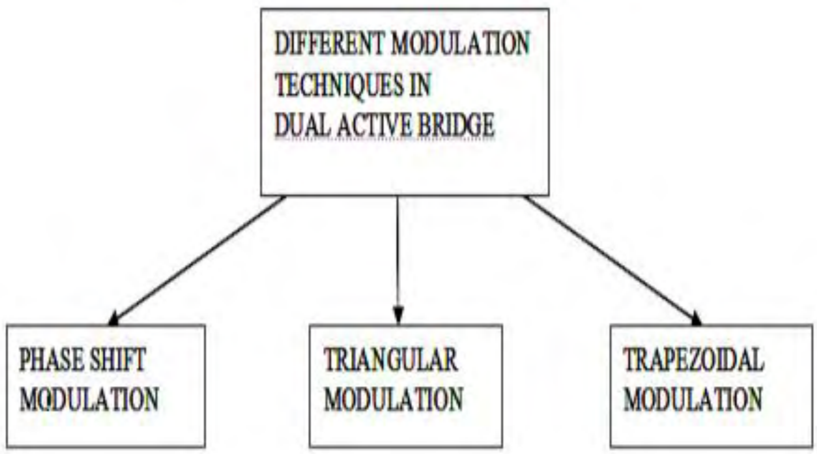


Figure 6. 3 Three different basic modulation techniques in DAB DC/DC converter [40]

6.3.1 Phase shift (PS) modulation

Thanks to adjustment of d1, d2, and ϕ, the transferred power is controlled from one bridge to the other. Phase shift is the most conventional modulation technique in DAB converter, which operates with a constant switching frequency and maximum duty cycle of both full bridges. For phase shift operation, rectangular transformer voltages on the primary and secondary windings with switching frequency fs and phase shift φ are applied to the transformer. The power transfer is characterized by simplicity as it depends only on the phase shift ϕ between the two full bridges. However, phase shift modulation has limited operating range with inherent soft switching capability and large rms current in the transformer leakage inductance, which makes it unsuitable modulation technique in wide voltage ranges and wide load variations. [29], [41], [43], [44].

There are mainly three kinds of phase-shift control:

- Single-phase-shift (SPS) control, which is the easiest control method. In SPS control, the cross-connected switch pairs in both full bridges are switched in turn, to generate phase-shifted square wave with 50% duty ratio to the transformer's primary and secondary sides. In this way, only one phase-shift ratio can be controlled.
- Extended-phase-shift (EPS) control. EPS is a typically improved control method of SPS control. In EPS control, the cross connected switch pairs in one full bridge are switched in turn. Switch pairs in the other full bridge are switched with an inner phase-shift ratio. [39].
- Dual-phase-shift (DPS) control. DPS control is another improved control method of SPS control. In DPS control, all the cross-connected switch pairs in the converter are switched with an inner phase-shift ratio. [43].

EPS and DPS controls can improve the performance of the DAB by increasing the control complexity compared with SPS control.

6.3.2 Triangular/ Trapezoidal modulation

In order to improve the efficiency of the DAB in terms of wide range operation and zero current switching on the low voltage switches, other modulation techniques are applied. Triangle modulation acts like a diode rectifier when d1, d2, and ϕ are carefully selected to switch the secondary side at zero current. Triangular Current Mode Operation enables the zero current switching in the LV side. It has a very high rms current reduction compared to conventional but within the limited power level. The trapezoidal Current mode Operation eliminates the limitation of power level in Triangular current Mode Operation. Hence, it allows the controller to extend the triangle modulation to a higher power level.
The advantage of alternative modulation mechanism is higher efficiency for wide range input and output voltages and load variations. However, these two types of modulation techniques introduce control complexity compared to conventional phase shift mechanism. [11].

6.3.3 Selected modulation

As the input and output voltages are usually already determined by the application area, the common phase shift modulation seems to be suitable modulation technique for the DAB DC/DC converter used in aircraft storage applications. Additionally, this method has inherent zero voltage switching in all ranges of the duty cycle with a fixed load requirement at steady state. These features contribute to a higher efficiency and less control complexity compared to the triangular or the trapezoidal modulation techniques. In this project, only the single phase shift control is discussed, as it is the less complex control. [34]

6.4 Circuit description and configuration

The basic structure of the Dual Active Bridge (DAB) DC/DC converter topology is shown in figure 6.4. The circuit is symmetrical. It consists of two active full semiconductor bridges coupled via a high frequency transformer $\mathrm{T_r}$, with a turns ratio n. On the one hand, the transformer determines the coarse transmission ratio between the primary and secondary side, and on the other hand, ensures galvanic isolation, which is an extremely valuable parameter for safety measures. The third core component is a coupled inductor L on the secondary side, in series with the transistor.

S1-S8 are the eight controllable switches implemented with anti-parallel diodes D1-D8, in order to direct current communication on switching events and to allow for zero voltage switching (ZVS). High frequency performance because of soft-switching at zero voltage (ZVS) occurs at all the semiconductor devices over a wide range. Due to the symmetry of this converter, with identical primary and secondary active bridges, the power flow can be bidirectional.

Vin is the DC-BUS input voltage and Vout is the output battery voltage. VHV and VLV are the voltages on High Voltage (HV) and Low Voltage (LV) sides of the transformer's windings respectively. The primary bridge on the left-hand-side of Fig is connected to the high voltage (HV) 270 V DC bus and the secondary bridge on the right-hand-side is connected to the low voltage (LV) 28 V batteries. Input and output capacitors *Cin* and *Cout* are used as low pass filter, due to the reasonable ripple current level.

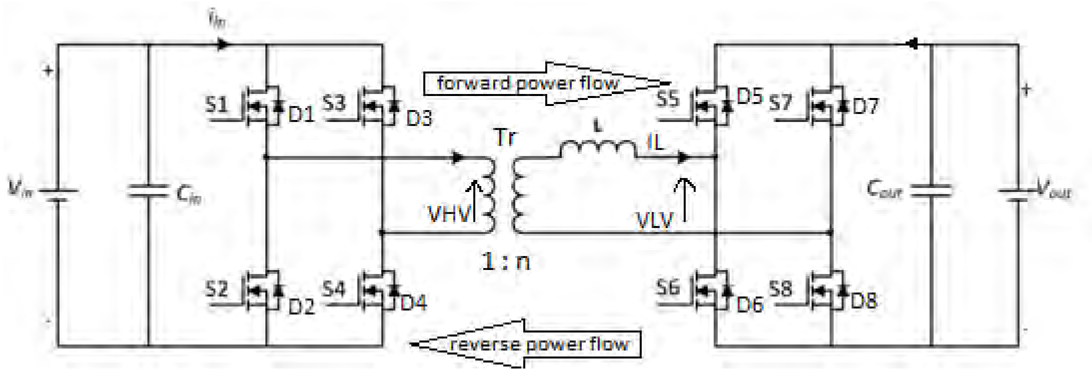


Figure 6. 4 Circuit of the DAB DC/DC converter

6.5 Theoretical power flow analysis

The full bridge on the left side is connected to the DC-bus, and the full bridge on the right side is attached to the battery.

The basic operation principle is as follows. Each full bridge inverts DC voltage and creates a voltage drop across the AC inductor which leads to a current variation. All the switching elements at both full bridges of the DAB converter are controlled with constant duty cycle D (50%). Each full bridge is controlled to provide a DC-bus high-frequency square wave voltage at the transformers terminals of the same frequency (f_s). Figure 6.5 reflects an equivalent system. The amount of power transferred from leading to lagging bridge, depends on the phase shift ϕ between the two full bridges. The two square waves can be phase-shifted with respect to each other to control the power flow through the transformer and inductor. Power can be made to flow from Vin to Vout or vice versa. Power always flows from the bridge generating the leading square wave to the other bridge. The link between the two full bridges is inductive.

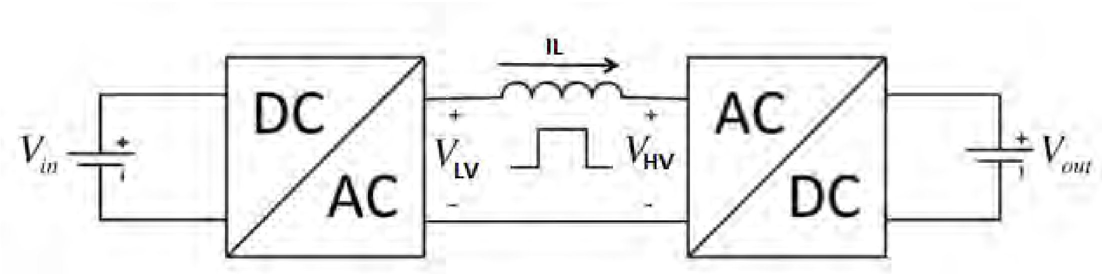


Figure 6. 5 High frequency equivalent Dual Active Bridge [26]

Considering that, the full bridge on the left hand side of fig. 6.4 is connected to the HV DC bus and the full bridge on the right hand side is attached to the low-voltage (LV) battery, the two modes of the bidirectional DAB converter in steady state, the buck and boost mode, will be analyzed. The voltages generated by the two full bridges, VHV from Vin across the primary winding of transformer and VLV at the secondary winding, are represented as square-wave voltages with 50% duty cycle (D). These waveforms are generated by operating all switches with 50% duty ratio (d) and turning on/off the diagonal switches in the same bridge at the same time.

6.5.1 Buck mode

During the buck mode, called charging mode, there is a forward power flow where the HV side bridge leads the LV side bridge by $\frac{dT_s}{2}$. T_s is the time of period for one cycle and d is the duty ratio. The current flowing through the coupling inductance is I_L and $Iout$ is the output current. The theoretical operating waveforms across primary and secondary winding of the transformer are depicted in fig. 6.6.

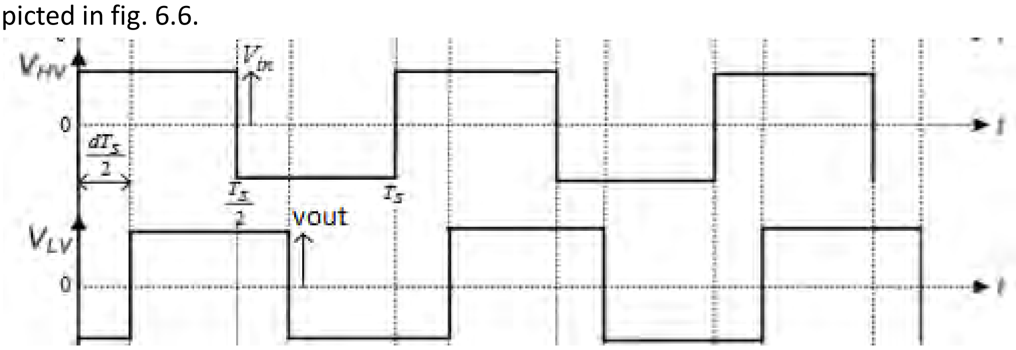


Figure 6. 6 Ideal waveforms of the DAB converter during charging mode [26]

During this operation, the primary HV side bridge performs an inverter operation and the secondary LV side bridge, performs rectification. According to the circuit in fig.6.4, three theoretical ideal operation stages are classified using steady state analysis[26]:

- **t0-t1**
  At t0 transistors S1 and S4 are turned on and their parallel diodes D1, D4 are conducting. The input voltage (Vin) is applied across the transformer's primary winding. On the LV side, transistors S5 and S8 are conducting, making the transformer's secondary winding reaching a voltage of –Vout, resulting in a gradual increase of the inductor current.
- **t1-t2**
  At t1, transistors S5 and S8 are turned-off under ZVS. Diodes D6 and D7 are conducting and the transformer's secondary voltage is clamped to vout, resulting the inductor current to reach its peak value.
- **t2-t3**
  At t2 transistors S1, S4 are turned off under ZVS and diodes D2, D3 are conducting. As a result, the primary voltage of the transformer is clamped to Vin in the opposite direction. On the LV side, diodes D6 and D7 continue to conduct and the transformer's secondary voltage is retained at Vout. The inductor current I_L becomes zero and increases in the opposite direction gradually. This completes one half cycle. At t3, the cycle is repeated, except with the corresponding opposite set of bridge transistors and diodes.

6.5.2 Boost mode

In the Boost mode, called discharging mode, the power flows from the LV side bridge to the HV side bridge. There is a reverse power flow while the battery is discharging into the DC-Bus. The key ideal operating waveforms of the converter during reverse mode are shown in fig. 6.7.

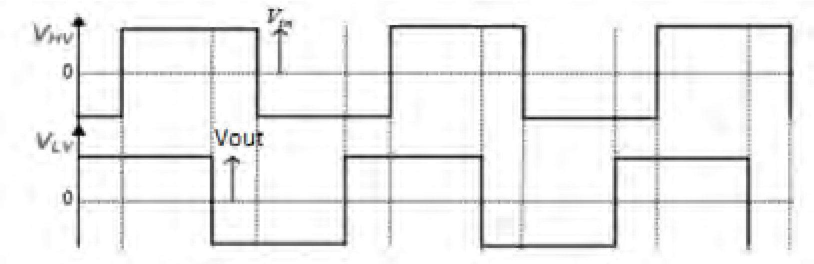


Figure 6. 7 Ideal waveforms of the DAB converter during discharging mode [26]

Similar to the buck mode, the current flowing through the coupling inductance is I_L and the output current is $Iout$. The time delay between VHV and VLV is $\frac{dT_S}{2}$.

In this circuit operation, the secondary LV side bridge performs an inverter operation and the primary HV side bridge performs rectification, in order to discharge the battery. The DAB converter enables power transfer for $V_{in} \leq nV_{out}$, where n is the transformers turns ration. As already mentioned, the so-called phase shift modulation method is used to analyze the DAB. Using Steady state analysis, 3 switching conditions stages of the device, during discharging mode, can be classified [8]:

- **t0-t1**
  At t0 transistors S7 and S6 are turned on. The battery voltage is applied across the transformer secondary. On the primary (HV side), transistors S2 and S3 are conducting. The transformer primary winding is clamped to Vin in the reverse direction. Since the resultant voltage impressed across the inductor is negative, a gradual increase of inductor current in the reverse direction occurs until it attains its peak value at time t1.
- **t1-t2**
  At t1, transistors S2 and S3 are turned-off under ZVS. Therefore, current is transferred from transistors S2, S3 to diodes AD1 and BD2 respectively. This clamps the transformer primary to the supply, Vin. Transistors C1 and D2 remain in conduction during this mode. The resultant voltage across the inductor is positive during this interval, which makes the inductor current fall from its negative peak.
- **t2-t3**
  During this interval, current flowing in S7 and S6 is transferred to diodes D8 and D5 respectively under ZVS, and transistors S7 and S6 turn-off. Now D8 and D5 are conducting, thereby the secondary of the transformer is kept at -V0. Switches at transistors S1 and S4 continue to conduct during this interval. As a result, inductor current falls to zero and charges in the forward direction gradually. This completes one half cycle in discharging mode. The next half cycle repeats at t3, except with the corresponding opposite set of bridge transistors and diodes.

6.6 Steady-State circuit analysis

In this section the above analytical process is simplified. Considering that every component of the converter is lossless, there is no magnetizing inductance, and the supply voltages are constant, equations for the device RMS and average currents, and the peak and RMS currents of the coupling inductor, indicate the losses that occur in the devices and passive components and allow a study of the converter's characteristics.

The difference between voltages of the two bridges appears across the coupling inductor and the inductor current changes with an essentially constant slope, which determines the peaks of the inductor current at different switching instants. In literature [] mathematical equations are proposed, in order to explain the above theoretical analysis for the two modes of the DC/DC DAB converter topology.

6.6.1 In charging mode

Over the first half cycle, the voltage across the inductor V_L is given by 6.1.

$$\int V_L dt = (nV_{in} + V_{out})\frac{dT_S}{2} + (nV_{in} - V_{out})\frac{[T_S - dT_S]}{2}$$

$$= \frac{nV_{in}T_s}{2} + V_{out}T_s(d - \frac{1}{2}) \qquad (6.1)$$

where n is the transformers turns ratio. The inductor current I_L changes from its negative to its positive peak I_p, during charging mode. According to equation 6.1, equation 6.2 expresses the peak to peak change of the Inductor current:

$$I_{Lpp} = \frac{T_S}{2L}[V_{out}(2D-1) + nV_{in}] \qquad (6.2)$$

The peak inductor current I_{L1}, which is the current at the HV switching instant is given by 6.3:

$$I_{L1} = \frac{T_S}{4L}[V_{out}(2D-1) + nV_{in}] \qquad (6.3)$$

Whereas the inductor current I_{L2} at the LV switching instant is given by 6.4:

$$I_{L2} = \frac{T_S}{4L}[nV_{in}(2D-1) + V_{out}] \qquad (6.4)$$

The average output current I_{out} is deriving by 6.5:

$$I_{out} = \frac{T_S nV_{in}}{2L}(D - D^2) \qquad (6.5)$$

6.6.2 In discharging mode

In discharging mode, the voltage across the inductor, VL, is analyzed, over a half cycle, in order to determine the peak to peak change in the inductor current. In the literature is proven that this integral voltage is expressed by 6.6:

$$\int V_L dt = (nV_{in} + V_{out})\frac{dT_S}{2} + (V_{out} - nV_{in})\frac{[T_S - dT_S]}{2}$$
$$= \frac{T_S}{2}[V_{out} + nV_{in}(2D-1)] \quad (6.6)$$

where n is the transformers turns ratio.

During this period of time, the difference in voltage between the two bridges appears across the coupling inductor L. As a result, the current through the inductor, changes from negative peak I_p to positive peak I_p with a constant slope. Equation 6.7 indicates the peak to peak change in the inductor current:

$$I_{Lpp} = \frac{T_S}{2L}[V_{out} + nV_{in}(2D-1)] \qquad (6.7)$$

Expressions for the inductor current are derived for switching instants I_{L1} and I_{L2} in boost mode. The current at the DC-bus side switching instant I_{L1} is expressed as follows:

$$I_{L1} = \frac{T_S}{4L}[V_{out} + nV_{in}(2D-1)] \qquad (6.8)$$

The battery switching instant I_{L2}, based on the current slope during the interval $\frac{dTs}{2}$ can be found as:

$$I_{L2=} \frac{T_S}{4L}[nV_{in} + V_{out}(2D-1)] \qquad (6.9)$$

The energy stored in the coupling inductance is sufficient to ensure charge/discharge of device output capacitances at the switching instants.

The currentI_0, represents the required average output current of the DAB converter and decides the direction and amount of power flow. A positive current demand gives rise to forward power flow that charges the Ultra capacitor, whereas a negative current demand results in a reverse power flow that discharges the Ultra capacitor.
An expression for the battery current is calculated in 6.10, for the interval t_B, which is the time needed for IL to become zero following the LV switching instant, the I_{out} current waveform is piece-wise linear.

$$I_{out} = \frac{T_S n V_{in}}{2L}(D^2 - D) \qquad (6.10)$$

The power transferred from primary to secondary is represented by equation 6.11. This expression shows a relationship between the power delivered to the output as a function of the duty cycle between the two bridges, the switching frequency of the converter, and the energy transfer inductance. Additionally, (6.11) also indicates that a negative duty cycle between bridges will cause power to be drawn from the output and delivered to the input dc bus. Fig. 6.8 shows the power transfer per unit vs the duty cycle of the two bridges. It can be obtained that, the maximum power transfer is achieved at a duty ratio of 0.5.

$$\mathrm{P}_{out} = \frac{nVinVout}{2f_S L}(D - D^2) \qquad (6.11)$$

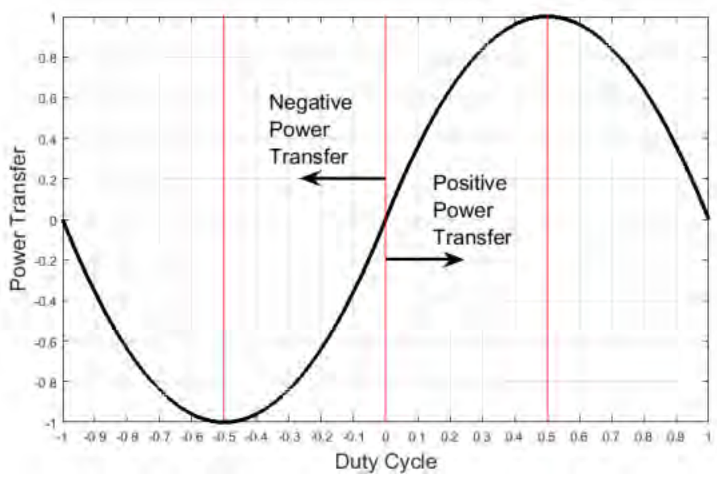


Figure 6. 8 Dual active bridge power transfer characteristic [26]

Chapter 7 Design implementations and considerations of the DAB converter

For aircraft applications, reliability and efficiency across a wide power range is at high importance. Thereby, several major converter components must be selected to withstand maximum anticipated current and voltage stresses and to facilitate desired power flow control. The most crucial components of the DAB converter are the transformer, the coupling inductor, the switches and the DC-link capacitors. Furthermore, all design criteria must operate at switching frequencies greater than 100 kHz. The key component values of the converter are determined by applying the worst case operating condition to the equations derived from the steady-state analysis.
In the following paragraphs, the key system parameters that will be used for component selection, are discussed. [45], [46], [52-54].

7.1 Selection of coupling Inductor (L)

In the DAB converter's power transmission process, the coupled inductor L is needed for the power transmission between the primary and secondary sides of the high frequency transformer. The leakage inductance is used as energy storage components in DAB converters and additionally, it reduces the dv/dt across switching devices during commutation transients, facilitates soft switching, and reduces switching losses.
Therefore, the inductance selection has a great influence on the operating ability of the DAB converter. Depending on the operating frequency and rated power, it can in the best case consist exclusively of the leakage inductance of the transformer, which can save costs and installation space. The transformer's leakage inductance, which is given by equation 7.1, stores and transfers the power. If the transformer leakage inductance is less than the calculated coupling inductor, an additional inductor in series can be inserted in the circuit. [56]

$$L = \frac{nV_{in}V_{out}}{8f_sP_{max}} \qquad (7.1)$$

Where P_{max} is the maximum output power transferred and n is the transformers turns ratio.
Equation 7.1 shows the dependence of coupling inductance L on the switching frequency f_s, and the maximum output power.

7.2 Transformer design

After the inductor has been sized and the converter power rating has been selected, the high frequency transformer must be designed to withstand current voltage stresses. The main parameters that have to be taken into consideration are the turn's ratio, the core material and the difference between the magnetizing inductance value and the coupling inductance value.

Assuming the voltage transfer ratio M, when M is higher than one the converter operates in buck mode and when M is lower than one operates in boost mode. [45], [56].

$$M = \frac{V_{out}}{nVin} \qquad (7.2)$$

In ideal cases, transferring enough energy to adequately charge or discharge the battery, is achieved with the voltage transfer ratio M to be equal to one. For this reason, a value of $n = \frac{Vout}{Vin}$ have to be choosen.

7.3 MOSFETS as semiconductors in DAB

The efficiency achievable with the DAB topology lies between 96% and 99% and is primarily determined by the nominal input and output voltage as well as by the switching frequency. Hence, in order to achieve a high power density, it is necessary to increase the switching frequency. The determination of the optimum frequency depends on the semiconductor switches used, the magnet materials and the available installation space. As with all switched converters, the size of the inductive components in the DAB is indirectly proportional to the switching frequency. Increasing switching frequency allows the transformer to be smaller. Additionally, voltage transients, switching power losses, on and off-state voltages, safe operating areas (SOA), soft recovery behavior, current carrying capacity and cooling conditions, make the selection of the appropriate power semiconductor devices very important. In order to select the suitable power devices, manufacturers have proposed several semiconductor devices. Among them, a performance comparison of insulated gate bipolar transistors (IGBTs) and MOSFETs from leading manufacturers was made to determine the most suitable devices in both bridges of the DC/DC converter. A power loss calculation was performed for all devices in the worst case operating condition, where the maximum ratings of the device blocking voltage, peak current, junction temperature and SOA indicated in the datasheet must not be exceeded.

In previous years, in the DAB converter topology, in order to accommodate high DC voltages (>300V), insulated gate bipolar transistors (IGBTs) have been commonplace. As such, S1–s8 switching cells have been traditionally implemented with antiparallel diodes and snubber capacitors in order to direct current commutation on switching events and to allow for zero voltage switching (ZVS) through the snubber capacitor and energy transfer inductance resonance. The motivation for developing high voltage MOSFETs is because these devices host an intrinsic body diode and drain-to-source output capacitance, which take the place of these external components and reduces the part count of the converter. Furthermore, MOSFETS are more suitable for frequencies above 100 kHz, due to their high switching losses, than IGBTS.

In Aircrafts applications the intrinsic noise from space-quantization effects can't be underestimated, being able to cause the destruction of some MOSFETs or alter control system. Nowadays Silicon Carbide is the best material possible as it is more resistant to space noise than Silicon. In the future, Gallium Nitride will be probably another good option, but it is still developing.

For this project, SiC MOSFETS are used. As already mentioned, SiC devices have numerous advantages. Firstly and importantly, SiC MOSFET leads to less switching losses and has the ability to block high voltages with low resistance. All these capabilities results in higher system efficiency and increase the system switching frequency. Higher frequency means decreased harmonic content, which results in less power quality issues. Lastly, SiC MOSFET can operate at high temperature which reduces cooling requirements. Till now, it is the most suitable for high voltage DC/DC converters which is the target of this project. [16], [17], [18].

7.4 Selection of filter capacitors

The design of input and output capacitors is a trade-off between the cost and stability of the system. Selection of large capacitance to achieve a high stability or low ripple voltage in the system will result in an uneconomical and an unrealistic system. Filter capacitors are selected based on their current handling capability, rated capacitance and maximum DC operating voltage. As a result, for the presented study, the DC-bus capacitor is selected by using the expression given in equation 7.3:

$$\mathrm{C} = \frac{1}{2F_R R}\left[\frac{1}{\sqrt{2}RF} + 1\right] \qquad (7.3) \qquad \text{, where RF} = \frac{1}{\sqrt{2}[2F_R RC - 1]}$$

In particular, capacitive input and output filters have selected to suppress the ripple on the output voltage. For the forward operation (buck mode) and the reverse operation (boost mode), the input and output capacitance are given by the equations 7.4 and 7.5 respectively:

$$C_{in} = D(1-D)V_{in} \text{ and } C_{out} = \frac{C_{in}}{2} \quad (7.4)$$

$$C_{in} = \frac{V_{in}}{D} \text{ and } C_{out} = \frac{C_{in}}{2} \quad (7.5)$$

7.5 Battery

There are various different alternatives of batteries available for rechargeable applications. For aircraft specifications, the two most common types of batteries used are lead-acid and nickel-cadmium (NiCd) batteries.

- **Lead-acid**

  Lead-acid batteries, also known as flooded or wet batteries, are assembled with electrodes (plates) that have been fully charged and dried. The electrolyte is added to the battery when it is placed in service, and battery life begins. 6 or 12 lead-acid cells are connected in series through the cell wall to give a nominal voltage of 12 or 24 volts respectively. This type of battery allows various speeds of charging, overcharging is not an issue and its cost per kWh is one of the lowest in the battery market. However, it is characterized by low energy density, which means an unfriendly battery technology.

- **Nickel-cadmium**

  A NiCd battery consists of a metallic box, usually stainless steel, plastic-coated steel, painted steel, or titanium containing a number of individual cells. These cells are connected by highly conductive nickel copper links in series, to obtain 12 volts or 24 volts. This battery technology has a ventilation system to allow the escape of the gases produced during an overcharge condition and provide cooling during normal operation. It has a low internal resistance which allows for quick charging and discharging as well as high power outputs. However, it can self-discharge if it is not in use, and is not possible to be recycled.

Because of the above mentioned characteristics, a NiCd battery technology is chosen as the most suitable for our application. Aircraft systems that have installed NiCd batteries, have a fault protection system that monitors the condition of the battery. The battery charger is the unit that monitors the condition of the battery. In addition, overheat condition, low temperature condition, cell imbalance, open and shorted circuit are also monitored. The capacity of the battery is measured in ampere-hours and it depends on cell design, discharge and charge rate and temperature. [57].

7.6 ZVS limits

Soft-switching operation is a major consideration for the design of the dual active bridge converter as it has direct correlation with the efficiency of the converter. ZERO voltage switching (ZVS) techniques must be imposed in order to improve the efficiency of the DC/DC converter. The converter operating conditions to achieve ZVS conditions are: [29], [47-49]

- At turn ON of any device, its anti-parallel diode is conducting. Hence, the voltage across this body diode is 0 or, in the case of a real diode, a forward voltage drop of typically of around 0.7 to 1.2 V. In this case, the body diode needs to be conducting in order to act as a clamp. Only after this, the ideal switch —that is part of the MOSFET— can turn on at ZVS or very low voltage if we take into account the forward drop.

- At turn OFF of any device, the minimum current flow through the device is positive. Since the body diode allows current to flow backwards, at turn off, the current must be flowing with a positive sign having for a reference the MOSFET typical path, that is, on an N-channel MOSFET, from drain to source. Otherwise, if the current is flowing through in the opposite direction, when the ideal switch turns off, the current could start flowing through the body diode, defeating the purpose and the control for ZVS.

In the charging mode, when the power is in forward mode, the current at the LV switching instant must be greater than zero to achieve ZVS in the LV side bridge. Therefore the following condition must be satisfied in order to achieve ZVS in the LV bridge:

$$I_{L1} = \frac{T_S}{4L}[V_{out} + nV_{in}(2D - 1)] \geq 0 \qquad (7.6)$$

Solving for the above inequality, the duty ratio at which ZVS occurs is obtained as:

$$D \geq 0.5 - \frac{V_{out}}{nV_{in}} \qquad (7.7)$$

Given that an increased energy must be stored in the leakage inductance to achieve soft switching (ZVS), the expression for the minimum inductor current is obtained as follows:

$$I_L = 2\sqrt{\frac{(\frac{V_{out}}{n})V_{in}}{(\frac{L}{n^2})/C_S}} \qquad (7.8)$$

When the converter operates in the discharging mode and power is transferred from the LV side to the HV side, the zero-voltage switching limit is found to occur in the LV side bridge like as in the charging mode. In order to achieve ZVS conditions in the battery side bridge, the current at the battery side switching instant must be greater than zero. Hence, the above conditions (7.6), (7.7), (7.8) must be satisfied.

7.7 Snubber Circuits

Although the turn-on of transistors is achieved at minimum (near zero) positive diode current, the instantaneous transistor currents that occur during the turn-off process are significant. In order to enhance the converter performance, limit switching transients, reduce current and voltage spikes and minimize electromagnetic compatibility (EMC) problems associated with high voltage transients (dv/dt), when a switch, electrical or mechanical, turns off, snubber circuits are introduced. A simple RC snubber circuit uses a resistor R in series with a capacitor C and is connected in parallel with every power MOSFET in the DAB converter circuit. (See fig. 7.1).

Without snubber circuits across the device during turn-off, resonance would naturally occur between the device output capacitance and the coupling inductance. Due to the low value of the device output capacitance, it would not be enough to produce a low dv/dt. As a result, there would be a high rate of initial current fall (di/dt) with a rapid voltage rise (dv/dt) across the device during turn-off. This results in turn-off switching losses, device stress and in the worst-case scenario, in the destruction of the MOSFET.

A snubber circuit should be designed in order to provide the proper protection of the switching device and the whole DC/DC converter. The snubber capacitor Cs should have a sufficient large value, so that current ringing during switching can be ignored. The effect of the added snubber circuit during device turn-off is explained in the following paragraph. Owing to the similarity of the transistor switching instants, only one transistor turn-off instant for the LV bridge side is explained. [28]

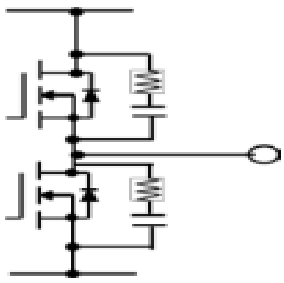


Figure 7. 1 Snubber circuit across a semiconductor device [28]

7.7.1 Device Turn-off

Considering the DAB circuit topology of the figure 7.2, it is assumed that transistors C1, D2 are on, forward current flows through the transistors and the snubber current is zero. The capacitors on these transistors, (C_{S-C1} ,C_{S-D2}) are discharged. When C1, D2 are off, the snubber capacitor reduces the high dv/dt by conducting the current. Thus, the current in the coupling inductor L discharges (C_{S-C2} ,C_{S-D1}) and charges (C_{S-C1} ,C_{S-D2}) in a resonant manner.
To summarize, the snubber capacitor allows the device current to fall before the device voltage rises significantly, during the switching period. This way the turn-off switching loss is minimized and the rise time of voltage across the transistor during turn-off is limited.

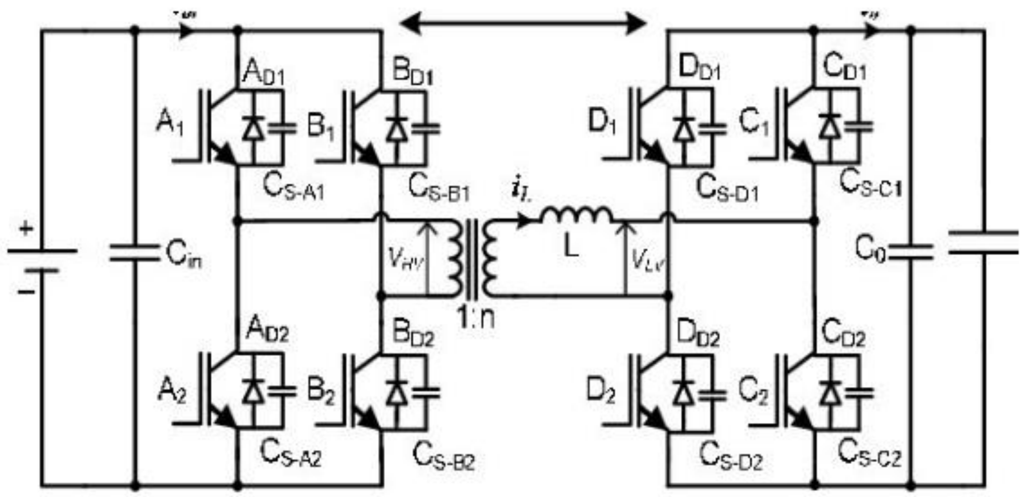


Figure 7. 2 A DAB converter topology with added snubber capacitors on every switching device

Chapter 8 Simulation results

In this chapter, simulation results are provided in order to verify the proposed model of the bidirectional isolated DAB DC/DC converter in the MathWorks MATLAB/Simulink software. Two simulation cases are conducted. The first case is in forward operation, when power flows from the HV side bridge to the LV side bridge; that is in the buck mode. The second case is in reverse operation mode, when power flows from the LV side bridge to the HV side; that is in boost mode.

The described dual active bridge DC/DC converter topology is run at constant speed of 0.1 seconds, with 50% duty cycle D, using the single phase shift modulation (SPS). In simulation, the device behavior is ideal. While the battery is charged and discharged, the value of its voltage changes. This was not taken into account during the simulation, as we only focus on the steady state of the converter. In order not to cause any trouble with the simulation, the battery was modelled as a load resistor with an appropriate value to draw the desired amount of power for the predetermined voltage. The maximum output power is set at 100W. The equation used for the load resistor is the following:

$$|R_{Load}| = \frac{{V_{out}}^2}{P_{out}} \qquad (8.1)$$

As shown in the above expression (8.1), the value of the resistor will always be considered as positive, regardless of the direction of the power because, if otherwise, the resistor will be generating power instead of drawing it.

The DC-Bus voltage will be considered constant at a value of 270V at the forward mode and at 28V in the reverse mode. As already mentioned in the previous chapter, MOSFETS are selected as the switching devices. Although we have minimize switching losses by using MOSFETS, the existence of parasitics in the circuit will also cause losses. These losses will be determined by how many times commutate the MOSFETs per second. That is the switching frequency. For this reason, we have chosen a switching frequency of 5 kHz.

8.1 Forward operation-Buck mode

According to the design specifications and equations discussed in chapter 7, table 8.1 shows the parameters used for the simulation in forward operating mode.

Input voltage	270V
Output voltage	28V
Rated maximum power	100 W
Switching frequency	5 KHz

Transformer turns ratio	270:28
Leakage inductance	1µH
Load resistor	7.84
Input filter capacitor	67.5 µF
Output filter capacitor	33.75 µF
R1,R2	0.1 Ω

Table 8. 1 DAB converter specifications in forward mode

Figure 8.1 shows the Simulink model of bidirectional dual active bridge DC/DC converter in forward operation mode, when the input voltage is charging the battery (Load). The input voltage at the HV side bridge is set constant at 270V and pulses with pulse width 50 % are given to each switching device. According to the single phase shift modulation, MOSFETS S1, S4 on the HV side and S5, S8 on the LV side are turned simultaneously on. After a phase delay of 0.01sec they are turned off and their antiparallel MOSFETs S2, S3 and S6, S7 are on.

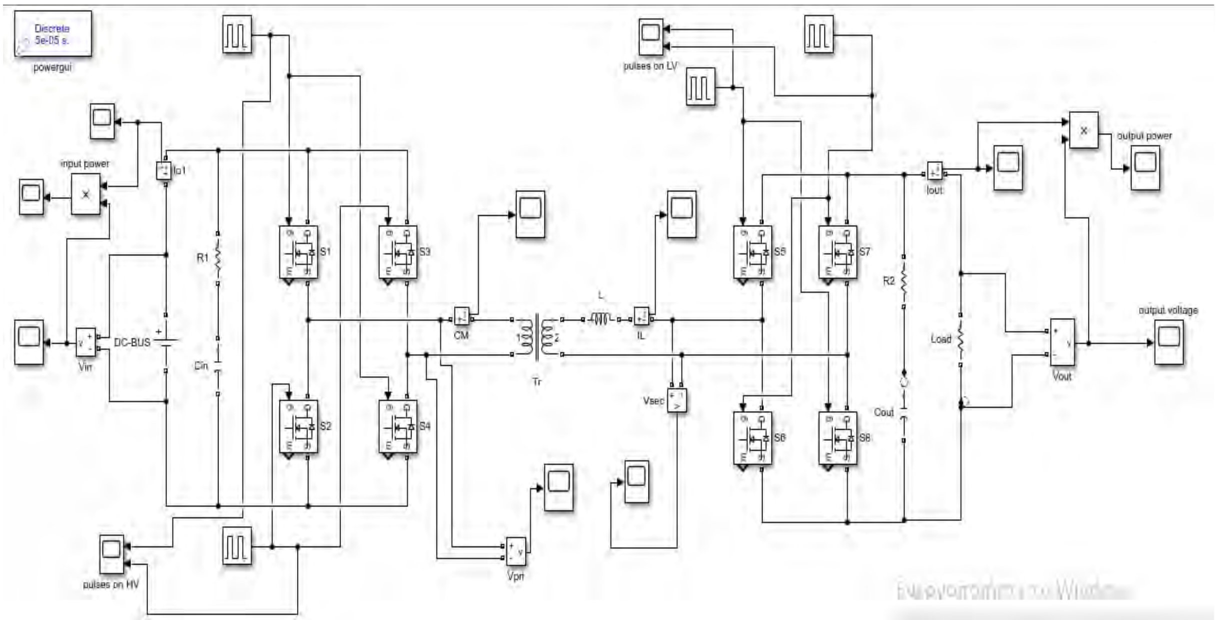


Figure 8. 1 Simulink model of bidirectional dual active bridge dc-dc converter in forward operation mode.

The waveforms obtained from the simulation running for 0.1 sec:

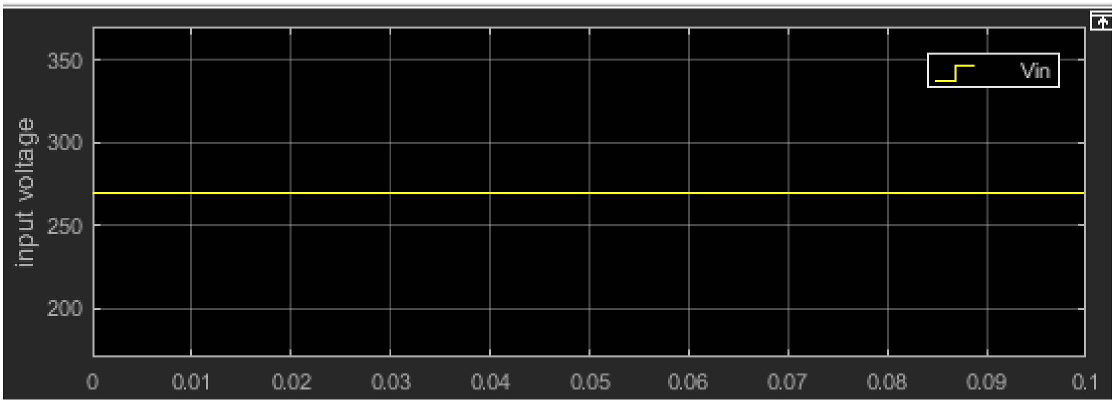


Figure 8. 2 Input voltage

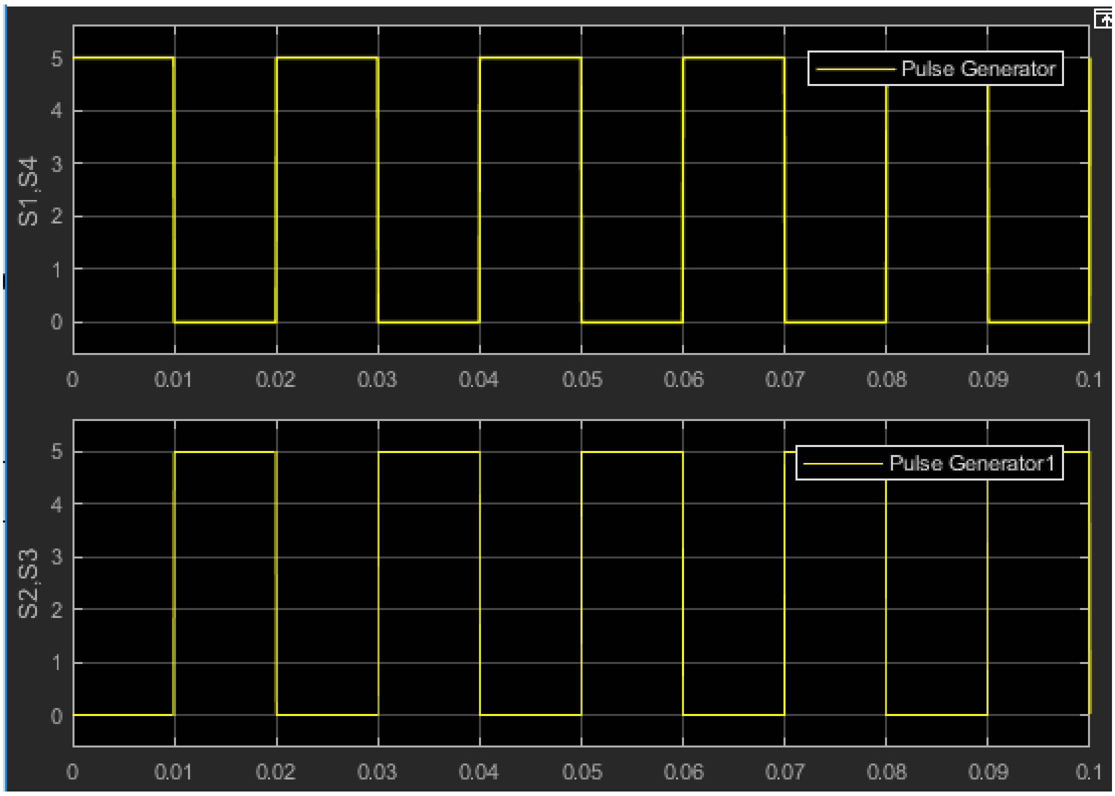


Figure 8. 3Typical waveforms of the switches on the HV side bridge

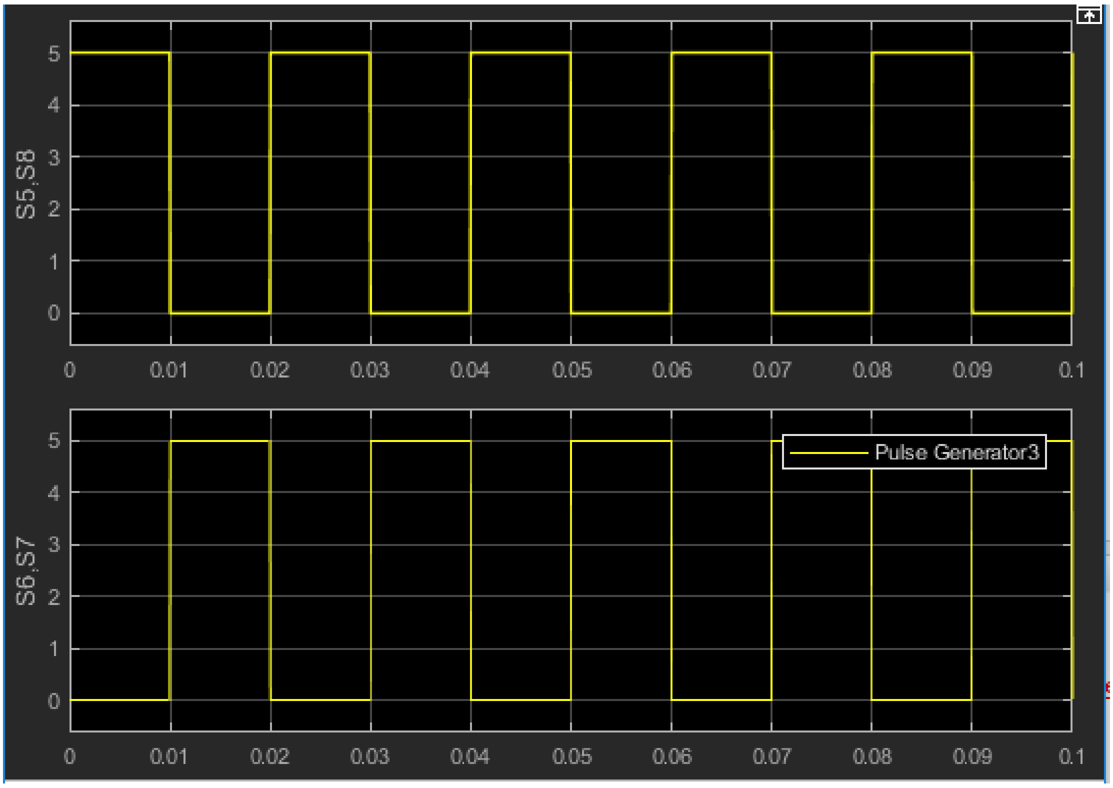


Figure 8. 4 Typical waveforms of the switches on the LV side bridge

Each bridge is designed to generate a square wave voltage across each winding of the transformer. As shown in the below plots:

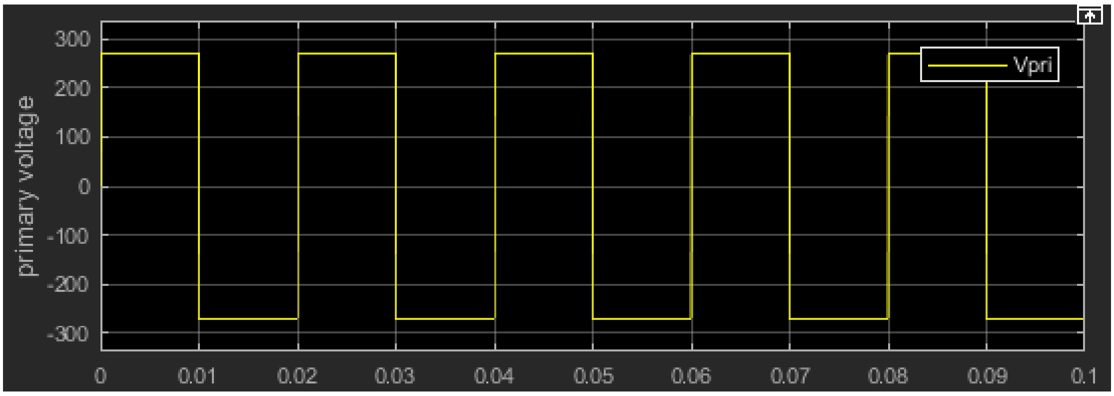


Figure 8. 5 square wave voltage across the primary winding of the transformer

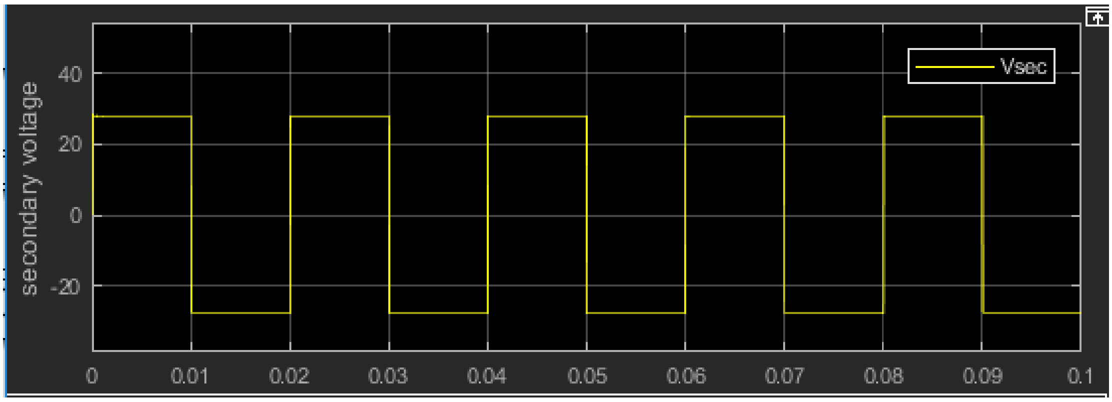


Figure 8. 6 square wave voltage across the secondary winding of the transformer

Fig. 8.7 shows the Inductor current waveform and fig. 8.8 indicates the output current waveform:

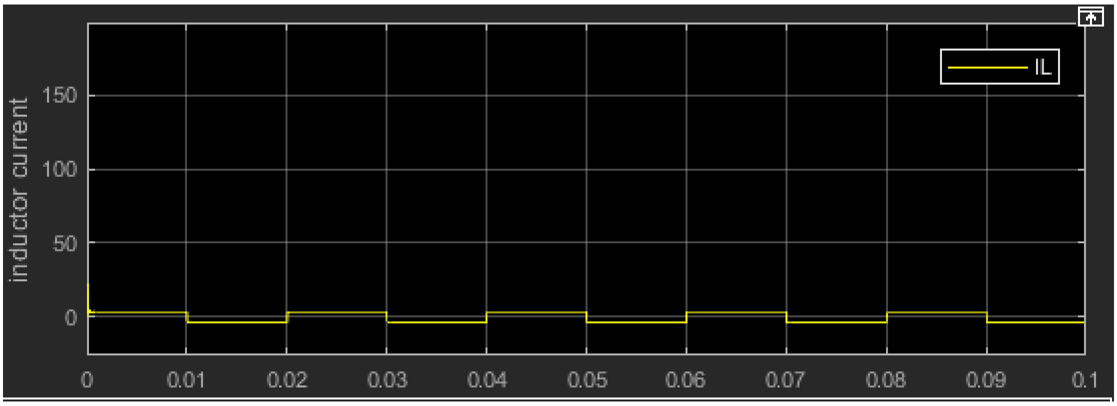


Figure 8. 7 Inductor current waveform in forward mode

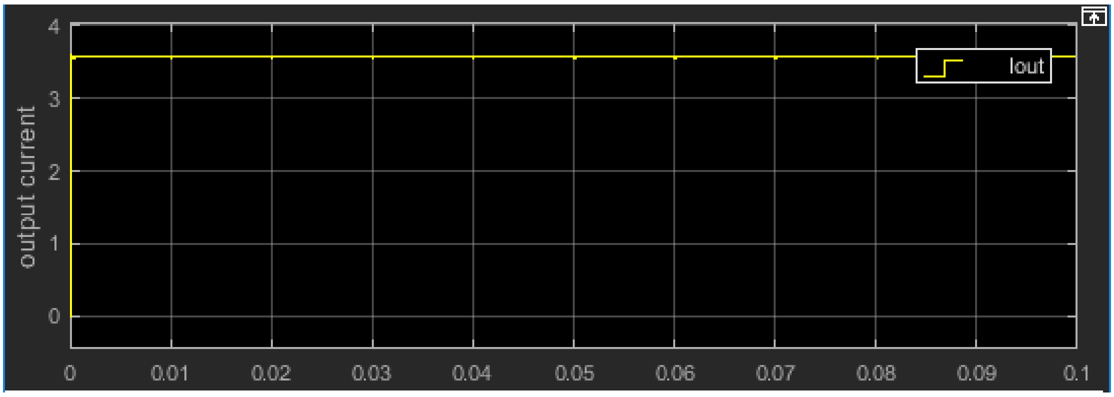


Figure 8. 8 output current waveform in forward mode

Goal of the simulation is to get an output voltage of 28V and a maximum output power of 100W. The plots of the output voltage and its peak value are depicted in figure 8.9 and 8.10 respectively. Figures 8.11 and 8.12 are plots of the output power and output power's peak value.

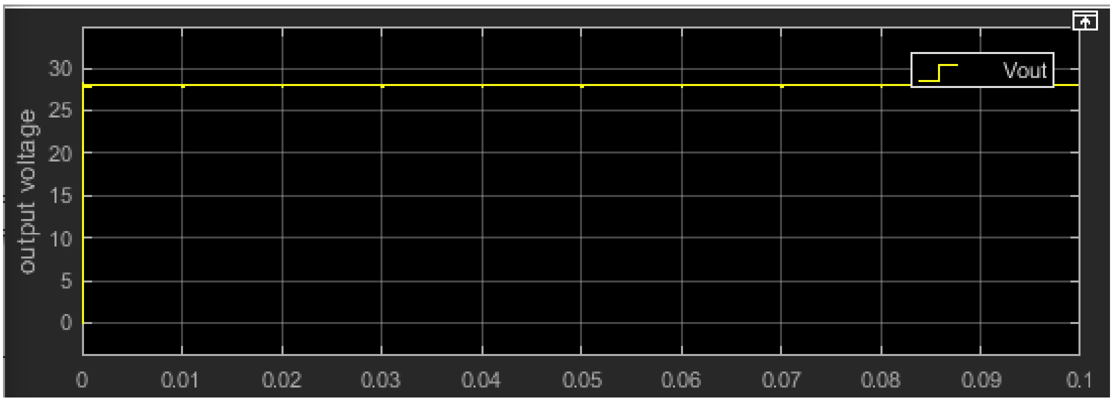


Figure 8. 9 output voltage in forward mode

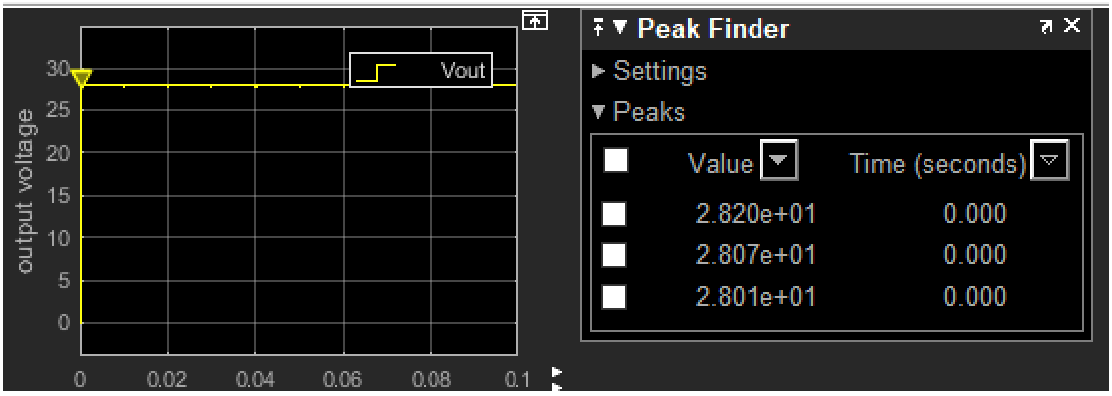


Figure 8. 10 peak value of the output voltage

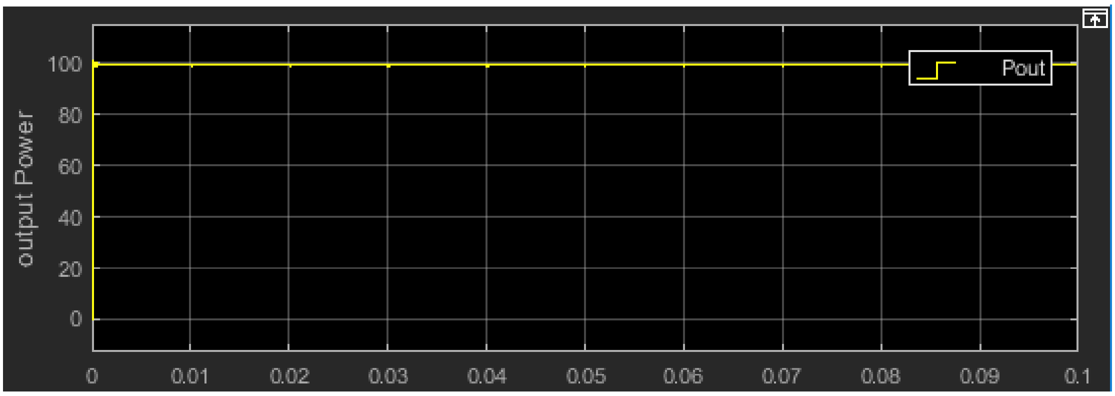


Figure 8. 11 output power in forward mode

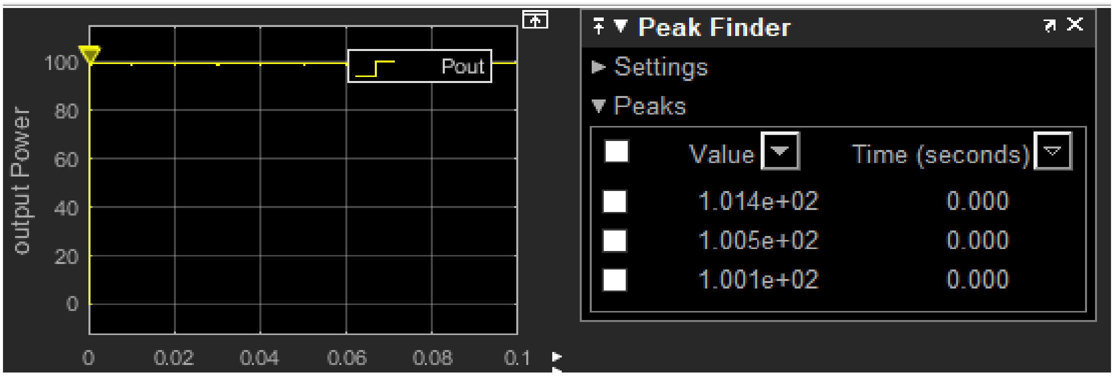


Figure 8. 12 peak value of the output power transferred

For the above waveforms and peak values, it is clear that the simulated DAB converter operates in ideal case. It can be seen that an efficiency of almost 100% is achieved.

8.2 Reverse operation-Boost mode

In this mode the power flows from the LV side bridge to the HV side bridge. For this reason, the LV voltage should be leading the HV voltage. According to the design specifications discussed in chapter 7, table 8.1 shows the parameters used for the simulation in reverse operating mode.

Input voltage	28V
Output voltage	270V
Rated maximum power	100 W
Switching frequency	5 KHz
Transformer turns ratio	270:28
Leakage inductance	1 μH
Load resistor	7.84MΩ
Input filter capacitor	56 μF
Output filter capacitor	28 μF
R1,R2	0.1Ω

Table 8. 2 DAB converter specifications in reverse mode

Figure 8.13 shows the corresponding Simulink model of the DAB converter topology in reverse mode.

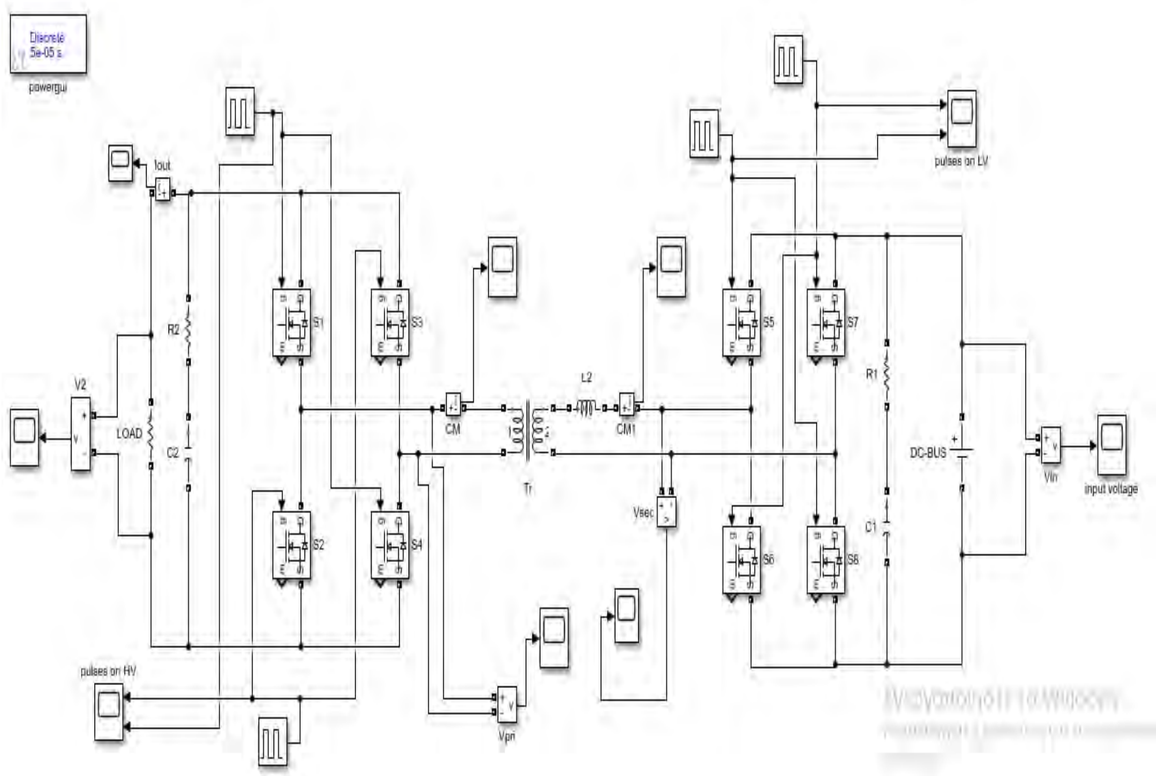


Figure 8. 13 Simulink model of bidirectional dual active bridge dc-dc converter in reverse operation mode.

In the boost mode the converter is reversed. The waveforms obtained from the simulation at 0.1sec are presented. The input voltage is set constant at 28V, as shown in fig. 8.14:

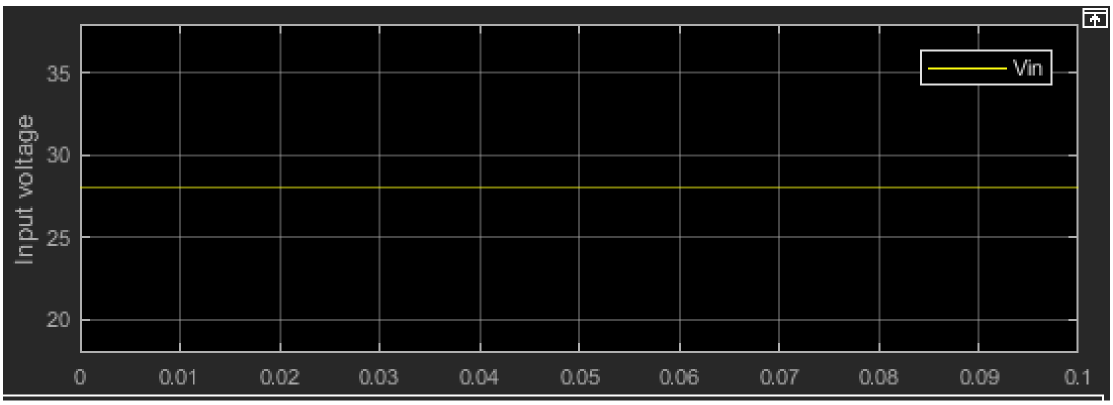


Figure 8. 14 Input voltage in reverse operation mode

Such as the forward mode, pulses with pulse width 50 % are given to each switching device. However, in reverse mode MOSFETS S7, S5 on the LV side and S2, S3 on the HV side are turned simultaneously on and after a phase delay of 0.01sec they are turned off and their antiparallel MOSFETs S5, S8 and S1, S4 are on. The square waveforms for the LV side and the HV side of the switches are shown in figure 8.15 and 8.16 respectively:

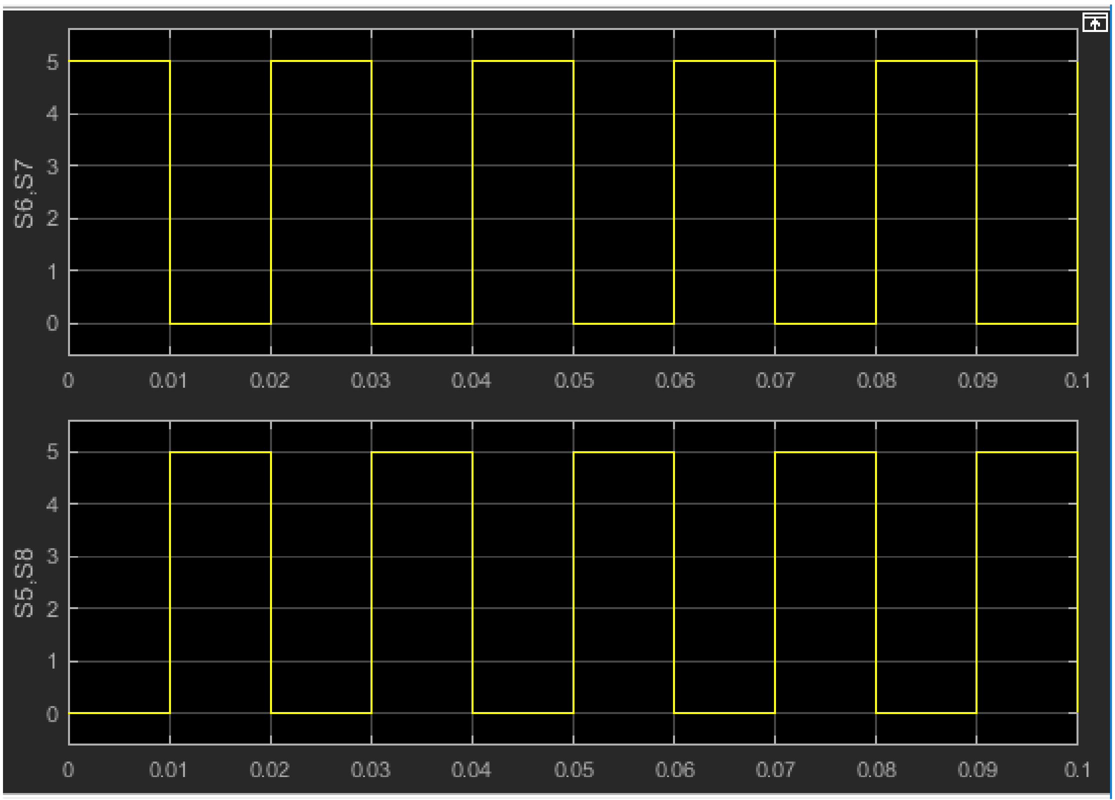


Figure 8. 15 square waveforms of the switches in LV side in reverse mode

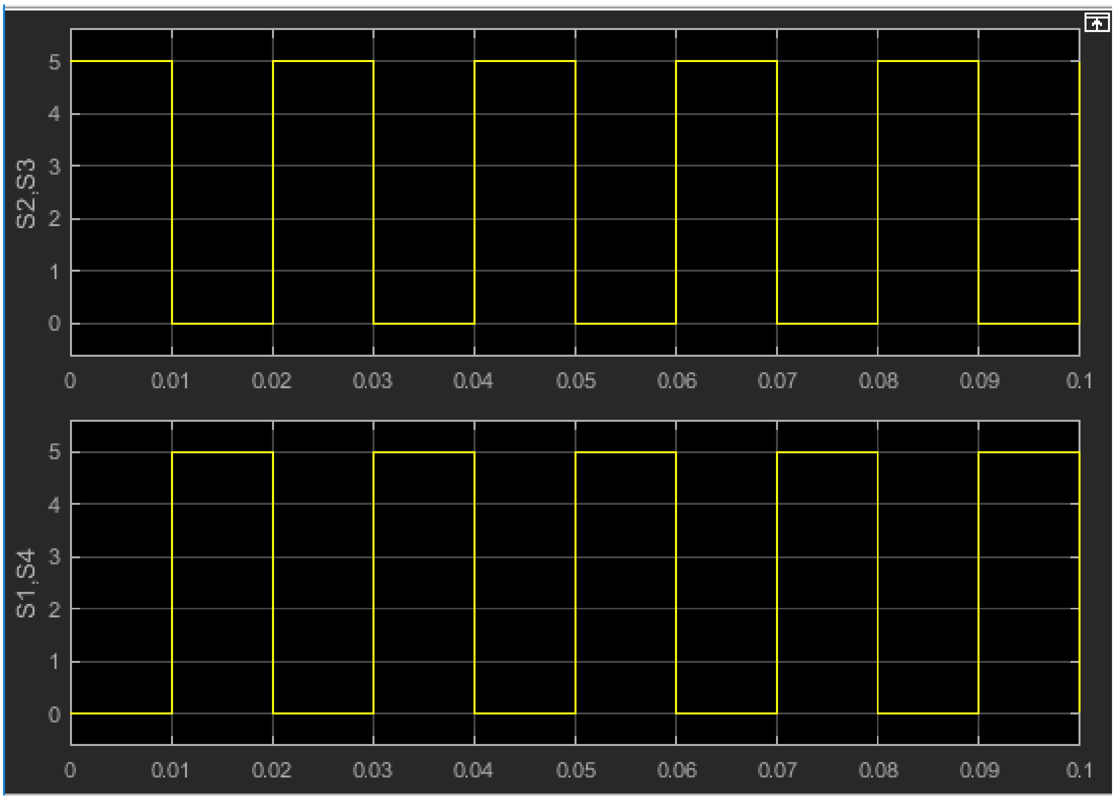


Figure 8. 16 square waveforms of the switches in HV side in reverse mode

Each bridge generates a square wave voltage across primary and secondary winding of the transformer. The corresponding waveforms are the following:

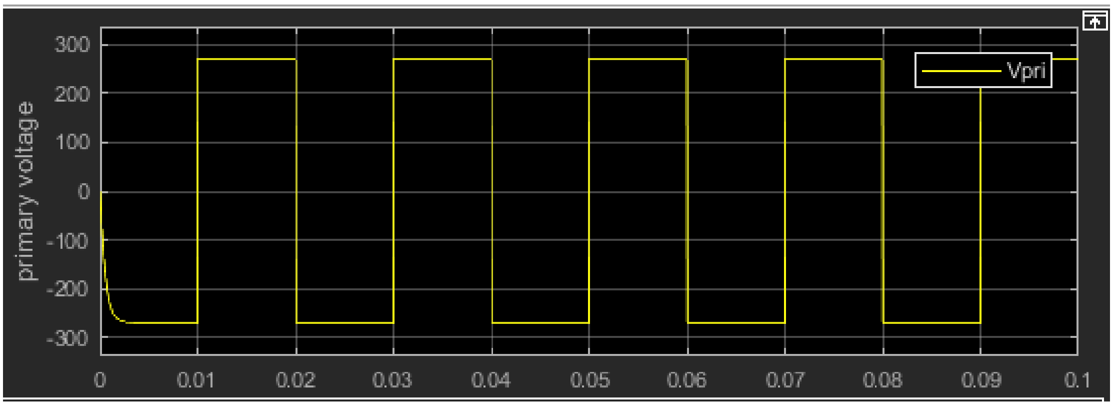


Figure 8. 17 square wave voltage across the primary winding of the transformer in the reverse mode

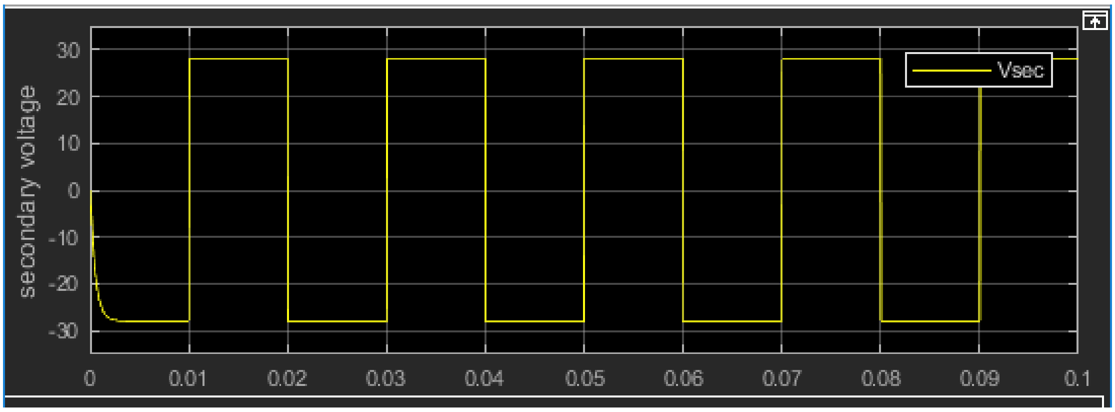


Figure 8. 18 square wave voltage across the primary winding of the transformer at the reverse mode

The inductor and output current plots in the reverse mode are depicted in figure 8.19 and figure 8.10 respectively.

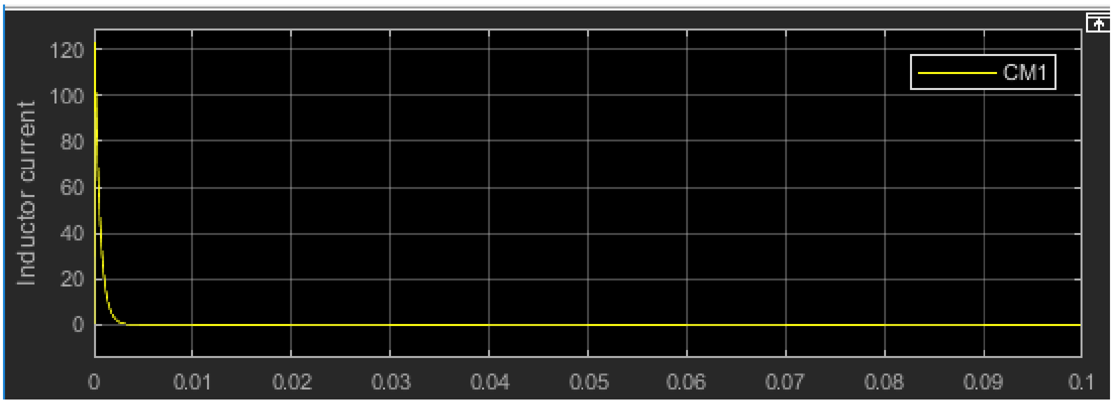


Figure 8. 19 Inductor current waveform in the reverse mode

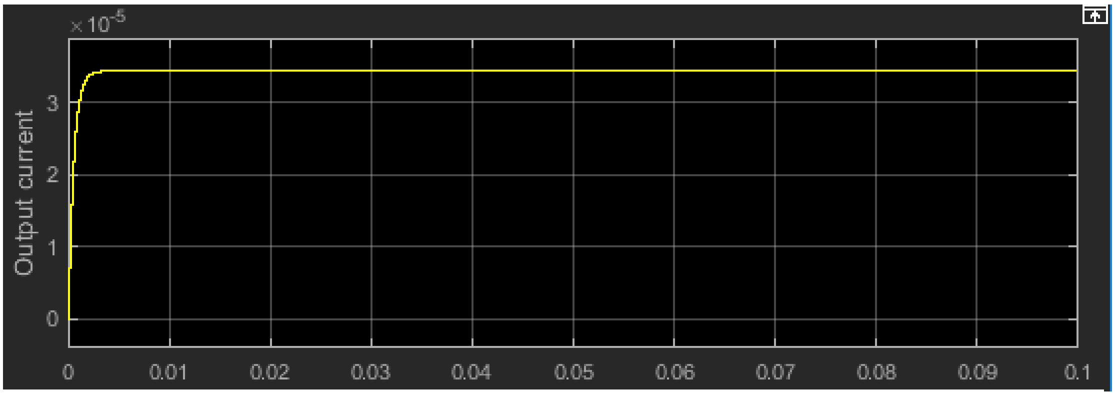


Figure 8. 20 output current waveform in the reverse mode

The output voltage should reach 270V. The plot for the boost mode shown in fig. 8.21.

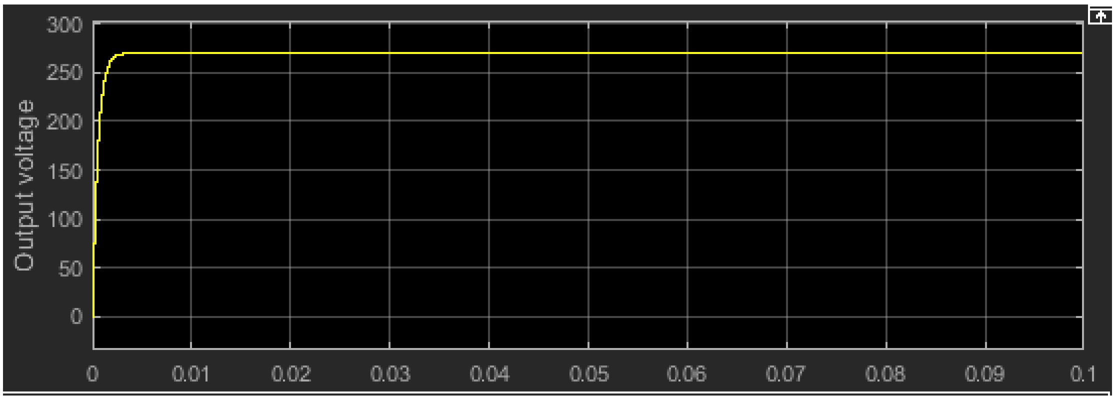


Figure 8. 21 output voltage waveform in reverse operation

During the simulation in this mode a larger load resistance of 10e6 Ω is used, in order to achieve the peak values indicated in fig. 8.22.

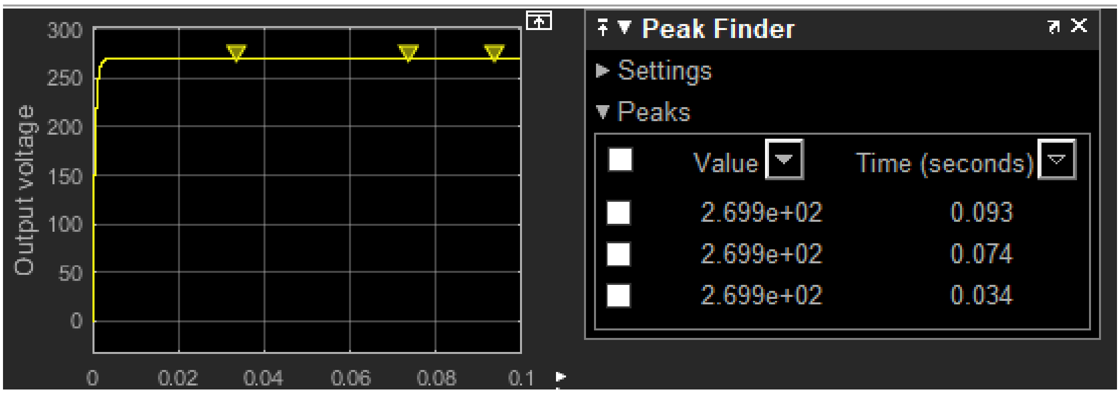


Figure 8. 22 peak values of the output voltage

Figures 8.23 and 8.24 plot the output power and the peak output power values.

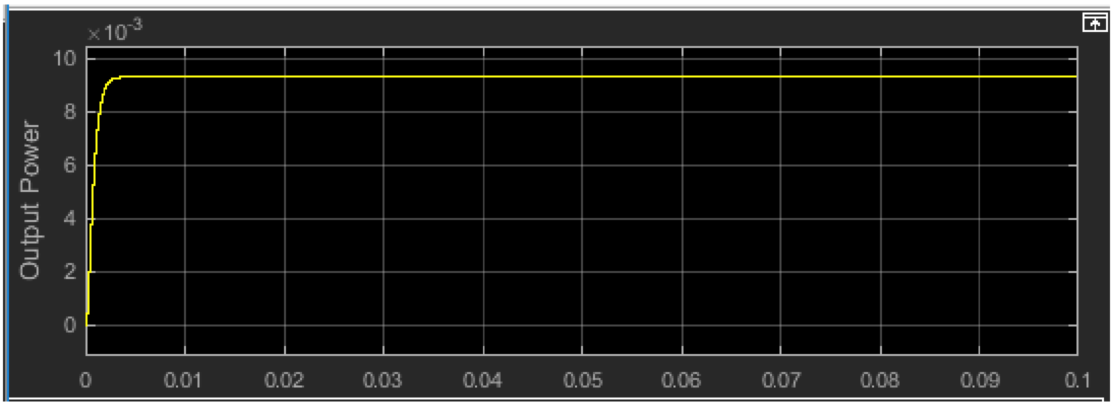


Figure 8. 23 output power in the reverse mode

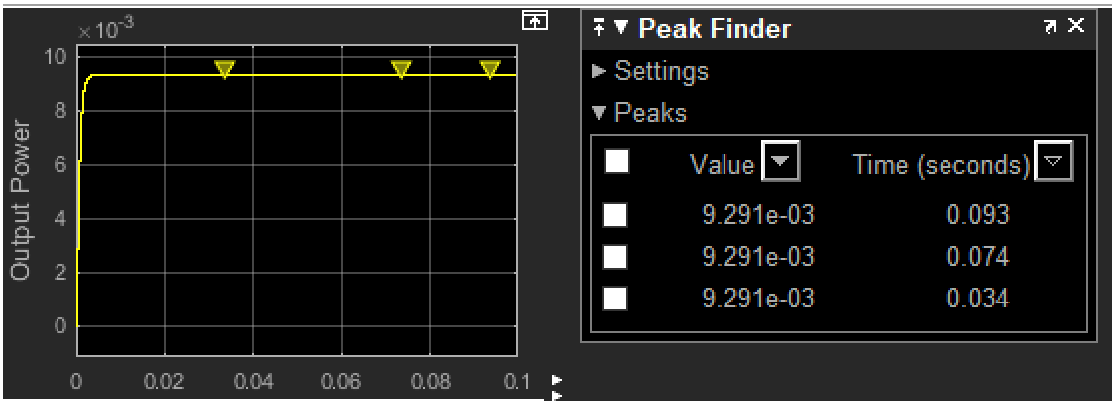


Figure 8. 24 peak value of output power in the reverse mode

Chapter 9 Conclusion

The ongoing technological progress has led to the increase of the high voltage step up DC/DC converters. This thesis studies high-step-up DC-DC converter topologies, which are suitable for various applications and provides a comparative summary of various voltage-boosting techniques in terms of their major characteristics. A bidirectional isolated DAB converter topology is presented for integrating in aerospace systems. The steady state analysis and the operating principle of the DAB converter was discussed. The DAB converter has been modeled using MATLAB in Simulink. The simulation results obtained for a 100 W maximum output power DAB converter, verify its performance during charging and discharging operating modes for battery based aerospace energy storage systems.

Implementing energy storage in our world through isolated DC-DC converters is becoming a reality. After having studied the dual active bridge converter topology and viewed its operating suitability for aircraft systems, it is concluded that while not having completed the full scope of the experiment, the initial results are promising.

Due to the limitations of time and research, there are still numerous issues that have to be implemented in this topic. Control units and dedicated test benches have to be realized to check the correctness of operation in both Buck and Boost modes and the fault tolerance of the converter. Moreover, the assessment for the cost of the proposed DC-DC converter has to be performed. With more time on our hands, more combinations for the high step-up technique and utilization of the topology to increase the system power density will be discovered.

References

[1] "Step-up DC-DC converters: A comprehensive Review of Voltage Boosting Techniques, Topologies, and Applications", ResearchGate, Article in IEEE Transactions on Power Electronics, March 2017.

[2] Mike Wens, Michiel Steyaert, "Design and Implementation of Fully-Integrated Inductive DC-DC Converters in Standart CMOS, Springer, ACSP-Analog Circuits And Signal Processing.

[3] Erik Blasch, Paul Kostek, Pavel Paces, Kathleen Kramer "Summary of Avionics Technologies", IEEE A&E SYSTEMS MAGAZINE, SEPTEMBER 2015.

[4] J.A. Rosero, J.A. Ortega, E. Aldabas, & L. Romeral "Moving Towards a More Electric Aircraft", IEEE A&E SYSTEMS MAGAZINE, MARCH 2007.

[5] Zhao Xin, Guerrero Josep M., Wu Xiaohao, "Review of Aircraft Electric Power Systems and Architectures", Aalborg Universitet, IEEE 2014.

[6] CHRISTOPHER MAK, "MODELING AND SIMULATION OF COMMERCIAL AIRCRAFT ELECTRICAL SYSTEMS", University of Illinois at Urbana-Champaign, 2015.

[7] Rory Telford, Catherine Jones, Patrick Norman and Graeme Burt, "Analysis tool for initial high level assessment of candidate MEA architectures", University of Strathclyde, Glasgow, UK, 2016-01-0072.

[8] “High Step Up DC-DC Converter topology for PV Systems and Electric Vehicles”, Ph.D. Thesis, Zhengzhao He Doctor of philosophy, ASTON University, December 2017

[9] Tsegay Gebremedhin Hailu, “DC/DC Converter for Helicopter Starter/Generator”, Electrical Engineering, Mathematics and Computer Science Faculty Delft University of Technology (TU Delft) Delft, Netherlands September 6, 2012

[10]“Topologies of Bidirectional PWM DC-DC Power Converters”, Marian K. Kazimierczuk, Senior Member, IEEE, and Dung Q. Vuong Wright State University Department of Electrical Engineering Dayton, OH 45435, U. S. A. , Bick T. Nguyen and Joseph A. Weimer USAF Wright Laboratory Wright-Patterson Air Force Base Dayton, OH 45433-6563

[11]Pablo perez Garcia, “DC/DC COVERTER FOR AIRCRAFT APPLICATIONS: DESIGN SPACE FOR INTERLEAVED TRIANGULAR FULL BRIDGE TOPOLOGY, CEIUPM, July 2016

[12]Deepanshu Gautam, Ashok kumar Sharma, Jyoti Shukla, “A Review of Voltage Boosting Techniques for Step-up DC-DC Converter”, Department of Electrical Engineering, Rajasthan Technical University, Kota, India, June 2019

[13]ROBERT W. ERICKSON, “DC–DC POWER CONVERTERS CHOPPERS SWITCHING POWER SUPPLIES”, University of Colorado, Boulder, CO

[14]Felinto S. F. Silva, Antônio A. A Freitas, Sérgio Daher, Saulo C. Ximenes, Sarah K. A. Sousa, Edilson M. S. Jr., Fernando L. M. Antunes, Cícero M. T. Cruz, “HIGH GAIN DC-DC BOOST CONVERTER WITH A COUPLING INDUCTOR” IEEE, 2009

[15]Junmin Lee, “Design and Optimization of Power MOSFET Output Stage for High-Frequency Integrated DC-DC Converters”, University of Toronto, 2012

[16]Rosa A. Mastromauro, Maria C. Poliseno, Sante Pugliese, Francesco Cupertino, Silvio Stasi, “SiC MOSFET Dual Active Bridge Converter for Harsh Environment Applications in a More-ElectricAircraft”, Bary Italy, IEEE, 2015.

[17]Arun Kadavelugu, Seunghun Baek, Sumit Dutta, Subhashish Bhattacharya, Mrinal Das, Anant Agarwal, James Scofield, “High-frequency Design Considerations of Dual Active Bridge 1200 V SiC MOSFET DC-DC Converter”, IEEE, 2011.

[18]Tariq Aldawsari, “Design, Simulation and Implementation of Three-Phase Bidirectional DC-DC Dual Active Bridge Converter Using SiC MOSFETs”, University of Arkansas, Fayetteville, 12-2014

[19]LucaTarisciotti, Alessandro Costabeber, Chen Linglin, Adam Walker, Mikiel Galea, “Evaluation of isolated DC/DC converter topologies for future HVDC aerospace mictogrids, EEE, Nottingham, UK, 2017

[20]Tao Lei 1, Cenying Wu, Xiaofei Liu, Article:“ Multi-Objective Optimization Control for the Aerospace Dual-Active Bridge Power Converter”, Energies MDPI, 7 May 2018

[21]Poola Reddi Kiran, B.K Singh, Vinod.S.Chippalkatti, T.Kanthimathinathan, “220W DC-DC Converter for Aerospace Applications”, 2014 International Conference on Advances in Electronics, Computers and Communications (ICAECC), Bangalore-106, India

[22]S.Sheikameer Batcha, Dr.T.Vijaya Kumar, Mr.B.Ram Kumar, G.Prabhu, “A Double Active Bridge Converter for High and Low Power Aerospace Applications”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, April 2015

[23]Alberto Cavallo, Beniamino Guida, Luigi Rubino, ResearchArticle: “Boost Full Bridge Bidirectional DC/DC Converter for Supervised Aeronautical Applications”, Hindawi Publishing Corporation International Journal of Aerospace Engineering, 22 january 2014

[24]G.Sridhar, M.Muneeswaran, "Implementation of Bidirectional DC-DC Converter for Aerospace Applications", International Journal of Digital Communication and Networks (IJDCN) Volume 1, Issue 1, July 2014

[25]Thaiyal Naayagi Ramasamy, "Bidirectional DC-DC Converter for Aircraft Electric Energy Storage Systems", School of Electrical and Electronic Engineering, 2010

[26]R.T. Naayagi, A.J. Forsyth, "BIDIRECTIONAL DC-DC CONVERTER FOR AIRCRAFT ELECTRIC ENERGY STORAGE SYSTEMS", School of Electrical and Electronic Engineering, The University of Manchester, UK

[27]"Reconfigurable Dual Active Bridge Converter for Aircraft Applications", B. Cougo, T. Meynard, H. Schneider, IEEE, Toulouse France, 2012

[28]"Power MOSFET Selecting MOSFFETs and Consideration for Circuit Design", Application Note, TOSHIBA, 2018-07-26

[29]German G. Oggier, Guillermo O. Garcıa, and Alejandro R. Oliva, "Modulation Strategy to Operate the Dual Active Bridge DC–DC Converter Under Soft Switching in the Whole Operating Range", IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 26, NO. 4, APRIL 2011

[30] "DC-DC POWER CONVERTERS FEATURING WIDE-BANDGAP DEVICES" Coordinatore: Prof. Marco Locatelli, Tutor: Prof. Paolo Cova, UNIVERSITÀ DEGLI STUDI DI PARMA

[31]Dottorato di Ricerca in Tecnologie dell'Informazione, Gennaio 2016

[32]R. T. NAAYAGI, N. E. MASTORAKIS, "Performance Verification of Dual Active Bridge DC-DC Converter ", Department of Electrical and Electronics Engineering Vel Tech, Tamil Nadu INDIA, Department of Industrial Engineering Technical University of Sofia BULGARIA

[33]Alberto Rodriguez Alonso, Diego G. Lamar, Aitor Vazquez, Javier Sebastian, Marta M. Hernando, "An overall study of a Dual Active Bridge for bidirectional DC/DC conversion". Universidad de Oviedo. Departamento de Ingeniería Eléctrica, Electrónica de Computadores y Sistemas. Electronic Power Supply Systems Group. Campus universitario de Viesques s/n. 33204. Gijón, Asturias. SPAIN.

[34]Said Talbi, Augustin Mpanda Mabwe, Ahmed El Hajjaji, "Control of a Bidirectional Dual Active Bridge Converter for Charge and Discharge of a Li-Ion Battery", IECON2015-Yokohama, November 9-12, 2015.

[35]Mohd Tariq1, Ali Iftekhar Maswood, Chandana Jayampathi Gajanayake, Amit Kumar Gupta, "A Lithium-ion Battery Energy Storage System Using a Bidirectional Isolated DC-DC Converter with Current Mode Control for More Electric Aircraft",Nanyang Technological University, Singapore.

[36]Maximin Blanc, Yves Lembeye, Jean-Paul Ferrieux, Corentin Rizet, Arnaud Mahe & Taoufik Bensalah, "Optimization of a DC/DC dual active bridge converter for aircraft application", EPE Journal European Power Electronics and Drives, 2018.

[37]Zhiyu Shen, Zheng Chen, Rolando Burgos, Dushan Boroyevich, Fred Wang, Jing Xue, "Modeling, Simulation and Design of a Very-High-Frequency Dual-Active-Bridge Converter", Virginia Tech, Blacksburg, VA 24061, USA.

[38]Mohd Tariq, Ali I. Maswood, Chandana J. Gajanayake, Amit K. Gupta, Firman Sasongo, "Battery Energy Storage System Integration to the More Electic Aircraft 270 V DC Power Distribution Bus using Peak Current Controlled Dual Active Bridge Converter", IEEE, 2017.

[39]Qin Zian, Shen Yanfeng, Loh Poh Chiang, Wang Huai, Blaabjerg Frede, “A Dual Active Bridge Converter with an Extended High-Efficiency Range by DC Blocking Capacitor Voltage Control”, Delft University of Technology, IEEE Transactions on Power Electronics, 2018.
[40]Mohammad Sadegh Moeinian, “Design and implementation of a proper modulation and control scheme for a single and three phase Dual Active Bridge Converter”, CHALMERS UNIVERSITY OF TECHNOLOGY Göteborg, Sweden, 2014.
[41]Marcos Felix Aguirre, “A SINGLE-PHASE DC-AC DUAL-ACTIVE-BRIDGE BASED RESONANT CONVERTER FOR GRID-CONNECTED PHOTOVOLTAIC APPLICATIONS”, B.Eng.(Hons) in Electrical Engineering, University of Ontario Institute of Technology, Oshawa, Canada, June 2015.
[42]A. Emadi and M. Ehsani, “Aircraft Power Systems: Technology, State of the Art, and Future Trends”, Texas A&M University, IEEE AES Systems Magazine, January 2000.
[43]Michael Evzelman, Ilya Zeltser, and Sam Ben-Yaakov, “DSP Control of Gyrator-Behaved Switch Mode Converter”, Power Electronics Laboratory, Ben-Gurion University of the Negev, ISRAEL.
[44]Songquan Deng, “Control And Topology Improvements In Half-bridge Dc-dc Control And Topology Improvements In Half-bridge Dc-dc Converters”, STARS University of central Florida, 2005.
[45]ALBERTO GONZALEZ ORTEGA, “DUAL ACTIVE BRIDGE DC/DC CONVERTER IN PHOTOVOLTAIC APPLICATIONS”, University of Illinois at Urbana-Champaign, 2018
[46]Peiwen He, “HIGH-FREQUENCY BIDIRECTIONAL DCDC CONVERTERS FOR ELECTRIC VEHICLE APPLICATIONS” University of Maryland, 2018.
[47]Germnan G. Oggier, Roberto Leidhold, Guillermo O. Garcia, Alejandro R. Oliva, Juan C. Balda, Fred Barlow, “Extending the ZVS Operating Range of Dual Active Bridge High-Power DC-DC Converters”.
[48] “Efficiency Evaluation for DAB Converter with Reactive Power Minimization Strategy and Full ZVS Operation”, IEEE, 2019.
[49]R.T Naayagi, A.J.Forsyth, R. Shuttleworth, “Performance Analysis of DAB DC-DC Converter under Zero Voltage Switching”, IEEE, 2011.
[50]S.Venkatesh , K.Gopiteja, D.Subba rao, “High-Power Bidirectional Dual Active Bridge And Double Dual Active Bridge DC-DC Converter”. Guntur, A.P, India, 2017.
[51]V. Karthikeyan, Rajesh Gupta, “FRS-DAB Converter for Elimination of Circulation Power Flow at Input and Output Ends”, IEEE, March 2018.
[52]FLORIAN KRISMER, “Modeling and Optimization of Bidirectional Dual Active Bridge DC–DC Converter Topologies”, Technische Universität Wien, 2010.
[53]Dong-Keun Jeong, Myung-Hyo Ryu, Heung-Geun Kim, and Hee-Je Kim, “Optimized Design of Bi-Directional Dual Active Bridge Converter for Low-Voltage Battery Charger”, Journal of Power Electronics, May 2014.
[54]Bo Liu, Maohang Qiu, Lei Jing, Xiaoqing Wang, Min Chen, “Design of high-performance bidirectional DC/DC converter applied for more electric aircraft”, 4th International Symposium on MEA, 2017.
[55]Vuppalapati Dinesh, E.Shiva Prasad, “Simulation of Dual Active Bridge Converter for Energy Storage System”, International Journal of Engineering Trends and Technology (IJETT), Telangana India, September 2015.

[56]“Design and Control of a Bidirectional Dual Active Bridge DC-DC Converter to Interface Solar, Battery Storage, and Grid-Tied Inverters”, Kenny George University of Arkansas, Fayetteville, 12-2015.
[57]AVIATONPROS, Aircraft Batteries, “A look at some of today’s aircraft battery technology”, Sep 17th, 2010.