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SIMULATION OF SiC MOSFET POWER CONVERTERS

A Thesis

Presented to

the Faculty of the Daniel Felix Ritchie School of Engineering & Computer Science

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In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

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June 2017

Advisor: Dr. Mohammad Matin

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Title: SIMULATION OF SiC MOSFET POWER CONVERTERS
Advisor: Dr. Mohammad Matin
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Abstract

This thesis discusses the use of wide bandgap devices (SiC-MOSFET) in the design and implementation of various power converters (Push-pull inverter, Buck converter). Different parameters and scenarios were discussed and implemented for both silicon and silicon carbide MOSFET cases. A comparison between same circuits is done using silicon in the first case and silicon carbide MOSFET was implemented under the same conditions and parameters to investigate the silicon carbide MOSFET enhancement to the circuit. The modeling for silicon and silicon carbide MOSFET was created using the spice model provided from leading electronics companies as ROHM, CREE and INFINION. This spice model is provided by these companies to examine the effect of these components. This spice model can be examined using simulation software such as Multisim, PSpice, LTspice and others. The results focused on many aspects such as on V_{out},V_{mos} stability, circuit efficiency and frequency change effect. It focused also on output power and MOSFET power loss because it is a very crucial aspect on any converter design. These results are done using the National Instrument simulation program (Multisim 14) and a sample of the results are validated using LT Spice.

In all tests and results it was found that SiC MOSFET made a significant improvement in the power efficiency and decreased power loss compared to Si MOSFET. Using SiC MOSFET in Push-Pull and Buck converter increased system efficiency and decreased MOSFET power loss. SiC is more immune against frequency change and performed better than Si MOSFET. Also, replacing Si MOSFET with SiC MOSFET added more voltage stability against the increase in load demand. These results will lead to design power converters with significant power loss and will decrease power dissipation. It will lead to better performance and a smaller circuit package because of the decrease in the heat sink and ventilation fans. It will save the power, decrease the cost and increase converter life time.

Acknowledgments

I would like to express my gratitude to my research advisor, Dr. Mohammad Matin, for his help, advice, support and valuable recommendations doing my thesis research. His knowledge and guidance was much appreciated.

Additionally, I would like to thank my defense committee, Dr Donnelly and Dr Zhang for their time and cooperation.

I would like to offer my thanks and gratitude to my wife who stood with me and offered me all the love and support that I needed to keep studying hard and complete all my degree requirements.

Also, special thanks to Higher Committee of Education Developments in Iraq for their financial support during my stay in the United States.

Finally, I would like to remember my Aunt and my Grandmother (RIPs) who passed away during my stays in the United States and didn't have the chance to see me getting my degree.

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Abbreviations

Si: Silicon

SiC: Silicon Carbide

DC: Direct Current

AC: Alternative Current

BJT: Bipolar Junction Transistor

MOSFET: metal–oxide–semiconductor field-effect transistor

GAN: Gallium Nitride

SJ: Super Junction

NPN: Negative Positive Negative

PNP : Positive Negative Positive

OPAMP: Operational amplifier

CPU: Central processing unit

RAM: Random access memory

USB: Universal Serial Bus

RMS: Root mean square

Nomenclature

V_{out}: output voltage

V_{mos}: MOSFET voltage

I_d: drain current

V_{ds}: drain to source voltage

V_{gs}: gate to source voltage

R_{ds}: drain to source resistance

P_{load}: load power

V_{load}: load current

I_{load}: load current

P_{in}: input power

P_{out}: output power

P_{av}: average power

C_{oss}: output capacitance

T_{on}: on time

T_{off}: off time

D: duty cycle

I_L: inductor current

ΔI_L: change in inductor current

K_w= filling factor of the core

Wa= window area winding

B_m= Maximum magnetic flux in the core

Cp = parasitic winding capacitance

A_c= is the effective cress sectional area of the core.

J: current density

F_s: switching frequency

Chapter 1: Introduction

1.1 Background

As world evolves every day, one thing that remains constant is the need for smaller, faster and more reliable electronics. Semiconductors are the foundation for every electronics. The Silicon has been used for decades to manufacture electronics. However, Silicon has been pushed to its limit and we need new substance for our increasing demands. Fortunately, Wide bandgap semiconductors have the solution for our needs. Wide bandgap semiconductors such as (SiC, GaN and Diamonds) who have bandgap (3.26, 3.45 and 5.4 eV) respectively have higher bandgap compared to Silicon (1.1 eV). This wide bandgap provides them with unique characteristic. Wide bandgap semiconductors can perform up to 300 degrees Celsius, handle 10 times the voltages of Silicon and eliminate a higher percentage power loss. This means that we can save millions of dollars and make smaller electronics because less power dissipated means that we need less and smaller heat sink and ventilation fans.

The wide bandgap make these new semiconductors very appealing in power electronics. Fig 1 shows the advantage of use wide bandgap semiconductors in Isolation for example

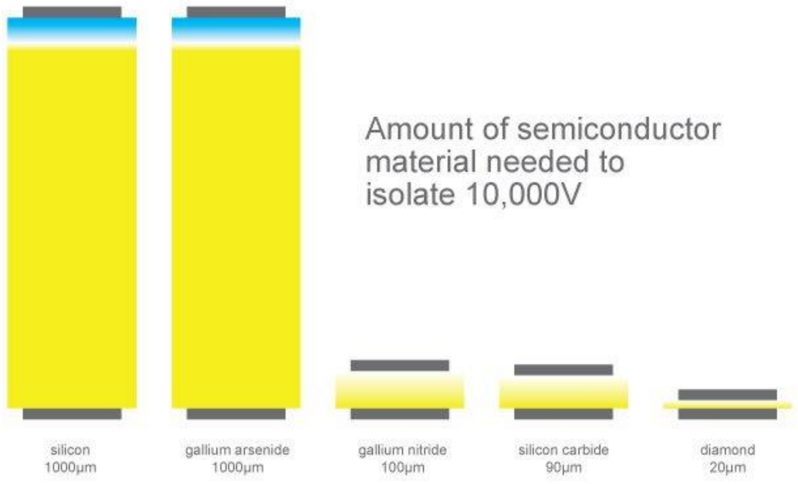


Figure 1.1: silicon VS wide bandgap isolation (1)

Figure 1 shows how wide bandgap semiconductor band gap play significant role and decrease package size to one tenth which lead to decrease and create more powerful semiconductors.

1.2 Thesis Objective

The main goal in this thesis is to investigate and test replacing of Silicon carbide MOSFET with ordinary silicon MOSFET and compare them. The Thesis will test three kind of converters which are: Push-Pull inverter, Boost DC-DC converter. These converters will be implemented using silicon MOSFET once and Silicon Carbide at second phase. A lot of scenarios will be done to test Circuit efficiency, Voltage stability, change in Frequency and Temperature effect. Results will show that Silicon Carbide MSOFET will add more stability and efficiency as well as less power loss.

1.3 Thesis Outline

This Thesis is presented in the following way.

First Chapter will be brief introduction that contain information about thesis outline and methodology.

Second Chapter will introduce SiC semiconductor, it will present its advantages over SI semiconductor devices as well as its applications.

The third Chapter have presented push-pull inverter. Converter theory and equation will be discussed and how to choose operating system frequency. It shows its main components and how it designed. Also, it shows it advantages and disadvantages.

Fourth Chapter will introduce Buck DC-DC converter. Converter theory and design will be introduced. A list of its applications, advantages and disadvantages will be presented. Also, it will be showed its components and all related equations.

Chapter Five Will discuss the results and with all applicable scenarios. List of tables and graph will demonstrate the results.

Chapter Six Will be Conclusion to the whole thesis.

And at last Chapter Seven will be my intended future work.

1.4 Methodology

The methodology of this thesis is done as below

Studying and understanding of wide bandgap semiconductors types and how at differ from the silicon semiconductor. Choosing between diverse types of wide bandgap semiconductor. In this Thesis, Silicon Carbide MOSFET was chosen among Diamond and GAN because of its wide support and availability as well as company support and manufacturing. Also, its best in switching and power loss.

Understanding principles of power converters (Push-pull, Buck and PWM converters) Design above converters and pick the right components values. Pick simulation software's that give freedom, have wide range of components libraries. Simulation Software should supports spice model. Pick the appropriate MOSFET for these converters based on its datasheet characteristics.

Simulate these converters with both Silicon and then applied same scenarios to Silicon Carbide MOSFET. Comparing Results and validating them. Give the Conclusion and propose the future Work.

Chapter 2: Silicon Carbide Semiconductor

2.1 Introduction

Silicon has been used in power devices since 1930 and has helped the world to progress as we see it today. However, power transistors are limited due to structural reasons. The low junction temperature and low blocking voltage make these power devices useless or at least high losses in the very high voltage, power and temperature circumstances. The last decade has witnessed a new evolutional solution to these problems, which are the wide bandgap semiconductors. SiC devices provide perfect solutions to high voltage, power, frequency and temperature applications.

Some of the companies that participate in the SiC devises are CREE, ROHM and INFINION.

One of the good examples of SiC MOSFET is the C2M0040120D. this MOSFET can handle 1.2KV, I_{ds} is 60A and can handle 150 C^o. The SiC MOSFET has 38% conduction loss and 60% less switching loss than the Si MOSFET which makes it a great fit for power converters, hybrid cars and RF high power applications.

2.2 Silicon Carbide Structure

Silicon Carbide SiC which is known also as carborundum, is a combination of silicon and carbon. It can be found in the nature but so rarely in the mineral Masonite. Synthetic silicon carbide powder has been produced in the late of 19th century to use an abrasive. silicon carbide Grains will be bonded by sintering to a hard ceramics form. These ceramics are widely used in high endurance applications. A good example for this application is a car brakes, ceramic plates in bulletproof vests and car clutches. Another important application is the Electronic applications of silicon carbide such as light-emitting diodes (LEDs) and detectors in early radios. SiC is used in semiconductor electronics devices that operate at hot temperatures, high voltages, or both. Lely method used to create Large single crystals of silicon carbide. Crystals have been cut into gems known as synthetic moissanite. Silicon carbide with high surface area can be manufactured from SiO_2 that exist in plant material.

The silicon carbide exists in about 250 forms. It has a lot of family crystalize structures called polytypes. These families have variation in chemical compounds. They are similar in two dimension and differ in the third.

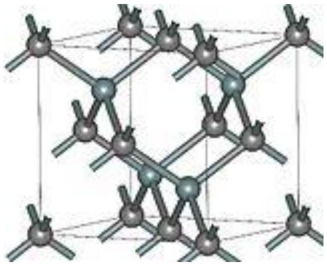


Figure 2.1: (β) 3C-SiC(2)

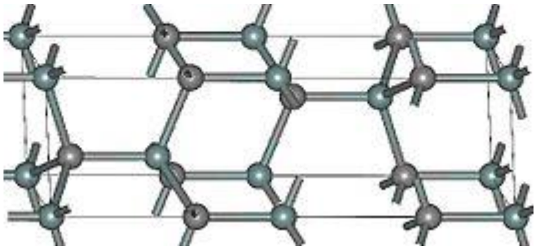


Figure2.2: 4H-SiC(3)

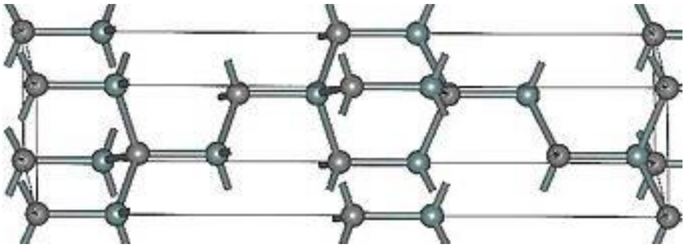


Figure2.3: (α) 6H-SiC(4)

The previous figures show us the different structural shapes of the silicon carbide crystal. This structural shape give each type its own characteristics. They differ in bandgap, density and lattice constant.

Below is a table showing the difference

Polytype	**3C (β)**	**4H**	**6H (α)**
Crystal structure	Zinc blende (cubic)	Hexagonal	Hexagonal

Space group	T^2_d-F43m	C^4_{6v}-$P6_3mc$	C^4_{6v}-$P6_3mc$
Pearson symbol	cF8	hP8	hP12
Lattice constants (Å)	4.3596	3.0730; 10.053	3.0810; 15.12
Density (g/cm3)	3.21	3.21	3.21
Bandgap (eV)	2.36	3.23	3.05
Bulk modulus (GPa)	250	220	220
Thermal conductivity (W m−1K−1) @ 300K (see [30] for temp. dependence)	360	370	490

Table1: Properties of major SiC polytypes

2.3 Applications

2.3.1 Automobile parts

Silicon infiltrated carbon composite has been used widely as an automobile brakes. Because of its unique structure, it can handle very high temperature. The silicon works with the graphite in the carbon composite to turn to fiber-carbon reinforced silicon carbide(C/SiC). These high-performance brakes have been used widely with high speed and sport cars as Bugatti and Porsche. It also been used as an oil additive to reduce harmonics and frictions.

2.3.2 Structural material

In the 80s and 90s a lot of research has been done for using SiC in the structure of elevated temperature gas turbine. The studies were focused on using SiC instead of nikel super alloy turbine blades or nozzle vanes.

Also, silicon carbide material has been used in army armors and in ceramic plates at bulletproof vests.

Recently, the silicon carbide infusion of silicon carbide Nano-particles in molten magnesium was proposed to produce an enhance strong and plastic alloy to use in aeronautics, aerospace.

2.3.3 Power electronics devices

One of the most contributions of the Silicon Carbide MOSFET in today world is on power electronics field. Its superior on silicon because its fast in switching, can handle higher power, voltage and temperature. The first SiC device which has been distribute and become available in the market was schottky diode. Next the junction-gate FET and followed by MOSFET which is been used widely in high power switching applications.

Recently Thyristor and Bipolar Transistor have been developed as well. The SiC device has great capability for future. The greatest challenges to unleash the full capability of the Silicon Carbide power electronics are:

a. Gate Drive: SiC require gate driving voltages different than similar silicon devices and probably they are not even and symmetric. For example, silicon power MOSFET requires voltage range between -15 V and 15 V, on the other hand the SiC MOSFET require gate voltage between -5V and 20V.

b. Packaging: SiC power MOSFET have higher power density than similar silicon power devices and can handle temperature over than 150 C^o without being breaking down. new die attach technologies such as sintering are demanded to efficiently ventilate the heat out of the power devices to ensure a reliable interconnection.

2.3.4 Astronomy

SiC has some of the great specification which make it great fit to make a mirror material for Astronomy telescope. These specifications are: high hardness, thermal conductivity, low thermal expansion coefficient and rigidity. Nowadays, several telescopes like the Herschel Space Telescope now using SiC optics material. Also, Gaia space observatory spacecraft subsystems are mounted on a rigid silicon carbide frame, which provides a rigid structure that will not affect, move and melt because of the excessive heat.

2.4 Silicon Carbide Vs Silicon

This is the most important topic which make a lot of scholars write a lot of paper regarding this issue. This section will summarize why we have been using SiC power devices over SI devices.

2.4.1 Conduction and Switching losses

SiC power devices has significant power loss, either conduction and switching loss due to its characteristic which are

10x the Dielectric Breakdown Field Strength (0.3 MV/cm vs 3 MV/cm)

3x the Energy Bandgap (1.12eV vs 3.26eV)

3x the Thermal Conductivity (1.5 W/cm°C vs 4.9 W/cm°C)

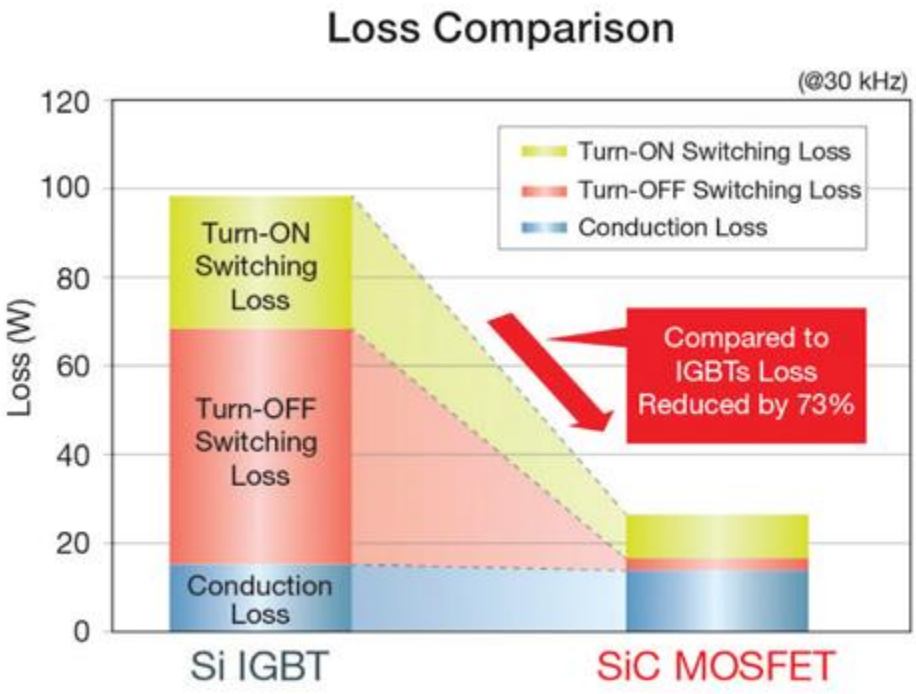


Figure 2.4: loss comparison between SI IGBT and SiC MOSFET(5)

2.4.2 High frequency losses

SiC power devices is more immune against fervency and perform well in high frequency and have relative less losses.

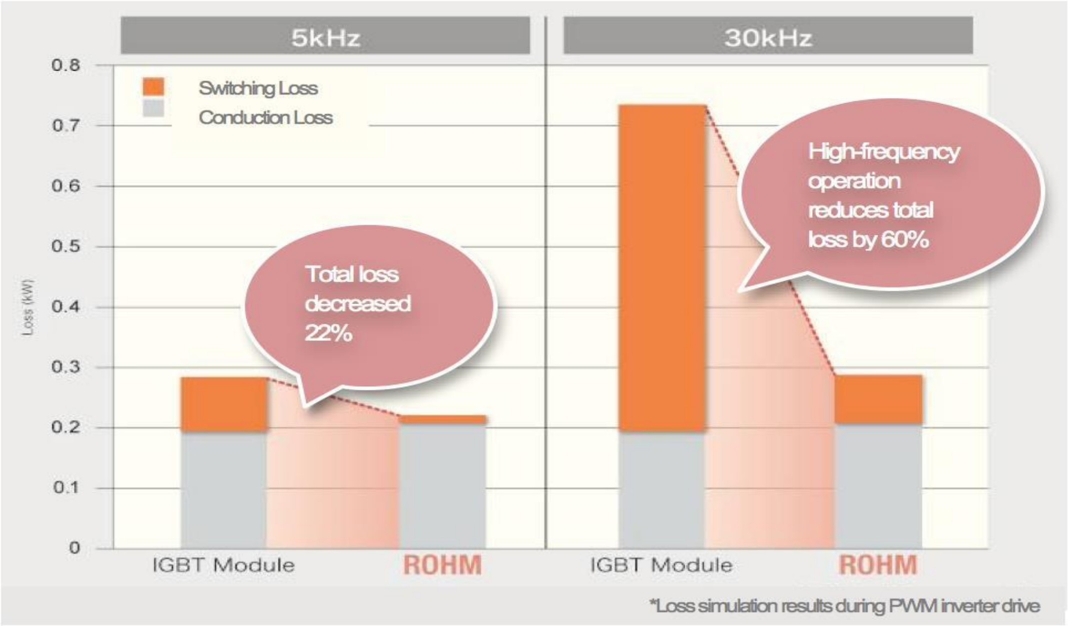


Figure 2.5: high frequency losses of the ROHM SiC MOSFET(6)

2.4.3 V_{ds}-I_d characteristic

According to ROHM website "SiC MOSFETs feature no rise voltage like with IGBTs, resulting in low conduction loss throughout the entire current range". Additionally, at 27C the ON resistance of Silicon MOSFETS will be increased by doublet at 150C.

But with SiC MOSFETs the rate of increase is relatively low, simplifying thermal design while ensuring low ON resistance even at hot temperature".

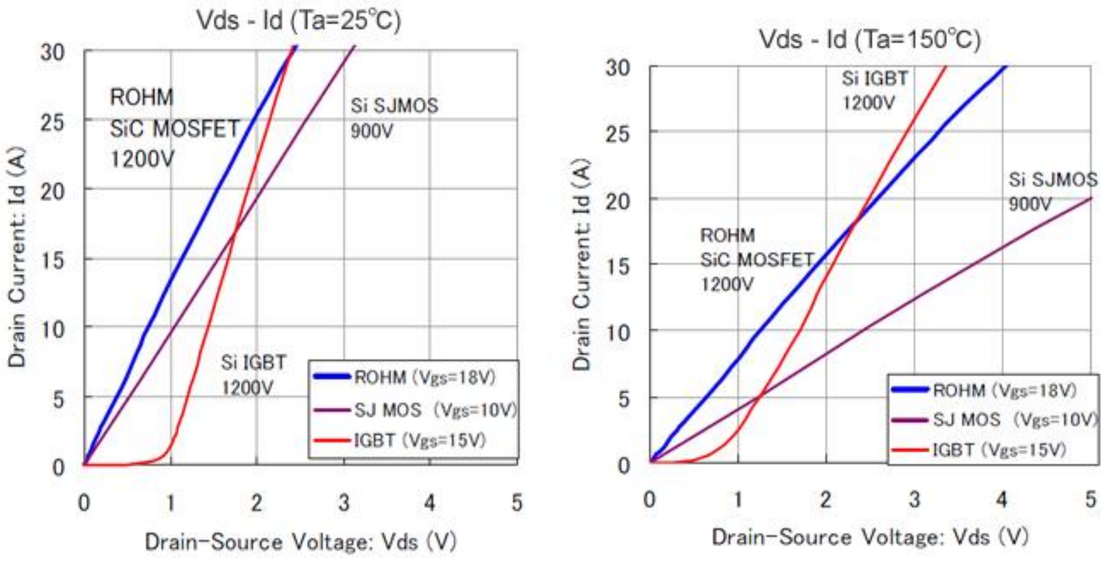


Figure 2.6: V_{ds}-I_d characteristic (7)

2.4.4 Normalized ON resistance

SiC has 10 times more of the dielectric breakdown electric field strength more than silicon. This feature make it capable of offering high breakdown voltage by using lower resistivity and thinner drift layer. This mean high breaking voltage with less power loss and smaller package size.

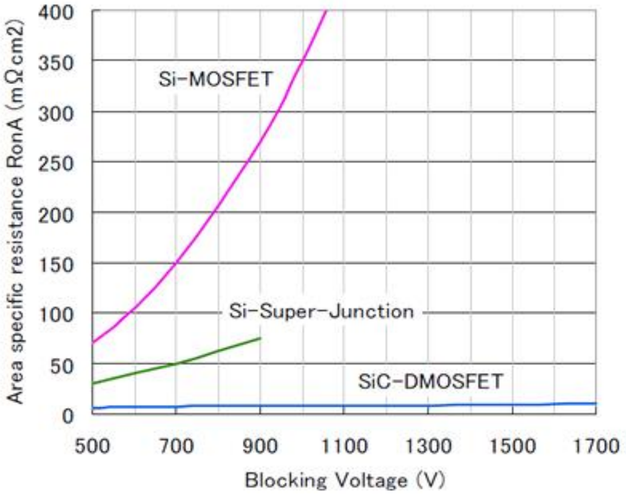


Figure 2.7: relation between blocking voltage and (mΩcm^2)for various MOSFETs(8)

For example, at 900V and the same ON resistance chip size can be reduced by 35x vs silicon MOSFETs and 10x compared with SJ MOSFETs.

Also, the above figure shows as that we still keep using SiC MOSFET for up to 1700V and keep using same small chip size.

2.4.5 Drive gate voltage and ON resistance

Although SiC MOSFETs has significant lower drift resistance than Si MOSFETs, at the current level mobility of the MOSFET channel section is low, this create higher MOSFET channel resistance.

This phenomenon makes it possible to get a smaller ON resistance at bigger gate voltages (gradual saturation at Vgs=20V+). However, inherent ON-resistance performance cannot be achived at drive voltages used for standard IGBTs and Si MOSFETs which they have (Vgs=10-15V). Therefore, to obtain enough ON resistance a drive voltage near Vgs=18V is recommended.

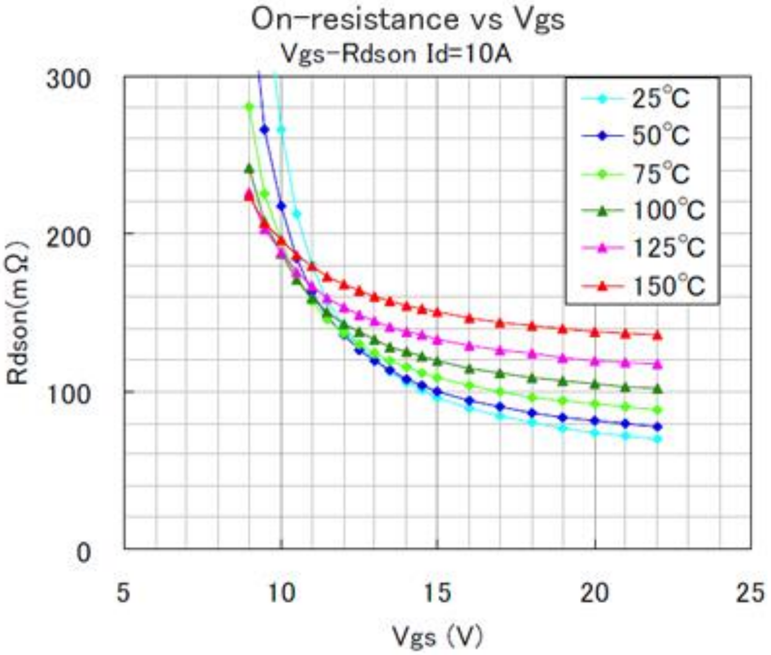


Figure 2.8: SiC MOSFET gate voltage at various temperatures (9)

Chapter 3: Push Pull Converter

3.1 Introduction

In General, A Push- Pull topology mean that there is an output stage drive the current in both direction. It contains two BJT or two MOSFET. The first one work as a current source which push the current. The other one work as a sink and pull the current and that’s the reason of this name. Push-Pull usually work as a signal amplifier. One of the famous applications is the audio amplifier. Push- Pull has a lot of topologies which are going to be briefed later. A Push-Pull Converter proposed in this thesis is based on class A Push-Pull topology. It is a simple and non-expensive converter which use a center tap transformer to change the dc voltage supply to ac. Two symmetrical transistors are used in this circuit. These two transistors are controlled using RC circuit. This capacitor is charge and discharge periodically depending on the value of the capacitor and the resistor. These two transistors are used to drive two MOSFET connected to a center tap transformer to generate ac voltages. MOSFET have been used to achieve the switching process instead of BJT because they can handle higher voltage and current as well as they are fast in switching which decrease the switching loss and improve the overall circuit efficiency [52].

3.2 Push-Pull Different Topologies

Push-Pull concept has different topologies. It has been used as an amplifier widely. One of the famous applications is an audio amplifier. Followed as a brief about some of these topologies.

3.2.1 Totem-pole push–pull output stages

This configuration is done by connecting back to back two transistors. One of them is NPN and the other is PNP. This configuration is used mainly to amplify low signal as the output 5v from microcontroller to a 12V load without need to any transformer.

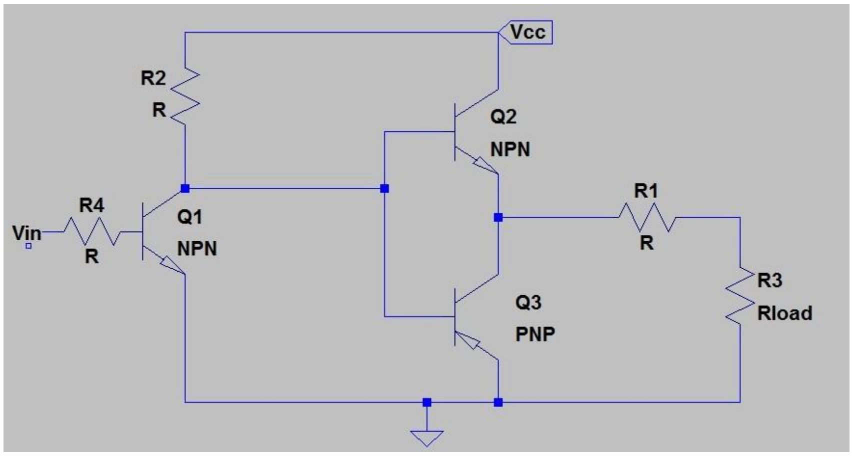


Figure 3.1: Totem pole configuration

Totem pole is fast swathing configuration in case for single output. But its limited to switch between power supplies or in the above configuration between power supply and ground.

3.2.2 Class B Push-Pull Emitter follower

In this configuration, the two transistor emitters will be connected. PNP and NPN transistors will be used in this type of configuration.

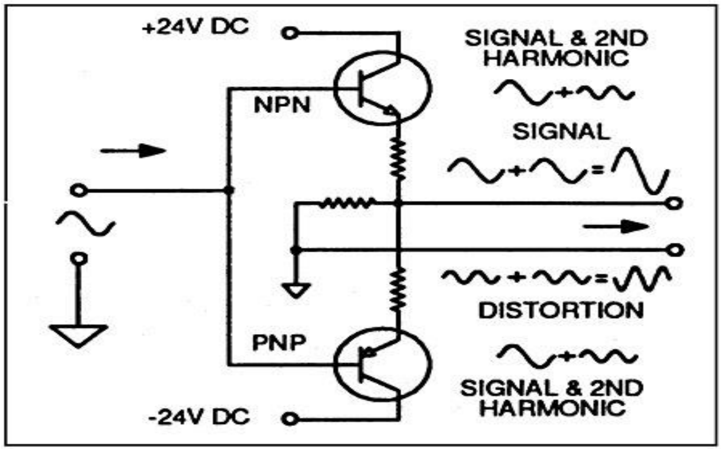


Figure 3.2: Class B Push-Pull Emitter follower (10)

So, in this type of amplifier both signal input to the transistors are in phase. When the input signal is input the current will flows from positive VCC through the upper NPN signal. When the input signal is negative the current will flow from negative power supply through the PNP signal. The disadvantage of this type of configuration is the distortion signal will through as well the input signal.

3.2.3 Class A Push-Pull

In this configuration two identical NPN BJT or N- MOSFETS are connected in this configuration as below.

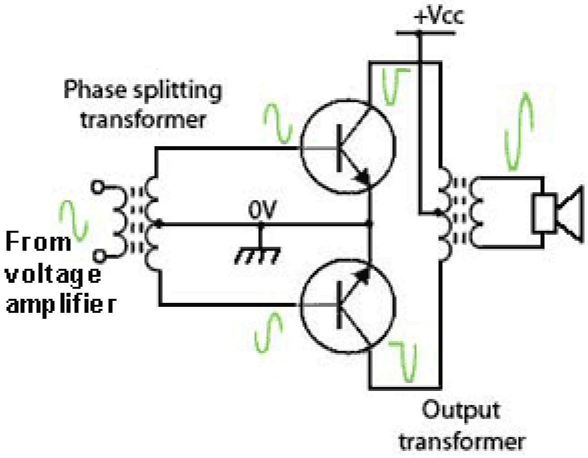


Figure 3.3: Class A Push Pull (11)

where their emitters are connected to the ground or to the negative power supply. There collectors will be connected to the first and second part of the transformer respectively. The transformer center tap will be connected to the positive power supply. First BJT or MOSFET will be driven in the first half and become on where the second MOSFET will be off. In the first half of the cycle the positive part will show through the output amplified by the value of the turn ratio. In the second half of the cycle the second BJT or MOSFET will be on and the first one will be off. The second part of the signal will show through the output.

3.3 Converter Block Diagram

The proposed push converter design will consist off the following stages described in the following block diagram

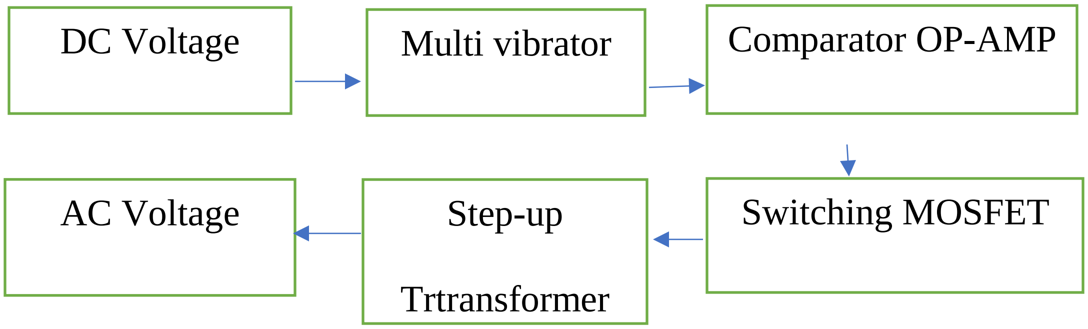


Figure 3.4: Push-Pull converter block diagram

- DC Voltage

  A 12V DC voltage source is used in this design

- Multi Vibrator Oscillator (Astable Multivibrator)

  Two NPN transistor (BC547C) are used with RC circuit to transform the DC voltage into half wave AC signal as below

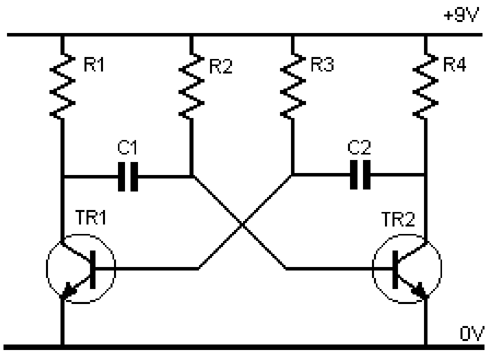


Figure 3.5: A stable Multivibrator(12)

This circuit is known by Two-phase square wave oscillator. Values of the Resistors and Capacitors will define the charge and discharge time where the f=1/1.38 RC. Each transistor will be on for the half of the cycle. The phase shift between two transistors will be 180 degrees. When the first transistor is on the second one will be off and vice versa and this on and off state will drive the push-pull MOSFET.

- Comparator op-amp

LM358 is used for this purpose to make the drive switching signal smoother and like sharp square wave. Where the output transistor signal is not smooth in the upper region.

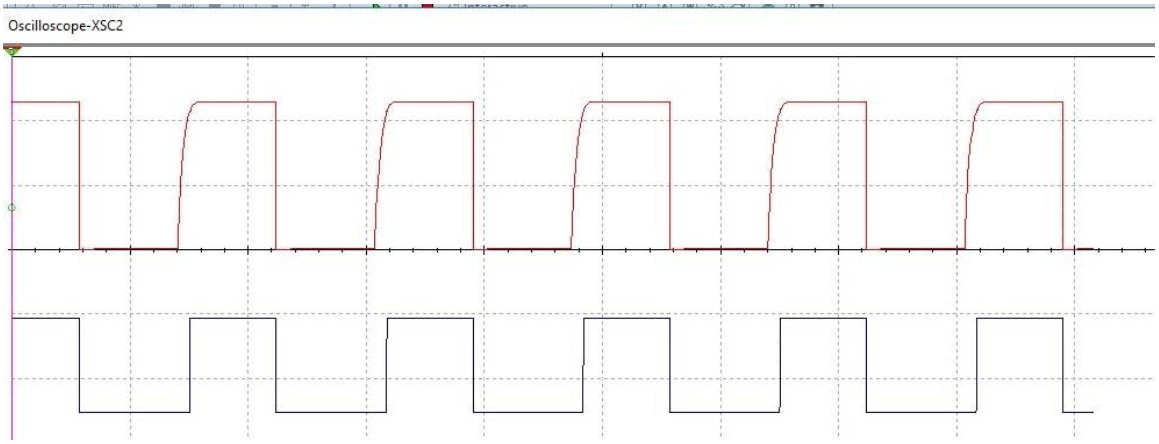


Fig 3.6: transistor and op-amp output

The upper part shows the transistor output. Where the bottom part shows the op-amp comparator output. The bottom result is important to decrease the switching loss in the MOSFET.

- Switching MOSFET

  This is the most important part in the entire process where the push-pull operation was happened. Two identical N-MOSFET was chosen to achieve the switching part. MOSFET where chosen instead of BJT because it can handle higher voltage, current and its fast switching. MOSFET base is connected to the switching drive signal which will turn it on and off. the emitter is connected to the ground. The output is taking from collector side which each MOSFET collector is connected to transfer side to achieve the push pulling amplification and switching purpose.

- Step-Up transformer

  A step-up transform is used to step up the voltage to 120V. 3 inputs and 2 outputs transformer is used in this simulation. Center tap is connected to the 12 VDC where the other inputs is connected to the collectors of the MOSFET. A transformer turn ratio is tuned to achieve the desired output voltage which is 120V.

3.4 Circuit Design and Schematic

The proposed circuit schematic is proposed as below

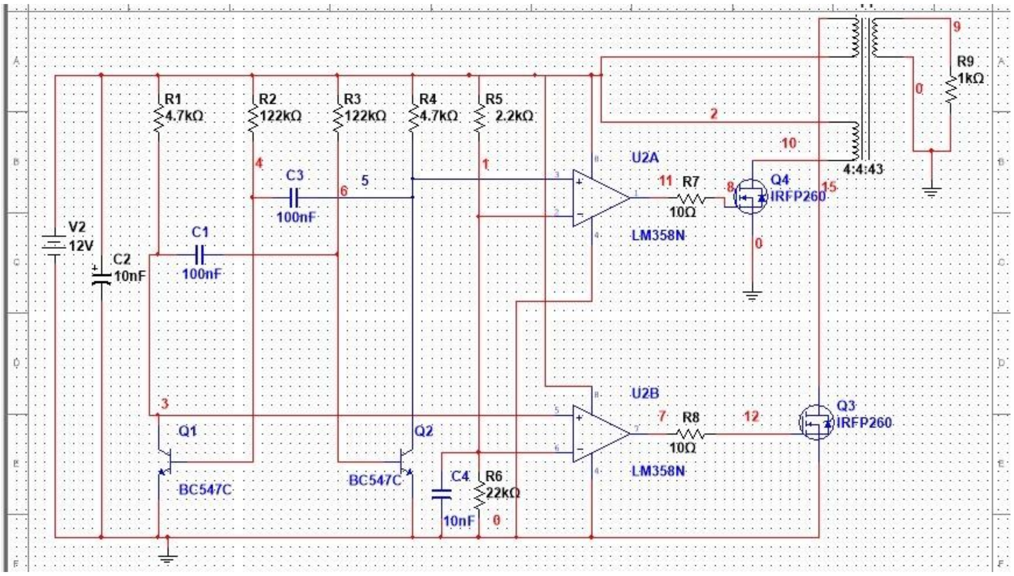


Figure 3.7: Push Pull Circuit Diagram

- The DC voltage is chosen to be 12 V to simulate a traditional car battery to operate the converter.
- 10 nF capacitor is placed with parallel dc voltage to give more stability to the power supply.

3.4.1 **multidirector oscillator (astable multivibrator)**

It is chosen to convert the dc to half wave ac. The transistor chosen is the BC547 NPN transistor which This device is designed for use as general purpose amplifiers and switches requiring collector currents to 300 mA. The 12 VDC can support the require current for this purpose. The periodic time of the astable circuit can be done using the following equations.

$$T=t_1+t_2 \quad (3.4.1)$$

$$t_1 = 0.69\ R_2C_1 \quad (3.4.2)$$

$$t_2 = 0.69\ R_3C_3 \quad (3.4.3)$$

$$f=1/T \quad (3.4.4)$$

$$f=1/1.38\ RC \quad (3.4.5)$$

so if we pick the C to be 100nf, the frequency is 60Hz

$$R= 1/1.38*f*C \quad (3.4.6)$$

$R=\frac{1}{1.38*60*100\ e-9}$ = 120.77K ohm

Note: in the simulation software, I have used R=122K ohm instead of 120.77K ohm that found in the calculation, because the simulation result give 60HZ output signal in these values.

3.4.2 **Op-amp**

LM358n is used for this purpose. The connection will be done as below

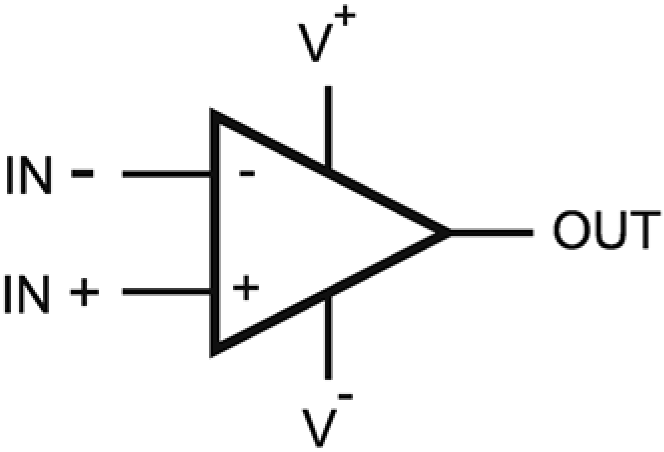


Figure 3.8: OPAMP

The plus input will be the output from the transistor. Where the negative output will be taken from the ground. RC parallel circuit is placed to protect the op-amp from excessive current. Where the positive and negative VCC is placed on the battery sides. The reason behind chosen this model is because its low loss and single operated source which will make it perfect for this purpose.

3.4.3 **Switching MOSFET**

The MOSFET that be chosen should have the following characteristic.

1) Fast switching ability
2) Low R_{ds} to achieve low lose
3) Drain to source voltage V_{ds} larger than 12 V
4) High drain to source current I_{ds}

To find the required drain to source current we need to establish our converter requirement.

The proposed converter should handle up to 500W load

$$P_{load}= I_{load}* V_{load} \tag{3.4.7}$$

If the Maximum load is set to be 500W and the output voltage is 120V

So

$$I_{load\ maximum}=P_{load\ maximum}/ V_{load} \tag{3.4.8}$$

$I_{load\ maximum}$= 500/120= 4.167 A

And then to find the voltage and current on the input side of transformer we apply

$$\frac{N1}{N2}=\frac{V1}{V2} \qquad (3.4.9)$$

$$\frac{N1}{N2}=\frac{I2}{I1} \qquad (3.4.10)$$

Where N_1 is the primary winding

N_2 is the secondary winding

V_1 is the primary voltage

V_2 is the secondary voltage

I_1 is the primary current

I_2 is the secondary current

So if the turn ratio is almost 1/10 because the input voltage is 12 and the output is 120V

$1/10= I_2/I_1$

So we know that $I_{2max}=4$

So according to equation number 10

$I_{1max}= 10*4=40$ A.

So we are looking for a MOSFET with at least $I_{ds}= 40$ A.

In Silicon case I have chosen IRFP260 which have

$V_{ds}=200$ V, $I_{ds}=46$ A and $R_{ds}= 55$ m ohm.

This MOSFET is manufactured by VISHAY electronics and have good specifications which make him perfect for this purpose. These specifications are :

- Dynamic dV/dt Rating
- Repetitive Avalanche Rated
- Isolated Central Mounting Hole
- Fast Switching
- Ease of Paralleling
- Simple Drive Requirements

In Silicon Carbide MOSFET case I have chosen C2M0040120D.

This MOSFET is manufactured by CREE electronics which have:

V_{ds}= 1200V, I_{ds}= 60A , R_{ds}= 40 m ohm.

This MOSFET have excellent features according to Company website such as:

- High Blocking Voltage with Low On-Resistance
- High Speed Switching with Low Capacitances
- Easy to Parallel and Simple to Drive
- Avalanche Ruggedness
- Resistant to Latch-Up
- Halogen Free, RoHS Compliant

These features give it the following benefits:

- Higher System Efficiency

- Reduced Cooling Requirements
- Increased Power Density
- Increased System Switching Frequency

This MOSFET is great for the following applications:

- Solar Inverters
- Switch Mode Power Supplies
- High Voltage DC/DC converters
- Battery Chargers
- Motor Drives
- Pulsed Power Applications

3.4.4 Step Up Transformer

1 to 10 winding ratio transformer is chosen to step up the voltage to 120 V It has 3 inputs and 2 outputs with center tap.

3.5 Simulation Procedure

This Simulation is done using the following steps:

- The original circuit uses two BJT N-type as an oscillator to charge and discharge with help of capacitors to convert battery DC voltage to an AC voltage.

- The simulation started with 12 Vdc, as an input to the inverter, using IRFP260n MOSFET first.
- Then the output load was set to be 1k ohm as an initial point to simulation and turn ratio of the transformer was set to make the output voltage 120 V at Rload= 1k ohm.
- The following parameters were recorded, V_{load}, I_{load}, P_{in},$P_{av\ out}$, and the total circuit efficiency.[52]
- R_{load} is gradually decreased to increase the output current and increase the output power[52].
- The MOSFETs are changed to the SiC power MOSFET and the entire procedure is repeated.
- Change power supply dc voltage into 14V and repeat all previous steps
- Recording all results and comparing them using Microsoft Excel graphs.

3.6 Power Loss

The most important calculation in any converter is the power loss. The most power loss in this converter is happened in the MOSFET. The most dissipated power happened in the MOSFET because it handles the switching process. It’s important to know the power loss and dissipated heat to design the proper heat sink and or ventilation fan if needed.

There are two losses in the MOSFET which are the switching loss and the conductions loss.

The conduction loss happened because of the MOSFET resistive parameters when its ON, when the current flows through R_{ds}, power dissipated as heat from the MOSFET.

The physical size play a role in the conduction loss. Cause increase the physical size will decrease the R_{ds} and will decrease the loss as well.

The second cause of the losses is the switching loss. When the switching MOSFET cause on and off, its intrinsic parasitic capacitance stores and then dissipate the energy during each switching process. These losses depend on the switching frequency as well as on the intrinsic capacitance values. The physical size of the MOSFET play a role in the switching loss. Increase MOSFET size will increase its intrinsic parasitic capacitance and this will cause increase in switching loss.

The switching loss can be found as

$$\text{Turn- on loss} = (C_{oss}+C_p).V^2.f/2 \qquad (3.6.1)$$

Where

V = drain voltage

F = switching frequency

C_p = parasitic winding capacitance

C_{oss} = output capacitance.

The Conduction loss can be found by

$$P_{conduction}= I^2_{ds(on)}*R_{ds(on)} \qquad (3.6.2)$$

Chapter 4: DC-DC Buck Converter

4.1 Introduction:

A Buck converter is dc-dc step down converter. It steps down the voltage from its input which is the dc- power supply to its output which is the load. The Buck converter contains two semiconductors which are diode and MOSFET[53].

The simple Buck converter layout is

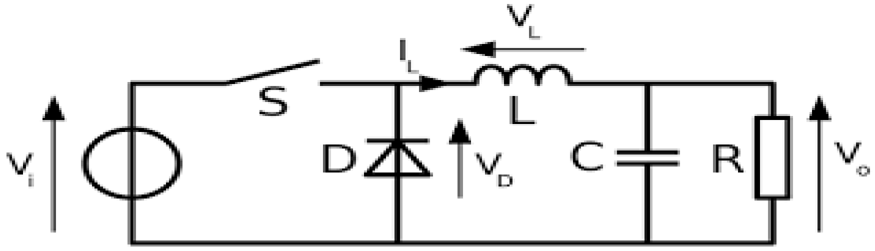


Figure 4.1: Buck converter layout (13)

In the output stage, an inductor or capacitor or both are added to the output load to decrease the output ripple. Also, a capacitor is added to the voltage supply side to offer higher power efficiency to the dc-dc converter.

In general, the buck converter is high efficiency converter (more than 90%) which make him a great fit for applications as PC power supply. where is step down the 12V into 5V, 1.8V and others which are needed to supply different PC components like USB. RAM, CPU and others.

4.2 Converter Concept

Buck converter is working in two states, the ON and off state. The figure below shows these two states

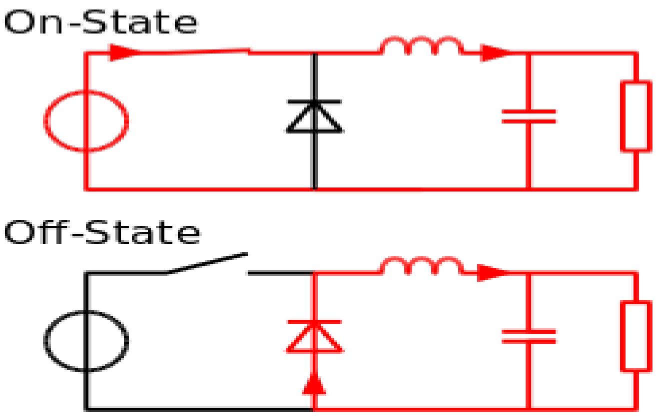


Figure 4.2: Buck converter working states [(14)]

The switch is control the flow of energy. The converter is containing inductor and/ or capacitor which they store the energy.

The switch is turn on and turn off periodically. T_{on} and T_{off} is the time that switch be on and off. the total time period can be defined as

$$T=t_{on}+t_{off} \qquad (4.2.1)$$

$$T=1/f \qquad (4.2.2)$$

Also, one of the important definition that we are going to use in this chapter is the duty cycle D

$$D=t_{on}/T \qquad (4.2.3)$$

We will analyze the circuit in both of ON and off state.

We will assume that the output ripple is so small. This assumption is known as (small ripple approximation)

a) **On State**

The ON state means when the switch is ON as the following figure

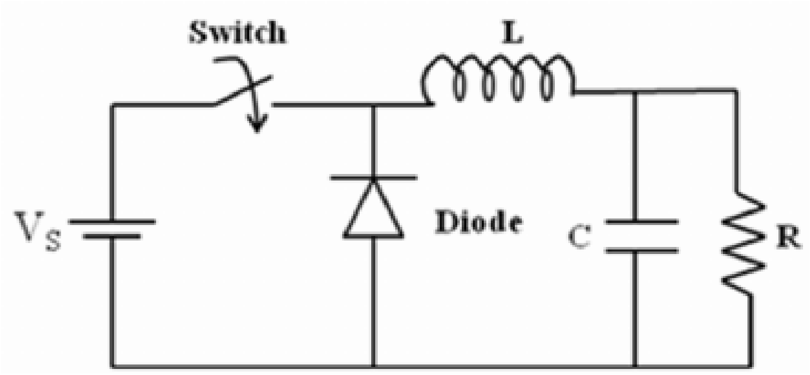


Figure 4.3: Buck on state (15)

Power supply is connected to the inductor, the diode is on reverse polarity. The current flows through inductor according to the next equation.

$$dI_L/dt=(V_{in}-V_{out})/L \quad (4.2.4)$$

where L is the inductance in Henry

and V is the voltage in volt.

b) Off state

In the off state the switch will be OFF as the following figure

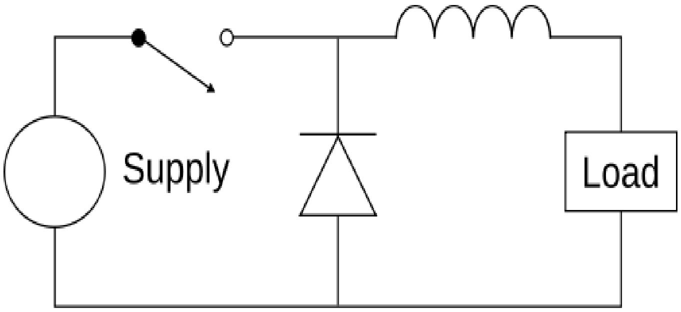


Figure 4.4: Buck Off state (16)

When the switch is off, and by assuming that the diode is ideal. In this case the diode will act as a short circuit and the voltage will be zero between the inductor and the ground.

The inductor will discharge the energy inside according to the following equation

$$dI_L/dt=(0-V_{out})/L \qquad (4.2.5)$$

in this case, we will have two different scenarios which are:

4.2.1 **Continuous mode**: in this mode, the inductor current will not reach the zero value during the off state.

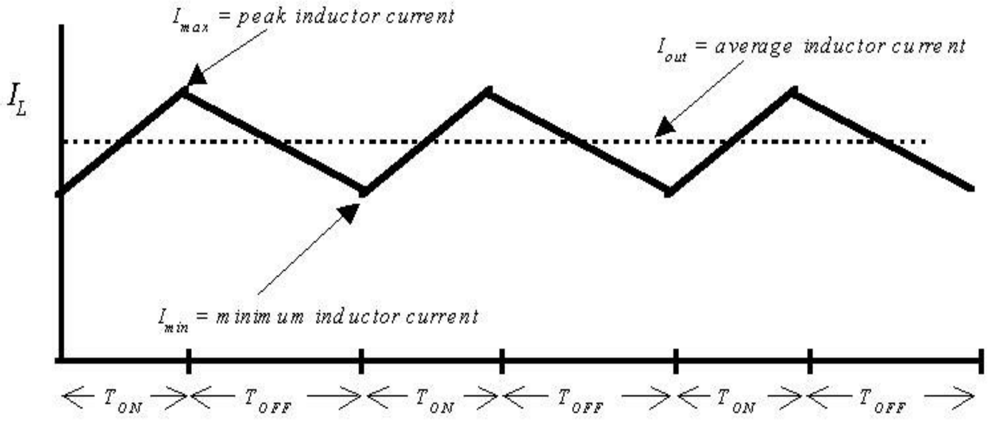


Figure 4.5: off state continuous mode (17)

$$\Delta\text{-}I_L=-(Vout/L)t_{off} = -V_{out}L(1-D)T \qquad (4.2.6)$$

So, in steady state, the rise in current in the inductor should be equal to the current declination in the fall state and this will lead to:

$$\Delta I^+_L+\Delta I^-_L=0 \qquad (4.2.7)$$

$(V_{in}-V_{out})\ DT/L-V_{out}\ (1-D)T/L =0 \qquad\qquad V_{in}D-V_{out}=0,$

$$V_{out}=V_{in}D \qquad (4.2.8)$$

4.2.2 Discontinuous mode:

In this mode, the current drops to zero as the following figure

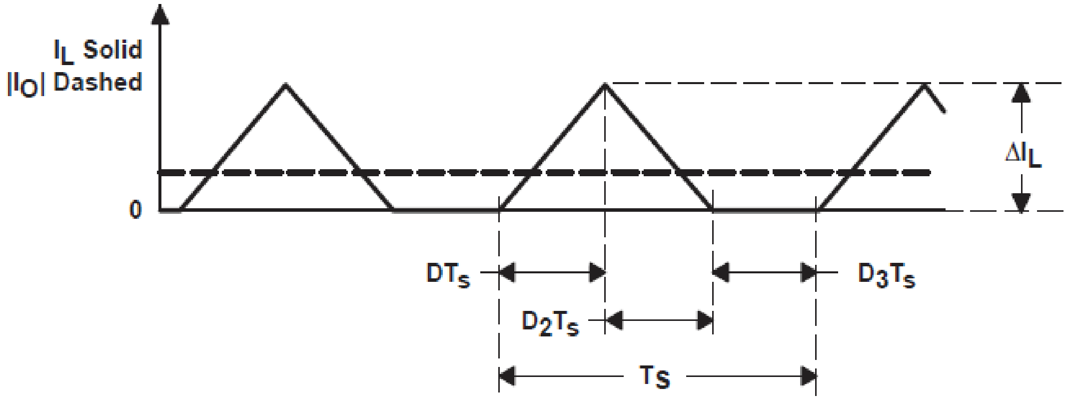


Figure 4.6: discontinuous mode (18)

To find out the transfer function in this case, we need to know t_{off}. but

it’s not as the previous case where t_{off}=1-D, let’s assume its equal a period of time α.

$\Delta I-_L=-V_{out}T\ \alpha\ /L$

$\Delta I^+_L+\Delta I^-_L=0$

$(V_{in}-V_{out})$ DT/L$-V_{out}$ α T/L =0

$$\alpha =(Vin-V_{out}D)/V_{out} \qquad (4.2.9)$$

α is defined as the piece of time in period where the inductor current goes to zero.

According to figure , the peak current can be found

$$I_{peak}=(V_{in}-V_{out})\ DT/L \qquad (4.2.10)$$

Then the average value is the area of triangle divided by the period T

$I_{out}=1/T\ [0.5\ I_{peak}\ (DT+\alpha\ T)]$

$I_{out}=1/\ [0.5\ I_{peak}\ (D+\alpha)]$

Now substitute I_{peak} equation with above equation we get

$Iout=0.5[\{(V_{in}-V_{out})/L\}*\ DT(D+\alpha)]$

The last step is to substitute α equation in the previous equation

$Iout=0.5[\{(V_{in}-V_{out})/L\}*DT\{D+(V_{in}-V_{out})D/\ V_{out})\}]$

$$V_{out}=V_{in}/1\{1/(2LI_{out}/D^2V_{in}T)+1\} \qquad (4.2.11)$$

The previous equation shows that the output voltage depends on almost all the circuit parameters which are values of the input voltage, inductor and the output current.

4.3 Ripples

One of the most important behaviors in the Buck Converter is the output ripple factor. It happened because of the switching action of the synchronize switching MOSFET causes the current in the inductor to have triangular waveform with dc shift.

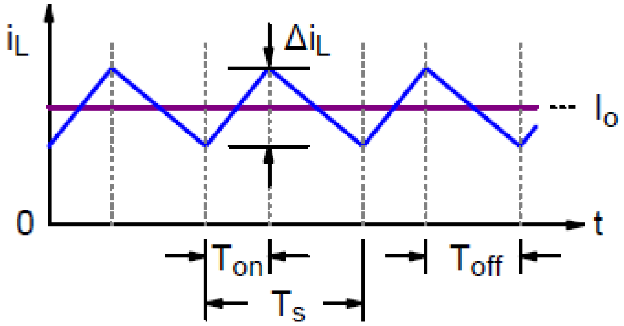


Figure 4.7: inductor current waveform (19)

The ripple current in the inductor can be expressed as

$$\Delta I_L=(V_{in}-V_{out})\ t_{on}/L=(V_{in}-V_{out})\ DT/L) \qquad (4.3.1)$$

The previous expression show as that the ripple current depends on the value of the inductor, applied voltage as well as on the switching time and the duty cycle.

So, we can use all these factors to determine the value of L

$$L=(V_{in}-V_{out})\ DT/\ \Delta I_L \qquad (4.3.2)$$

4.4 Inductor Area Product

In the Buck Converter, the inductor will store the energy during the on state, and then it will release at the off state. The ripple factor is depending on the size of the inductor. Big inductor will lead to less ripple factor which enhance the output current. However, it is going to make the circuit bigger. Which cause to increase the cost of the converter.

So, a new index is proposed for measuring the inductor size. It's called the (area product). It can be defined as the is the product of the cross-section area of the core and area of the winding window. The area product is depend on the volume of the core.

By using Faraday low

$$L.I_{peak}= N.B_m.A_c \tag{4.3.3}$$

Where

L: inductor value, Ipeak= peak current ,N= turn of the winding, B_m= Maximum magnetic flux in the core and A_c= is the effective cress sectional area of the core.

Also

$$N.A_{wr}=N.I_{rms}/J = K_w.W_a \tag{4.3.4}$$

Where

A_{wr} = winding conductor cross sectional area, J= current density

K_w= filling factor of the core, W_a= window area winding

By combining the two-previous equation we got

$$AP=A_c.W_a=L.I_{pk}.I_{rms}/K_w.J.B_m \tag{4.3.5}$$

Hence the rms current of the inductor is a combination from dc and ac component

$$I_{rms}=[I_o^2+(\Delta I_L^2/12)]^{0.5} \tag{4.3.6}$$

So

the ripple factor y can be defined as the ratio between the change in inductor current to the dc current

$y= \Delta I_L/I_o$

$$AP= (V_o.I_o/K_w.J.B_w)(1-D)T_s\sqrt{}[(1+y+\frac{y^2}{4}).(1+y^2/\sqrt{12})]/4 \qquad (4.3.7)$$

According to this equation, the following figure will show the normalized relationship between inductor core size and the ripple factor, at different duty cycles.

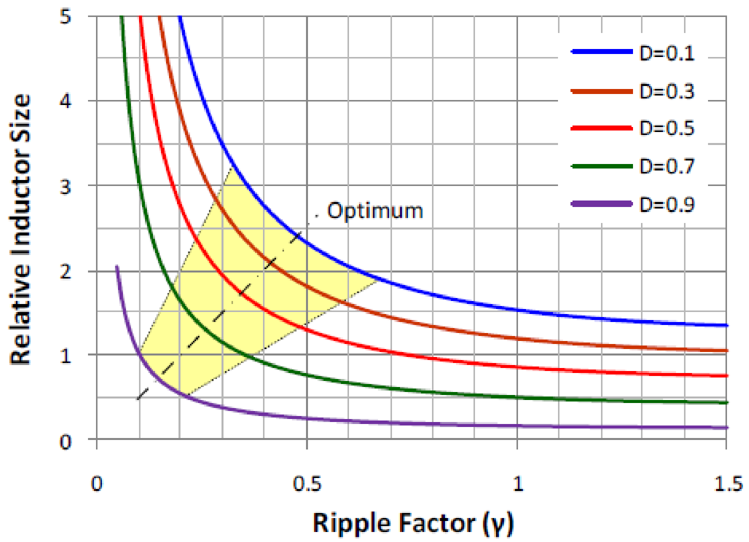


Figure 4.8: Relationship between inductor size and ripple factor with change of duty cycle. (20)

The figure shows if we need extremely low ripple factor, we must increase the core size too high which lead to a bigger circuit size and a prohibitive cost converter. but we can see from the figure, that we can choose optimum value which achieve very satisfactory results with the ripple factor without risking increasing the inductor size too much.

4.5 Converter Block Diagram

The Buck Converter block diagram can be representing as

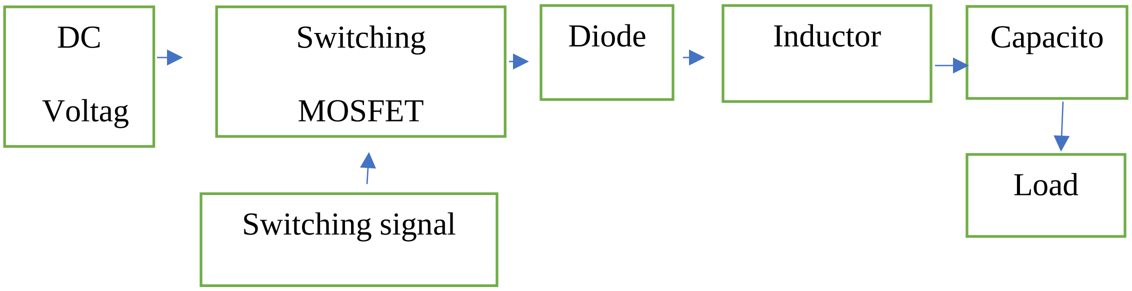


Figure 4.9: Buck Converter Block Diagram

4.6 Circuit Design and Schematic

The Buck Converter Design have been proposed as below

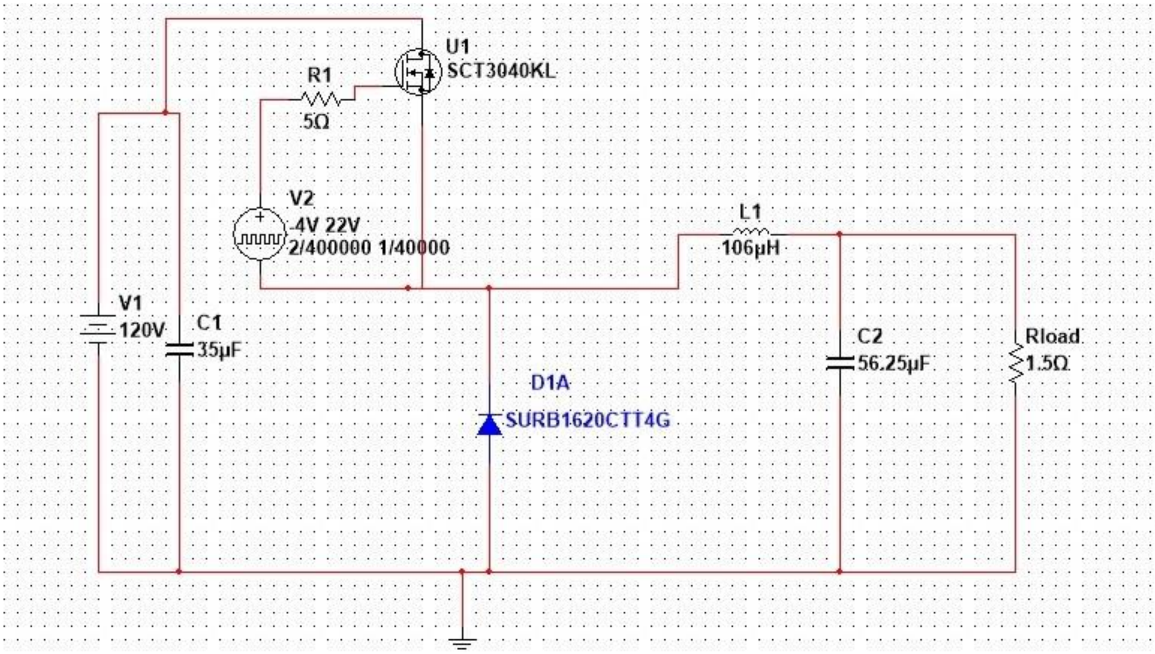


Figure 4.10 : Buck converter schematic

The purpose of this design is to convert a 120 V-dc voltage to a 24 V-dc.

The design components will be briefed below.

4.6.1 DC Voltage

The input to the converter will be a dc voltage. This will be either a battery or dc output from solar cell or from ac to dc converter. Also, it may be a 12-dc output from ac-dc converter as like in the computer power supply.

4.6.2 Input Capacitor

This 35-micro farad input capacitor was chosen to keep the dc voltage stable.

4.6.3 Switching Controlled signal

A pulse controlled signal was chosen to drive and control the switching MOSFET. The switching frequency chosen is a 40KHZ.

The duty cycle has been selected to achieve the desired 24 V

Where

D=V_{out}/V_{in}

D=24/120= 0.2

The voltage has been chosen to comply with MOSFET gate voltage input In the silicon MOSFET case the voltage has been chosen between -15V and 15V.

In the SiC MOSFET the voltage has been chosen between -4V and 22V to comply with SiC MOSFET data sheet.

The switching signal looks as below

Figure 4.11: Switching signal output

4.6.4 Switching MOSFET

Switching MOSFET is the heart of the Buck Converter.it handle the switching process and most of the power dissipation is happened through it. The switching MOSFET must have the following parameters.

Fast switching ability

1. Low R_{ds} to achieve low lose
2. Drain to source voltage V_{ds} larger than 240 V so he can handle the input voltage
3. drain to source current I_{ds} don't have to be 10A and above

according to the above requirements.

I have chosen the SPP11N60C3 silicon MOSFET from INFINION electronics which has the following specifications.

VDS= 650V

R_{ds}=0.38 ohm

ID= 11A

It has also some of the notable feature to make it fit with this converter as

- New revolutionary high voltage technology
- Ultra low gate charge.
- Periodic avalanche rated.
- Extreme dv/dt rated.
- High peak current capability.
- Improved transconductance.

For the SiC MOSFET scenario, I have chosen SCT3040KL from ROHM which has the following specification and comply with circuit requirements.

V_{ds}= 1200V, I_{ds}= 55A, R_{ds}= 40 m ohm.

The application for this MOSFET are

4. Solar inverter
5. DC-DC converter
6. Switch mode power supply
7. Induction heating
8. Motor drives

4.6.5 MOSFET gate resistance

A gate resistance has been added to the MOSFET input. Values of this gate resistance have been chosen according to the MOSFET datasheet.

In the silicon MOSFET scenario. SPP11N60C3, the resistance is 0.86 ohm.

In the SiC MOSFET scenario. C2M0040120D, the resistance is 5 ohms.

4.6.6 Freewheeling Diode

This diode is important to keep the current flows in a loop when the switch is off. when the MOSFET is on the diode will be on reverse bias and the current will flow from the power supply to the switch and then to the inductor and the load. When the switch is off, the inductor will discharge and the current will need a loop. If there is no diode, the current will face a problem to complete closed loop. The diode will help to keep the current flows through the load smoothly.

the diode requirement we need of this operation are:

1- Diode reverse voltage should be bigger than the input voltage. In our case, it should be greater than 120V
2- The forward current of the diode should exceed the output current which is

   $I_{output}=V_{out}/R_{load} = 24/1.5= 16A$

   The needed diode forward current should greater or equal than 20A

   The diode has been chosen in this circuit is RFN60TS6D from RHOM electronics. It has following specifications:

   V_r=200V, I_f=19A ,

   In addition, it has very promising features as

   1- Low switching loss
   2- Low forward voltage
   3- High current overload capacity.

4.6.7 Inductor

The inductor is very crucial component in the Buck converter. It gives the output signal the unique triangular shape. The inductor store the energy when the switch is on, then it releases it when it off. the angle of the triangle depends on the input voltage, output voltage and the inductance value. To achieve more smoothing in the output signal and decrease the triangle angle, we should increase the switching frequency as well as increase inductor value. Increase inductor value will increase the slope angle and make the signal less ripple and more similar to pure dc- output. However, increasing the inductor value without any boundary will increase core size and increase the cost. Good design should into consideration all these factors and make balance between ripple and overall circuit efficiency and cost.

I_L=(V_i-V_o)/L (when switch is on)

I_L= -V/L (When switch is off)

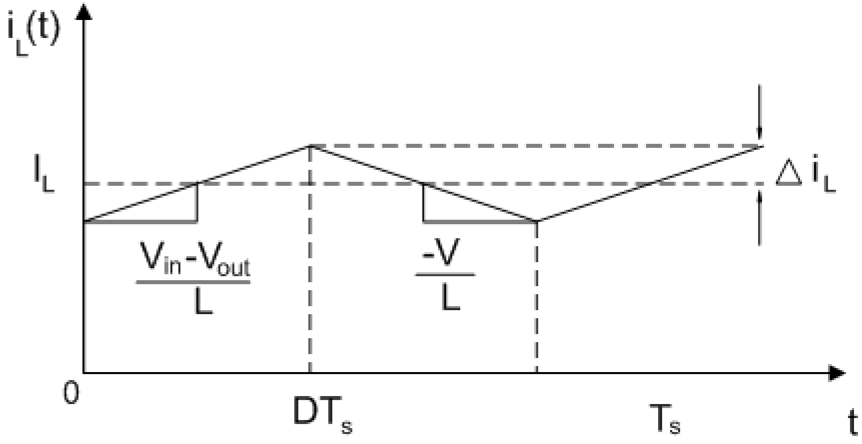


Figure 4.12: inductor current in Buck Converter (21)

To design the inductor, we need the following equation

L=V_{out}(1-D)/ (F_s* ΔI_L)

ΔI_L=ripple factor*I_L

Ripple factor is usually between 20%-40%.

30% has been chosen in this design

I_L= 15A due to voltage loss on MOSFET and diode.

L=(24*0.8)/(40000*15*0.3)= 106µH

4.6.8 Output capacitor

The output capacitor is important to reduce the output voltage and current ripple. The output capacitor helps to keep the inductor small to maintain better performance. By keeping inductor value smaller, the design package will be smaller and less expensive.

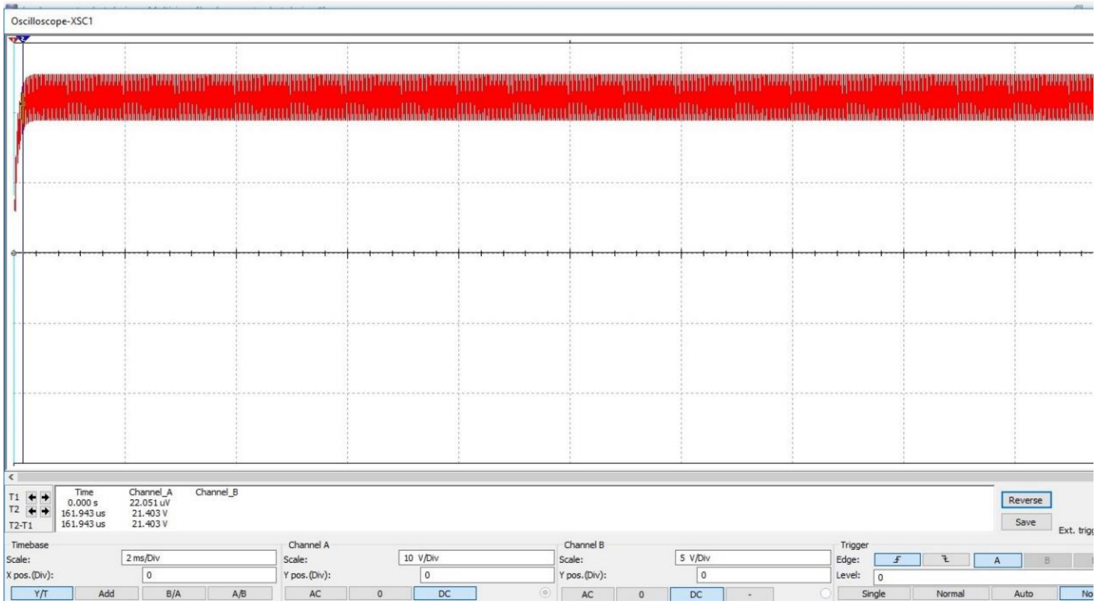
The following equation describe the capacitor value

$C_{out}= \Delta I_L/8*f_s*\Delta V_{out}$

Where ΔV_{out} is the desired output voltage ripple.

ΔV_{out} will be assumed to be 0.25 V

C_{out}=0.3*15/(8*40000*0.25)= 56.25 µC



	Time	Channel_A	Channel_B
T1	0.000 s	22.051 uV	
T2	161.943 us	21.403 V	
T2-T1	161.943 us	21.403 V	

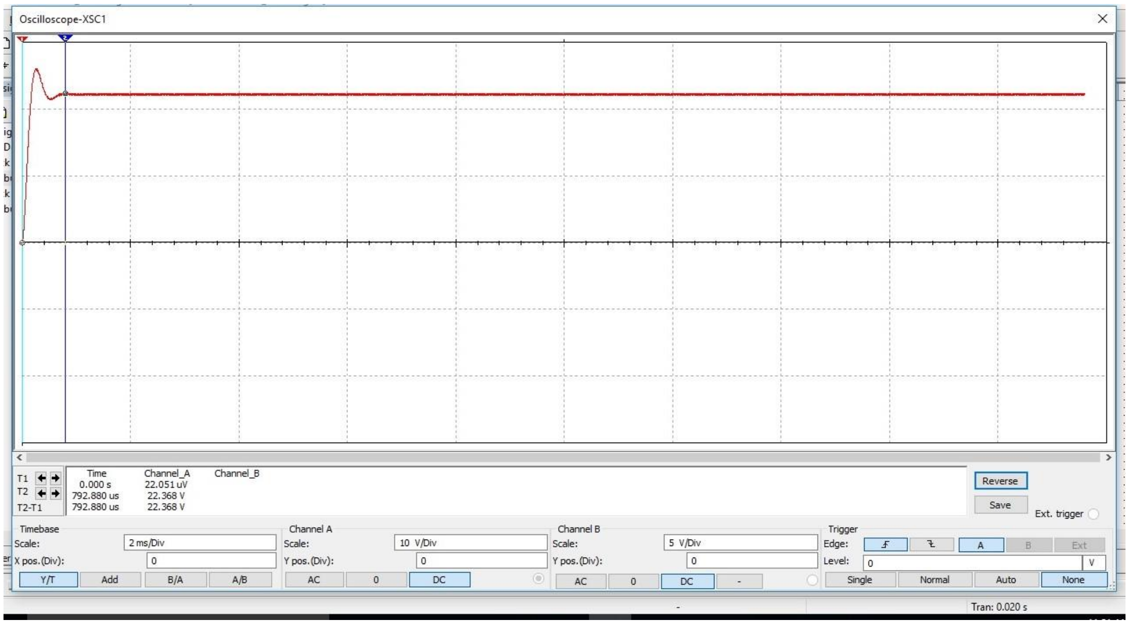
Timebase
Scale: 2 ms/Div
X pos.(Div): 0

Channel A
Scale: 10 V/Div
Y pos.(Div): 0

Channel B
Scale: 5 V/Div
Y pos.(Div): 0

Trigger
Edge:
Level: 0

Figure 4.13: Buck output without output capacitor



	Time	Channel_A	Channel_B
T1	0.000 s	22.051 uV	
T2	792.880 us	22.368 V	
T2-T1	792.880 us	22.368 V	

Timebase
Scale: 2 ms/Div
X pos.(Div): 0

Channel A
Scale: 10 V/Div
Y pos.(Div): 0

Channel B
Scale: 5 V/Div
Y pos.(Div): 0

Trigger
Edge: A
Level: 0 V
Ext. trigger

Tran: 0.020 s

Figure 4.14: Buck output with output capacitor

4.7 Simulation Procedure

Simulate the BUCK circuit with SPA11N60C3 silicon MOSFET and record the output voltage, MOSFET loss, input and output power and efficiency. Simulate the BUCK circuit with SCT3040KL silicon carbide MOSFET and record the output voltage, MOSFET loss, input and output power and efficiency.

Change the switching frequency for both circuits from and record the results. Change the load resistor in the SI MOSFET from 1.5 ohm to 1 ohm by 0.1 ohm in each step and record the output voltage, MOSFET loss, input and output power and efficiency.

repeat the previous procedure but at the SiC MOSFET.

Chapter 5: Results

5.1 Push Pull

5.1.1 SI MOSFET at 12VDC input

R(Ω)	I_{out}(A)	V_{out}(V)	P_{out}(W)	P_{in}(W)	Efficiency
1k	0.12	120	14.4	14.5	99.31034483
500	0.256	119	28.5	28.8	98.95833333
250	0.508	118	56.1	57	98.42105263
100	1.15	115	134	139	96.4028777
75	1.52	114	174	183	95.08196721
50	2.22	111	248	268	92.53731343
40	2.72	109	298	329	90.5775076
25	4.14	103	428	298	85.9437751

5.1.2 SI MOSFET at 14VDC input

R(Ω)	Iout(A)	Vout(V)	Pout(W)	Pin(W)	Efficiency
1k	0.12	120	14.4	14.5	99.31034
500	0.24	120	28.7	28.9	99.30796
250	0.477	119	56.9	57.7	98.61352
100	1.17	117	137	142	96.47887
75	1.55	116	180	187	96.25668

50	2.28	114	259	275	94.18182
40	2.81	112	315	339	92.92035
25	4.3	107	464	520	89.23077

5.1.3 SiC MOSFET 12VDC input

R(Ω)	Iout(A)	Vout(V)	Pout(W)	Pin(W)	Efficiency
1k	0.12	120	14.5	14.5	100
500	0.24	120	28.8	28.8	100
250	0.48	120	57.7	57.9	99.82698962
100	1.19	119	142	143	99.3006993
75	1.59	119	188	190	98.94736842
50	2.35	117	274	280	97.85714286
40	2.89	116	334	346	96.53179191
25	4.36	109	476	524	90.83969466

5.1.4 SiC MOSFET 14VDC input

R(Ω)	Iout(A)	Vout(V)	Pout(W)	Pin(W)	Efficiency
1k	0.12	120	14.5	14.5	100
500	0.24	120	28.8	28.8	100
250	0.48	120	57.8	57.9	99.82729
100	1.2	120	143	144	99.30556
75	1.59	119	190	192	98.95833

50	2.37	118	280	284	98.59155
40	2.94	117	345	353	97.73371
25	4.52	113	510	543	93.92265

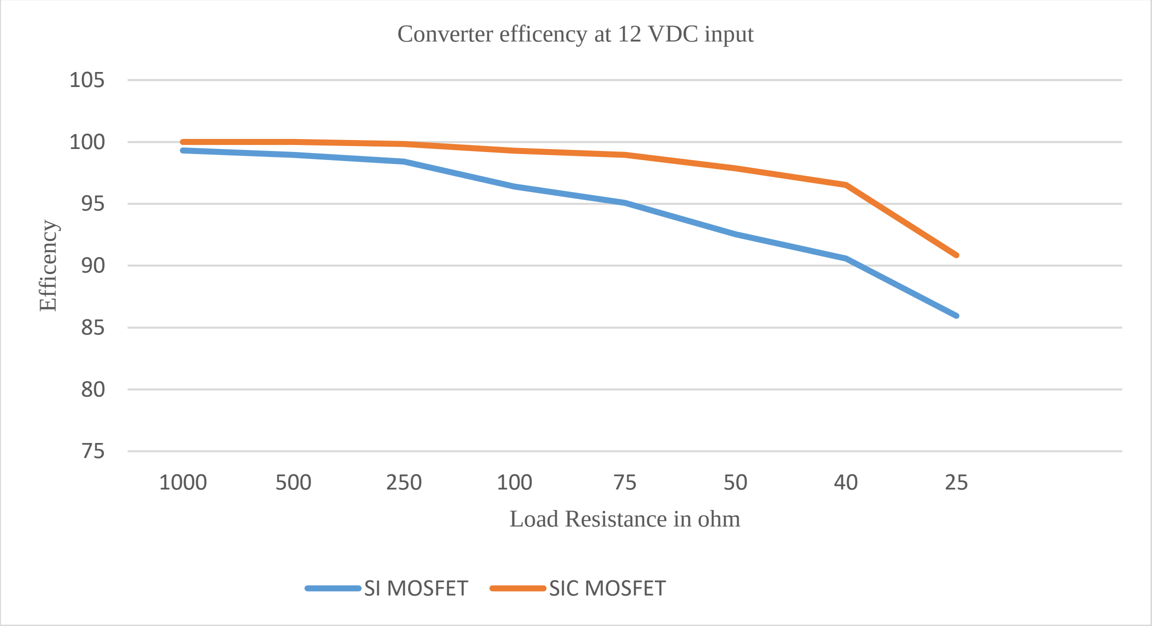


Figure 5.1: converter efficiency in 12VDC case

This figure shows the difference between Si MOSFET and SiC MOSFET circuit efficiency in the 12 VDC input circuit. Where the efficiency is the ratio between output power and the input power. It's clear that SiC MOSFET has significantly less power loss in comparison to the Si MOSFET and that mean higher efficiency. When the R_L range between 1k ohm and 500 there is a small difference in efficiency due to the low output current. The real difference starts to show when R_L is 250 ohms and less. In this point the load current become higher and the load absorbing more power. This mean more current will through in the MOSFET and dissipating more power.

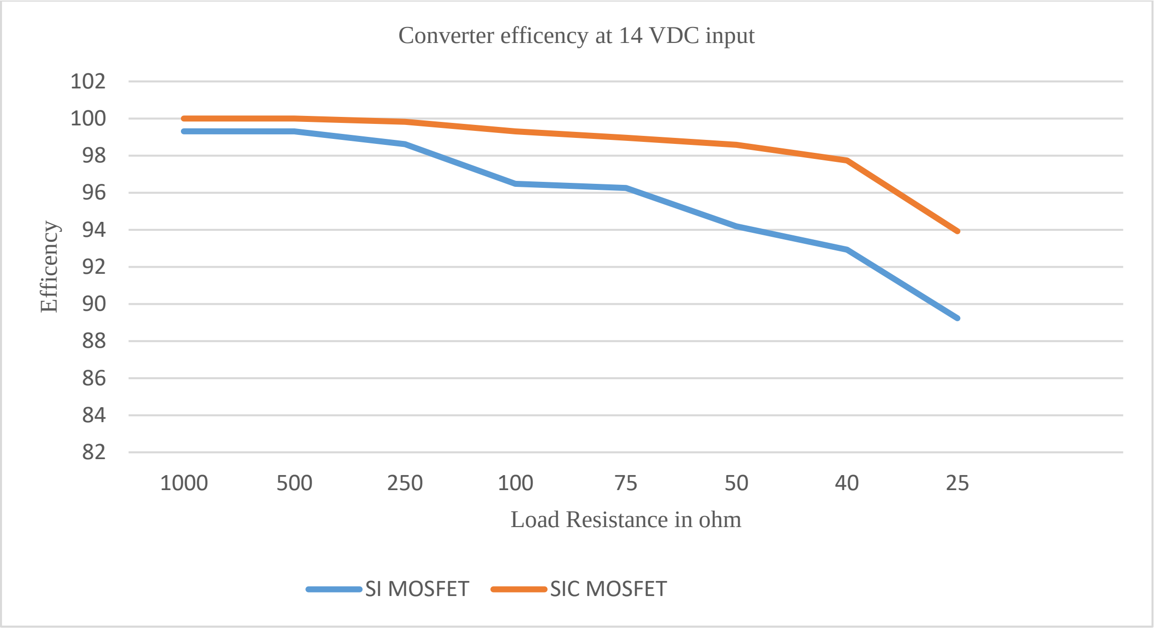


Figure 5.2: converter efficiency in 12VDC case

Same way this figure shows the difference between Si MOSFET and SiC MOSFET circuit efficiency in the 14 VDC input circuit. Same scenario is happened again and SIC MOSFET have higher efficiency and less power loss. We also notice that in case of 14VDC input. Both SI and SiC MOSFET have better performance than the 12VDC case. The explanation is because increase in input voltage will increase the gate voltage will due to higher performance and less loss.

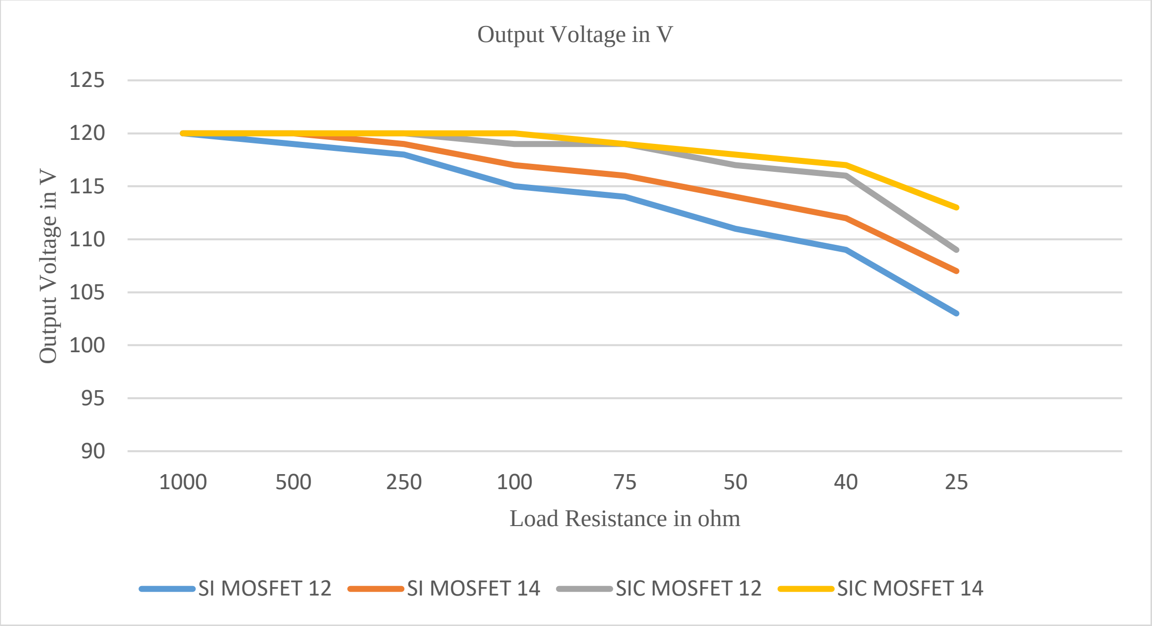


Figure 5.3: output voltage at different cases

This graph shows the difference in the voltage stability between SI MOSFET circuit and SiC MOSFET circuit in both 12 VDC and 14VDC input cases. The SiC MOSFET has better performance and stability than the SI MOSFET circuit. Also, it shows that 14 VDC input has better stability than 12 VDC case. Even though, the SiC MOSFET in 12VDC still perform better than SI MOSFET in the 14VDC case.

According to the above results and graphs. It's clear that using SiC MOSFET in push pull inverter will add more voltage stability to the circuit. Also, using SiC MOSFET will increase overall converter efficiency and decrease power loss in the circuit. This will lead to cheaper, smaller and better performance converter because less power loss mean smaller heatsink and we can even eliminate the ventilation fan and this will reduce the cost and improve overall performance.

5.2 DC-DC Buck Converter

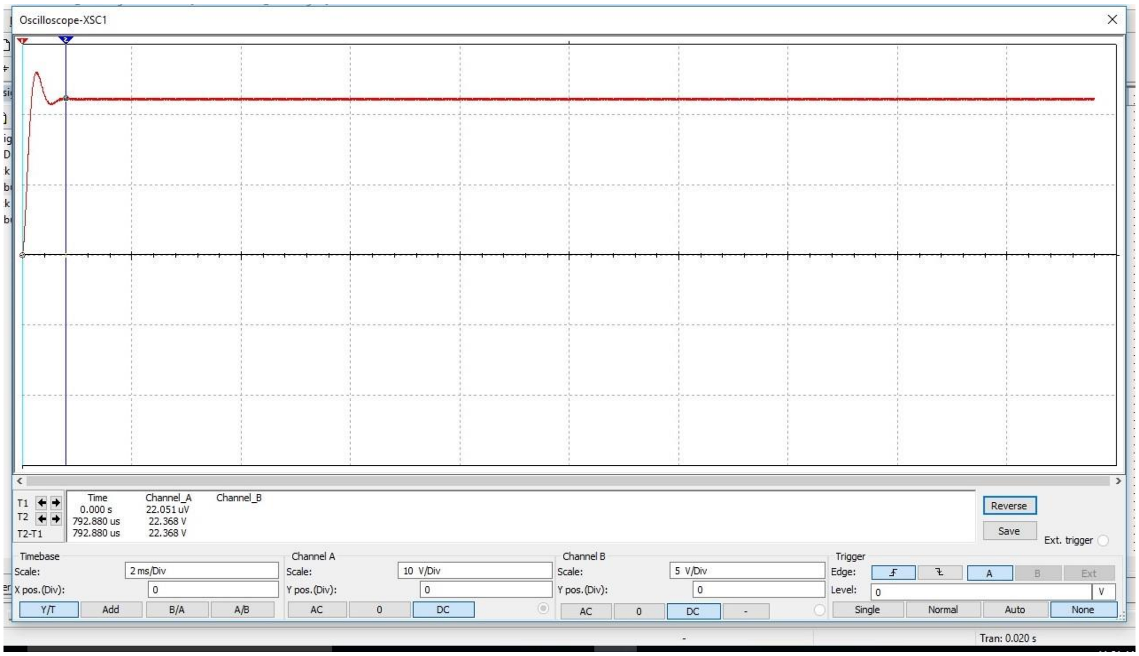
5.2.1 Si MOSFET

at 40 KHZ switching frequency

the simulation set first according to the design parameters, then the load resistor has been changed to see the effect.

R	P_{in}	P_{out}	V_{out}	$MOSFET_{loss}$	Efficency
1.5	357	328	22.2	18.3	91.87675
1.4	381	348	22.1	21.4	91.33858
1.3	407	369	22	24.7	90.66339
1.2	437	393	21.8	29.9	89.93135
1.1	471	418	21.5	37.4	88.74735
1	510	446	21.2	47	87.45098

Table 2 : Buck with SI MOSFET results with R change



Oscilloscope-XSC1

	Time	Channel_A	Channel_B
T1	0.000 s	22.051 uV	
T2	792.880 us	22.368 V	
T2-T1	792.880 us	22.368 V	

Timebase

Scale: 2 ms/Div

X pos.(Div): 0

Channel A

Scale: 10 V/Div

Y pos.(Div): 0

Channel B

Scale: 5 V/Div

Y pos.(Div): 0

Trigger

Level: 0 V

Tran: 0.020 s

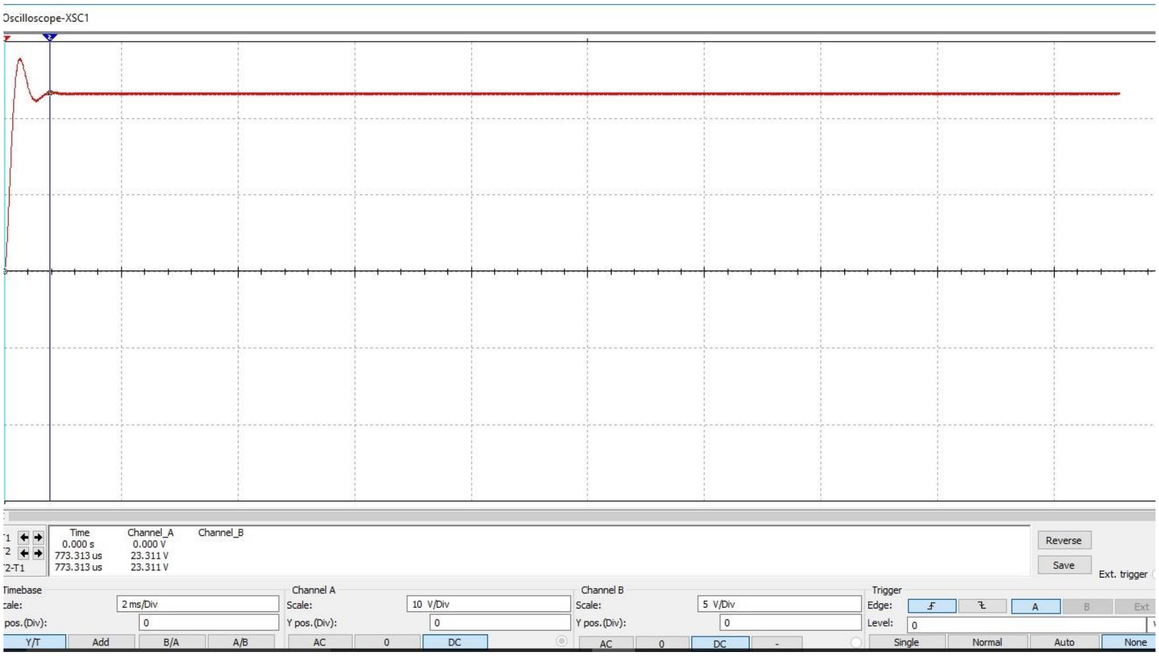
Figure 5.4: SI Buck Converter output voltage

5.2.2 SiC MOSFET

The simulation set first according to the design parameters, then the load resistor has been changed to see the effect.

R	P_{in}	P_{out}	V_{out}	$MOSFET_{loss}$	Efficiency
1.5	377	359	23.2	6	95.22546
1.4	403	384	23.2	6.75	95.03722
1.3	434	412	23.2	7.72	94.93088
1.2	469	445	23.1	8.91	94.88273
1.1	511	484	23.1	10.51	94.71624
1	561	531	23.1	11.7	94.65241

Table 4 : Buck with SiC MOSFET results with R change



```
        Time         Channel_A    Channel_B
1       0.000 s      0.000 V
2       773.313 us   23.311 V
2-T1    773.313 us   23.311 V
```

Timebase
cale: 2 ms/Div
pos.(Div): 0

Channel A
Scale: 10 V/Div
Y pos.(Div): 0

Channel B
Scale: 5 V/Div
Y pos.(Div): 0

Trigger
Level: 0

Figure 5.5: SiC Buck Converter output voltage

5.2.3 Si MOSFET with frequency change

Simulation is set first to the designed 40 KHz switching signal, then changed to see the effect with 20KHz increments.

Frequency	P_{in}	P_{out}	V_{out}	$MOSFET_{loss}$	Efficiency
40KHz	357	328	22.2	18.3	91.87675
60KHz	360	327	22.2	22.1	90.83333
80KHz	362	325	22.1	26.7	89.77901
100KHz	365	324	22.1	30	88.76712

5.2.4 SiC MOSFET with frequency change

Simulation is set first to the designed 40 KHz switching signal, then changed to see the effect.

Frequency	P_{in}	P_{out}	V_{out}	$MOSFET_{loss}$	Efficiency
40KHz	377	359	23.2	6	95.22546
60KHz	381	361	23.2	7.2	94.75066
80KHz	384	361	23.2	9	94.01042
100KHz	388	362	23.1	11	93.29897

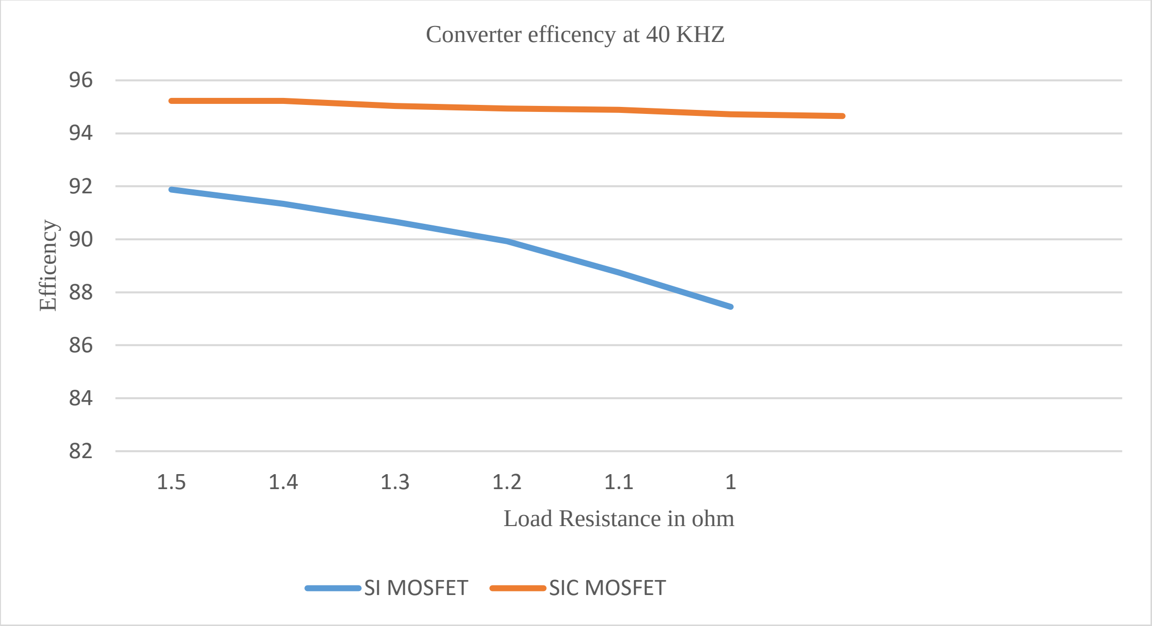


Figure 5.6: converter efficiency comparison at different load

The above figure shows the difference between converter efficiency at 40KHz switching frequency at different load resistance. In both cases the converter have high possible efficiency at the designed load resistor. We have noticed that there are 4 % deference in the efficiency between SI MOSFET converter and the SiC MOSFET one. Also, it’s clear that SiC MOSFET has been affected very little by the change in the load and its more immune and still have higher overall efficiency.

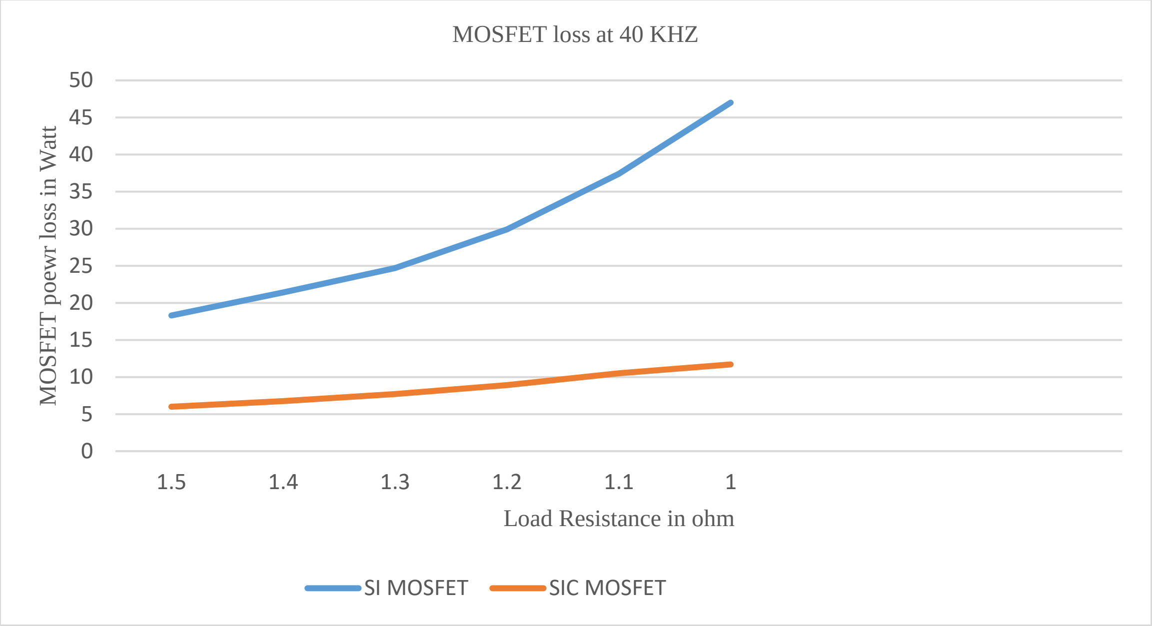


Figure 5.7: MOSFET loss comparison at different load

The above figure shows the difference between Si and SiC MOSFET at 40KHz switching frequency at different load resistance. In both cases the MOSFET lowest possible loss at the designed load resistor. We have noticed that there are 12 W deference in the loss between Si MOSFET and SiC MOSFET.

Also, it’s clear that SiC MOSFET has been affected very little by the change in the load and it is more immune. On the other hand, Si MOSFET have been affected badly with change in the load and made higher loss.

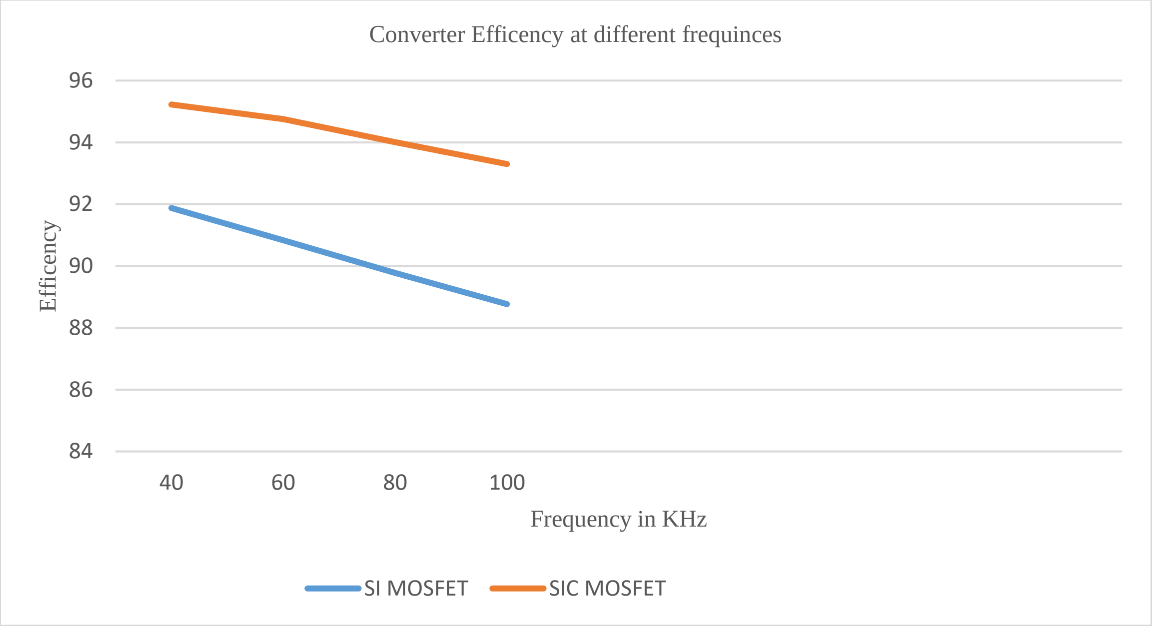


Figure 5.8: efficiency at different switching frequency

Above figure show the effect of changing the switching frequency on the converter.

At both cases, higher efficiency is occurred at the designed 40 KHz switching frequency signal. However, SiC MOSFET converter has higher efficiency. When frequency has been increased. In both circuit efficiency has been dropped. However, Si MOSFET has higher negative slop and SiC MOSFET converter looks more immune to frequency change.

Chapter 6: Conclusion, Future Work and Publications

In this thesis, a simulation for a push-pull DC-AC inverter, and DC-DC Buck Converter are obtained using both silicon and silicon carbide power MOSFET. Output voltage, current and power loss was obtained and compared between the two models. The simulation program used in this paper is NI MULTISIM which is used to obtain all parameters above. The SiC MOSFET model was created using the Model wizard in the NI MULTISIM simulation program. The data used to create the model was taken from evaluation spice models from companies such as ROHM, CREE and INFINION.

The results show that using Silicon Carbide MOSFET enhances the output voltage in cases of the load current increasing. Increasing voltage stability is very important in case of load demand change. This will lead to increases in converter value as well as increases in the efficiency of the inverter. Additionally, using SiC MOSFET will decrease losses in the converter. SiC MOSFET has significantly less conduction and switching loss. As a result, the converter will have better performance, less power dissipation and a decrease in the power loss of the circuit.

Lastly, it shows that SiC MOSFET has better performance than Si MOSFET in case of frequency change. The SiC MOSFET is more immune against frequency change than Si MOSFET in high frequency applications. SiC MOSFET will be a great fit in high frequency applications such as high frequency switching devices and converters. Also, SiC MOSFET will be perfect for RF applications which need high frequency and high power devices.

According to that, using SiC MOSFET will improve the design, save money, and decrease the size of the converter package because of the elimination of ventilation fan and the decreasing of the heat sink size.

Future Work

In the future, more investigation about SiC MOSFET will be done. I already have started to work on other converters like PWM, BOOST DC-DC, 3 Phase inverter converter and Cascaded converter**.**

Also, I intend to study GaN as a substitute to SiC in some applications and make a comparison between their performance.

Publications

1. Mustafa Al-badri and Mohammed A. Matin, Simulation of push-pull inverter using wide bandgap devices”, Proc. SPIE 9957, Wide Bandgap Power Devices and Applications, 99570H (19 September 2016); doi: 10.1117/12.2238362
2. Ali Mahmoud Salman Al-bayati, Salah S. Alharbi, Saleh S. Alharbi, Mustafa Al-badri, and Mohammad Matin, A High-Performance Non-Isolated DC-DC Buck Converter Design Based on Wide Bandgap Power Devices, 2017 IEEE International Conference on Electro Information Technology (EIT) (accepted)

Bibliography

1. Keith Billings, Taylor Morey, “Switching Power Supply” Third edition, (p1.145,2.102, p2.109, p2.125-p2.126).

2. Hull, Brett, et al. “Status of 1200 V 4H-SiC Power DMOSFETs,” International Semiconductor Device Research Symposium, December 2007.

3. Burger, B.; Kranzer, D.; Stalter, O.; and Lehrmann, S. “Silicon Carbide (SiC) D-MOS for Grid-Feeding Solar-Inverters,” Fraunhofer Institute, EPE 2007, September 2007.

4. Burger, B.; Kranzer, D.; and Stalter, O. “Cost Reduction of PV Inverters with SiC DMOSFETs,” Fraunhofer Institute, 5th International Conference on Integrated Power Electronics Systems, March 2008.

5. Yang, Yungtaek; Dillman, David L.; and Jovanovic, Milan M. “Performance Evaluation of Silicon Carbide MOSFET in Three-Phase High-Power-Factor Rectifier,” Power Electronics Laboratory, Delta Products, www.deltartp.com.

6. Das, Mrinal K., et al. “State-of-the-Art 10-kV NMOS Transistors,” 20th Annual International Symposium on Power Semiconductor Devices and ICs, May 2008.

7. http://www.farnell.com/datasheets/59764.pdf (accessed 9/19/2016)

8. http://www.vishay.com/docs/91215/91215.pdf (accessed 4/22/2016)

9. http://darrenyates.com.au/electronics/archives/50 (accessed 2/2/2017)

10. EE times magazine, calculating power loss in switching MOSFET.

11. Bob Dildine, “Buck Converter basics”

12. Surinder P. Singh, “Output Ripple Voltage for Buck Switching Regulator”

13. Edwin Wang, “Current Ripple Factor of a Buck Converter”, AN010 – April 2014.

14. Hsin-Ju Chen, “POWER LOSSES OF SILICON CARBIDE MOSFET IN HVDC APPLICATION”

15. Cheung, Rebecca (2006). Silicon carbide microelectromechanical systems for harsh environments. Imperial College Press. p. 3. ISBN 1-86094-624-0.

16. Top 10 Fast Cars". topmost10.com. Archived from the original on 2009-03-26. Retrieved 2009-06-06.

17. Meißer, Michael (2013). Resonant Behaviour of Pulse Generators for the Efficient Drive of Optical Radiation Sources Based on Dielectric Barrier Discharges. KIT Scientific Publishing. p. 94. ISBN 978-3-7315-0083-4.

18. Horio, Masafumi; Iizuka, Yuji; Ikeda, Yoshinari (2012). "Packaging Technologies for SiC Power Modules". Fuji Electric Review. 58 (2): 75–78.

19. The largest telescope mirror ever put into space". European Space Agency. Retrieved 2009-06-06.

20. http://www.mouser.com/ds/2/308/MURB1620CT-D-355756.pdf (accessed in 4/7/2017)

21. http://www.rohm.com/web/global/datasheet/SCT3040KL (accessed in 4/4/2017)

22. S.S Shema, I. Daut, Syafwati A.N, M. Irwanto, Shwatri C " Simulation of Push-Pull Inverter for Photovoltaic application via Multisim, The 5th International power Engineering and optimization Conference (PEOC2011), Shah Alam, Selangor, Malaysia:6-7 June 2011.

23. Rajenrda Pratap, R.K Singh, Vineeta Agrwal, " Spice Model Development for SiC power MOSFET" ,2012 IEEE International conference on power electronics, Drives and Energy systems December 16-19, 2012 Bengaluru, India.

24. Multisim Component Reference guide by NI Multisim

25. IRFP260n data sheet http://www.infineon.com/dgdl/irfp260n.pdf?fileId=5546d462533600a4015356289dcf1fe2 (accessed in 4/1/2017).

26. SiC power MOSFET datasheet

    http://www.wolfspeed.com/media/downloads/165/C2M0040120D.pdf (accessed in 4/1/2017).

27. B. Ozpineci and L.M. Tolbert, "Comparison of Wide-Bandgap Semiconductors for Power Electronics Application".

28. US Department of Energy Brochure in Energy Efficiency& Renewable Energy/ Advance Manufacturing office.

29. Jose Millan and Philippe Godignon, "Wide BandGap Power Semiconductor Devices". IBM-CNM-CSIC.

30. Yustin Cui, Madhu Chinthavali, Leon M. Tolbert, "Temperature Dependent Pspice Model of Silicon Carbide Power MOSFET".

31. Nando Kaminski, Oliver Hilt, " SiC and GaN Devices-Wide Bandgap is not all the same".

32. K.H Edelmoser , L.L Erhartt, " Simulation of Multiphase DC-to-AC Power Inverter System".

33. Oliva, A.R., H. Chiacchiarini y G. Bortolotto "Developing of a state feedback controller for the synchronous buck converter", Latin American Applied Research, Volume no 35, Nro 2, Abril 2005, pp. 83–88. ISSN 0327-0793.

34. Robert W. Erickson, “DC-DC Power converter” Article in Wiley Encyclopedia of Electrical and Electronics Engineering.

35. David Jauregui, Bo Wang, and Rengang Chen “Power Loss Calculation with Common Source Inductance Consideration for Synchronous Buck Converters.

36. Jens Ejury, Infineon Technologies North America (IFNA) Corp, “Buck Converter Design”.

37. Brigitte Hauke, “Basic Calculation of a Buck Converter's Power Stage”. Application Report, SLVA477B–December 2011–Revised August 2015.

38. H. L. Krauss, “Class A Push- Pull Amplifier theory” Class-A Push-Pull Amplifier Theory”, Proceedings of the IRE, Year: 1948, Volume: 36, Issue: 1Pages: 50 - 52, DOI:10.1109/JRPROC.1948.230913.
39. Xu She, “High Performance Silicon Carbide Power Block for Industry Applications”: IEEE Transactions on Industry Applications (Volume: PP, Issue: 99)
40. Xu She, “Review of Silicon Carbide Power Devices and Their Applications”, IEEE Transactions on Industrial Electronics (Volume: PP, Issue: 99).
41. Kazwaki Nakayama, “Emitter Follower type single ended push pull circuit” Pioneer electronics corporation, Tokyo, Japan 1986.
42. Zabrel Holsman, “Silicon Could Be Key to Making Diamond Semiconductors a Reality”.
43. Emma Wang, “Silicon Carbide”, https://www.slideshare.net/EmmaWang38/silicon-carbide-66387144. (accessed in 4/11/2017)
44. LT spice website, www.linear.com/designtools/software/ (accessed in 2/1/2017)
45. Steve Roberts, “DC/DC book of knowledge”, (p20-p22).
46. Sira Ramirez, Silva Ortigoza, “Control Design Technique in Electronics devices”, (p11-p17)
47. Marty Brown, “Practical Switching Power Supply Design”, (p20-p21).
48. http://www.learnabout-electronics.org/Amplifiers/amplifiers53.php (accessed in 4/13/2017)

49. http://www.learnabout-electronics.org/Amplifiers/amplifiers54.php (accessed in 4/22/2107)

50. http://www.electronics-tutorials.ws/waveforms/astable.html (accessed in 4/27/2017)

51. R. Shenbagalakshmi, Sree Renga Raja Thangaswamy, "Implementation of Robust Prediction Observer Controller for DC-DC Converter", Journal of Electrical Engineering and Technology 8(6) · November 2013 with 77 Reads DOI: 10.5370/JEET.2013.8.6.1389.

52. Mustafa Al-badri; Mohammed A. Matin, Simulation of push-pull inverter using wide bandgap devices", Proc. SPIE 9957, Wide Bandgap Power Devices and Applications, 99570H (19 September 2016); doi: 10.1117/12.2238362.

53. Ali Mahmoud Salman Al-bayati, Salah S. Alharbi, Saleh S. Alharbi, Mustafa Al-badri, and Mohammad Matin, A High-Performance Non-Isolated DC-DC Buck Converter Design Based on Wide Bandgap Power Devices, 2017 IEEE International Conference on Electro Information Technology (EIT)

Appendix A

Figures Citation

1. https://www.allaboutcircuits.com/news/silicon-could-be-key-to-making-diamond-semiconductors-a-reality/
2. Seminar on material engineering by “Tushar Aneyrao” Roll NO 16.
3. Seminar on material engineering by “Tushar Aneyrao” Roll NO 16.
4. Seminar on material engineering by “Tushar Aneyrao” Roll NO 16.
5. www.rohm.com
6. www.rohm.com
7. www.rohm.com
8. www.rohm.com
9. www.rohm.com
10. http://www.stereophile.com/content/boulder-500ae-power-amplifier-complementary-symmetry#0kuMcICdqGwAV5XR.97
11. http://www.learnabout-electronics.org/Amplifiers/amplifiers54.php
12. http://www.davidbridgen.com/astable.htm
13. https://www.quora.com/What-is-a-buck-converter
14. https://www.slideshare.net/satabdyjena/buck-converter-41535853
15. https://www.researchgate.net/figure/264027444_fig2_Fig-2-Schematic-diagram-of-Buck-converter
16. https://shriramspark.wordpress.com/2015/02/14/buck-converter-an-efficient-way-step-down-voltages/

17. http://www.eetimes.com/document.asp?doc_id=1225917
18. http://www.homemade-circuits.com/2013/06/exploring-buck-boost-circuit-concept-in.html
19. http://www.richtek.com/Design%20Support/Technical%20Document/AN009
20. http://www.richtek.com/Design%20Support/Technical%20Document/AN009
21. https://www.ika.rwth-aachen.de/r2h/index.php/Power_Electronics.html

Appendix B

Simulation of Push-Pull Inverter Using Wide bandgap Devices

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Abstract

This paper discusses the use of wide bandgap devices (SiC-MOSFET) in the design of a push-pull inverter which provides inexpensive low power dc-ac inverters. The parameters used were 1200V SiC MOSFET(C2M0040120D) made by power company ROHM. This modeling was created using parameters that were provided from a device datasheet. The spice model is provided by this company to study the effect of adding this component on push-pull inverter ordinary circuit and compared results between SiC MOSFET and silicon MOSFET (IRFP260n). The results focused on V_{out} and V_{mos} stability as well as on output power and MOSFET power loss because it is a very crucial aspect on DC-AC inverter design. These results are done using the National Instrument simulation program (Multisim 14). It was found that power loss is better in the 12 and 15 vdc inverter. The V_{out} in the SIC MOSFET circuit shows more stability in the high current low resistance load in comparison to the Silicon MOSFET circuit and this will improve the overall performance of the circuit.

Keywords*:* Push-pull inverter, SIC MOSFET, NI Multisim, Simulation, Wide bandgap semiconductors

1. INTRODUCTION

As world evolves every day, one thing that remains constant is the need for smaller, faster and more reliable electronics. Semiconductors are the foundation for every electronics. The Silicon has been used for decades to manufacture electronics. However, Silicon has been pushed to its limit and we need new substance for our increasing demands. Fortunately, Wide bandgap semiconductors have the solution for our needs. Wide bandgap semiconductors such as (SIC, GAN and Diamonds) who have bandgaps (3.26, 3.45 and 5.4 ev) respectively have higher bandgap compared to Silicon (1.1 ev). This wide bandgap provides them with unique characteristic. Wide bandgap semiconductors can perform up to 300 degrees Celsius, handle 10 times the voltages of Silicon and eliminate a higher percentage power loss. This means that we can save millions of dollars and make smaller electronics because less power means that we need less and smaller heatsink and ventilation fans.

2. INVERTER CIRCUIT AND BLOCK DIAGRAM

a. Block Diagram

The block diagram contains the following

1- 12 or 15 V dc Battery
2- Inverter circuit which includes the following
    - Oscillation circuit: this includes BJT transistor(BC547C),a Resistor and capacitors. Values of resistors and capacitors determine the needed frequency which is in our case 60 Hz. F=1/RC where F is the circuit frequency
    - 2 OPAMPs (LM358N) to provide smooth square output signal to feed the power MOSFET.
    - Power MOSFET which is considered as the heart of the inverter and it's the part that causes the main power loss in the inverter.
3- Step Up power transformer to provide 110 V ac to the load.

b. Circuit Schematic

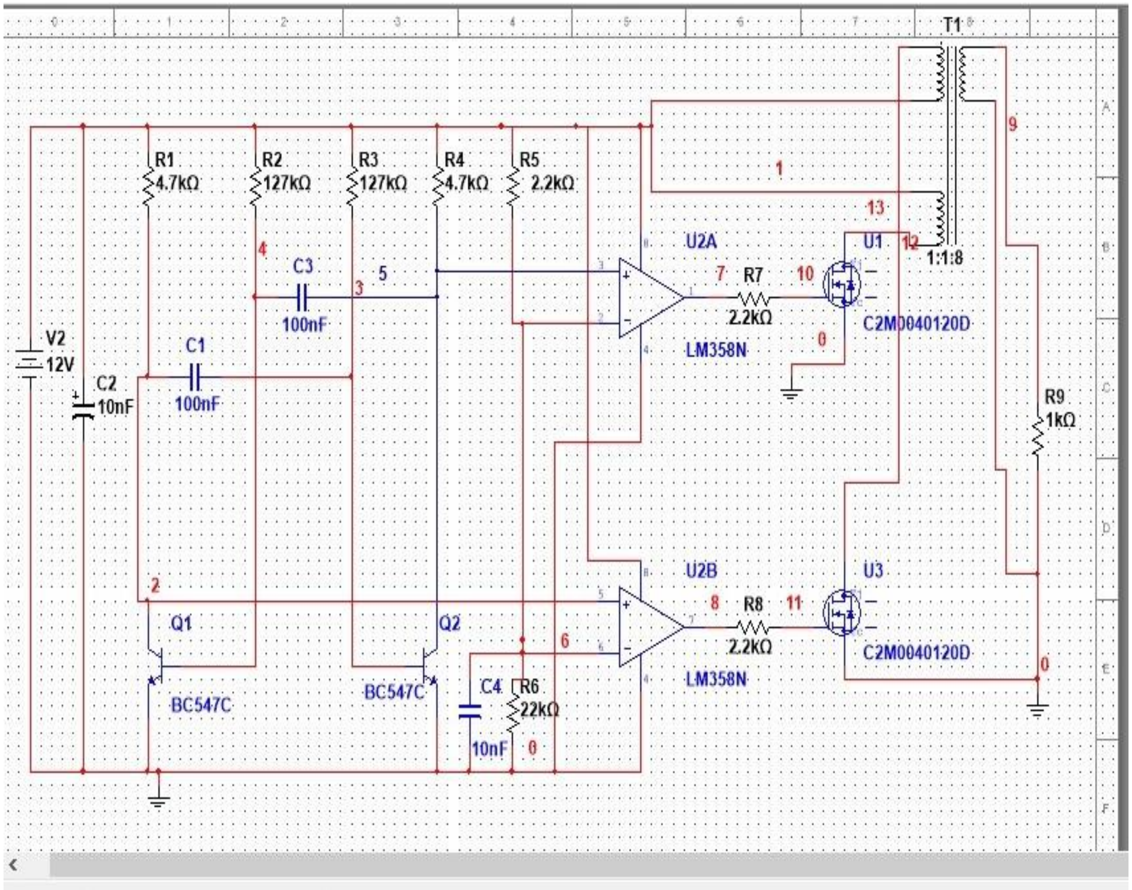

Figure 1 (push-pull inverter circuit schematic)

3. SIMULATION SOFTWARE

While there were many multi simulation programs around such as Matlab Simulink, PSpice , LTspice and others This Simulation was created using NI Multisim simulation software. This software was chosen Particularly because it gives a lot of space to modify and create models and change parameters to meet the designated model that we wanted to simulate. It also has a huge selection library which contains exact models and part number that will help to provide more accurate results. Multisim has ease of use, clear and easy interface. It Also provide a lot of simulation and analysis methods such as dc-operation point, ac sweep, transient in addition to Fourier and other simulation methods. Multisim provides the possibility to create new models that are not available in its library selection using different methods. For example, by using spice simulation files like .models and .subsckt that are provided by a lot of manufactures company to help designers. Also it provides a great method to create models from scratches by using its own datasheet in the component wizard.

4. PROCEDURE

This Simulation is done using the following steps

- A particular push-pull inverter is used depending on a paper published by Shah Alam, Selangor, Malaysia by S.S Shema and three other authors. on the 5th international power engineering and optimization conference (PEOCO2011)
- The original circuit uses two BJT N-type as an oscillator to charge and discharge with help of capacitors to convert battery DC voltage to an AC voltage fig (1).
- The output of the transistor AC voltage is a high ripple square signal which will be the input to an OPAMP making the square signal more smooth.
- The main stage of the inverter is the power MOSFET, the original circuit used was silicon IRFP260n MOSFET.
- The last stage was three inputs-, and two output transformer producing 110 V output signal
- The simulation started with 12 Vdc, as an input to the inverter, using IRFP260n MOSFET first.
- Then the output load was set to be 1k ohm as an initial point to simulation and turn ratio of the transformer was played with to make the output voltage 110 V at R_{load}= 1k ohm.
- The following parameters were recorded, V_{load}, I_{load}, P_{av} out, I_{mos}, V_{mos} and V_{loss} of the MOSFET.
- R_{load} is gradually decreased until the output voltage became 90 % of the original output voltage which is in our case is less than 99 V
- The MOSFET$_s$ are changed to the SIC power MOSFET and the entire procedure is repeated.
- The next step is to change the dc input to 15 V instead of 12 V and repeat the same steps for silicon MOSFET and SIC MOSFET.
- Recording all results and comparing them using Microsoft Excel graphs.

5. RESULTS

a- At VDC=12 V

- Using MOSFET IRFP260n

Load Resistor (ohm)	Vout (V)	I out (A)	P(avg) out (W)
1000	110	110 m	12.1
500	109.371	219 m	23.987
250	108.578	434 m	47.44
150	108	717 m	77.1
100	106.2	1.063	113
75	105	1.4	147
50	102.5	2.052	211.75
40	100.75	2.52	254
30	98	3.27	320

Load Resistor (ohm)	Vmos (V)	I mos (A)	P loss of 2mos (W)	Loss %
1000	11.268	757 m	66.148 m	0.546
500	11.219	1.51	220.166 m	0.91
250	11.136	2.99	774.78 m	1.63
150	11.028	4.94	2	2.59
100	10.892	7.32	4.25	3.76
75	10.76	9.65	7.5	5.1
50	10.5	14.1	16	7.58
40	10.338	17.4	24	9.45
30	10	22.5	40	12.5

- **Using MOSFET(C2M0040120D)**

Load Resistor (ohm)	Vout (V)	I out (A)	P(avg)out (W)
1000	110	110m	12.1
500	110	220m	24.1
250	110	439 m	48.1
150	109	729 m	79.8
100	109	1.09	118
75	108	1.44	155
50	105	2.11	222
40	103	2.56	263
30	99	3.4	336.6

Load Resistor (ohm)	Vmos (V)	I mos (A)	P loss of 2mos (W)	Loss %
1000	11.266	757 m	7 m	0.0546
500	11.262	1.51	16 m	0.067
250	11.25	3	82 m	0.17
150	11.218	5	350 m	0.43

100	11.157	7.5	1.174	1
75	11.066	9.92	2.8	1.8
50	10.795	14.5	9.6	4.3
40	10.515	17.7	18.6	7
30	9.92	22.5	38.8	11.52

b- At VDC= 15V

- Using MOSFET (IRFP260n)

Load Resistor (ohm)	Vout (V)	I out (A)	P(avg) out (W)
1000	110	110 m	12.2
500	109.9	220m	24.2
250	109.445	438 m	47.9
100	107.96	1.08	117
75	107.218	1.43	153
50	105.679	2.11	223
40	104.6	2.62	274
30	102.876	3.43	353
25	101.5	4.06	412
15	96.23	6.42	617

Load Resistor (ohm)	Vmos (V)	I mos (A)	P loss of 2mos (W)	Loss %
1000	14.1	569 m	44.6 m	0.365
500	14.05	1.16	146 m	0.6
250	13.987	2.42	490 m	1.02
100	13.79	5.94	2.7	2.3
75	13.7	7.09	4.7	3.07
50	13.5	11.7	10	4.48
40	13.375	14.5	16.2	5.9
30	13.147	19	26	7.36
25	12.97	22.5	36.4	8.83
15	12.3	35.5	90.4	14.65

- **Using MOSFET(C2M0040120D)**

Load Resistor (ohm)	Vout (V)	I out (A)	P(avg) out (W)
1000	110	110 m	12.2
500	110	221 m	24.3
250	110	441 m	48.6
100	110	1.1	121
75	110	1.46	161
50	109	2.19	239
40	109	2.72	296
30	108	3.6	386

25	106	4.26	454
15	100	6.66	665

Load Resistor (ohm)	**Vmos (V)**	**I mos (A)**	**P loss of 2mos (W)**	**Loss %**
1000	14.08	612 m	7.2 m	0.0546
500	13.078	1.22	10.5 m	0.04
250	14.072	2.54	26.4 m	0.055
100	14.036	6.11	266 m	0.23
75	14.01	8.13	610m	0.4
50	13.95	12.1	2	0.9
40	13.88	15.1	4	1.35
30	13.7	19.9	9.25	2.4
25	13.5	23.6	16	3.5
15	12.75	37	69.2	10.4

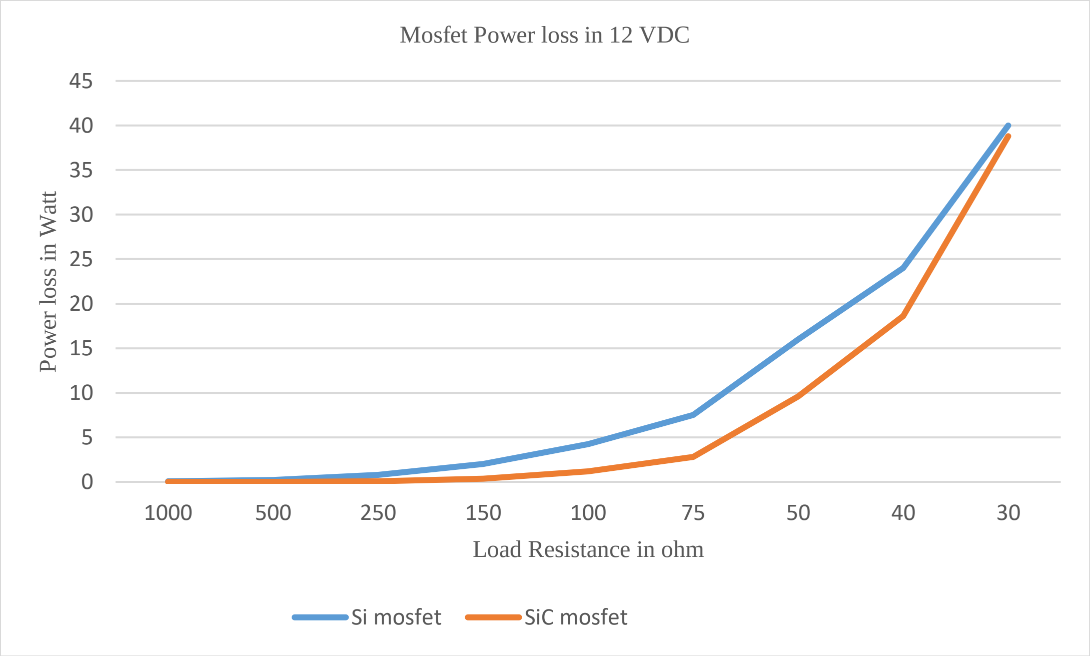

Figure 2 (at 12 VDC MOSFET power loss)

This figure shows the difference between Si MOSFET and SIC MOSFET power loss in the 12 VDC circuit. It's clear that SIC MOSFET has significantly less power loss in comparison to the Si MOSFET. In the R_l there is a difference between 1k ohm and 500 however, it is not very clear due to the low output current. The real difference starts to show when R_l is between 250 ohm and 35 ohm. When R_l reach 30 ohm the loss start to be equal. This is probably because of the nature of the inverter, which is designed for low power and low current application.

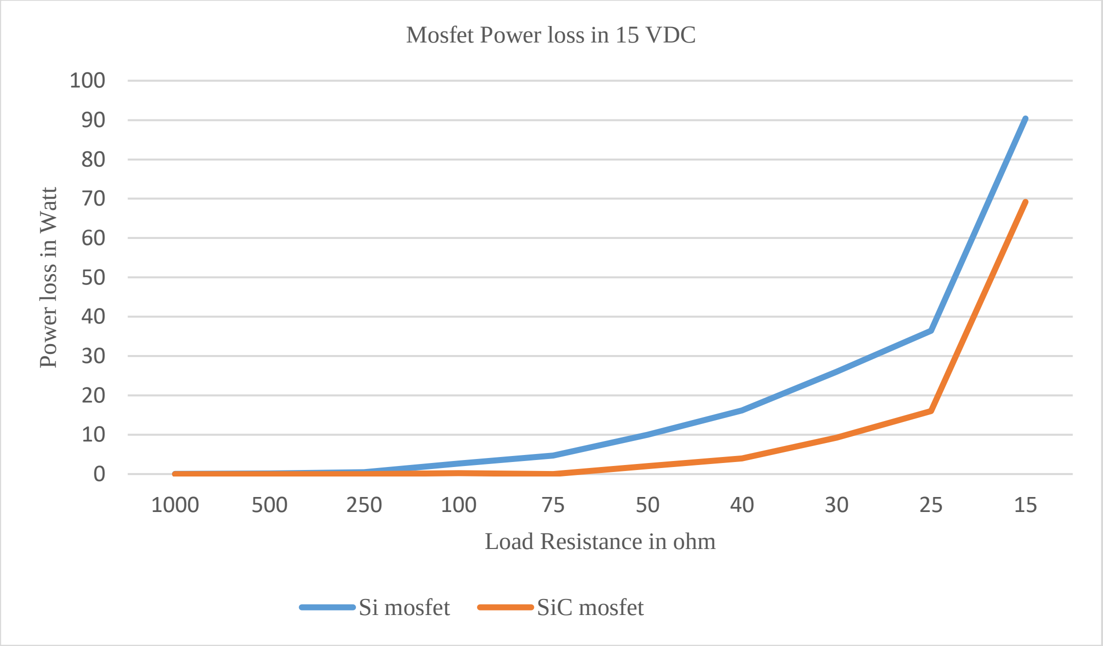

figure 3 (At 15 VDC MOSFET power loss)

Similar to figure 2, Figure 3 shows almost the same result, but there is a small difference in the place where the enhancement of the power loss is clearer. Overall, the power loss in 15 VDC is better in comparison to the 12 VDC and the reason is because V_{gs} is relatively higher and that makes MOSFET more stable and less loss of power. The previous graph shows that the real difference in power loss looks clear between 250 ohm up to 15 ohm. There is sharp a increase in power loss in the 25 ohm output Resistance in both $MSOFET_s$ types because of the nature of the circuit, but it is still quite better in the SiC MOSFET circuit.

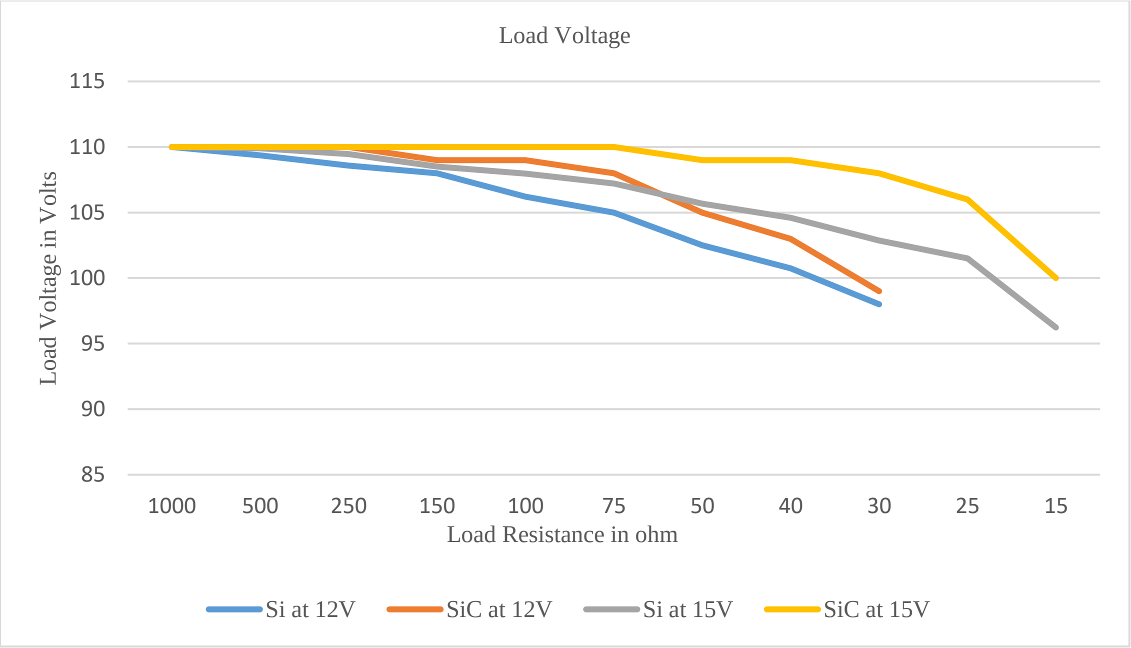

Figure 4 (Load Voltage Comparison)

Figure 4 shows that using Silicon MOSFET enhances Load voltage stability in high current cases. In 12 VDC cases there is up to 3 volts difference between Si and SIC cases. In the 15 VDC the enhancement looks clearer ,and in the 30 ohm load there is more than 6 volts difference between Si and SiC MOSFET.

6. CONCLUSION

In this paper, a simulation for a push-pull dc-ac inverter is obtained using both silicon and silicon carbide power MOSFET. Output voltage, current and power loss was obtained and compared between the two models. The simulation program used in this paper is NI multisim which is used to obtain all parameters above. The SiC MOSFET model was created using the Model wizard in the NI multisim simulation program. The data used to create the model was taken from www.rohm.com.

The results show that using Silicon Carbide MOSFET enhances the output voltage in cases of the load current increasing as well as increases the efficiency of the inverter and decreases the power loss of the circuit, This will improve the design, save money, and decrease the size of the circuit.

7. FUTURE WORK

Another type of DC-AC inverter will be simulated using Wide-Bandgap semiconductors and will compare results to push-pull inverter results. Trying different kinds of SiC power MOSFET as soon as they are released from manufactured companies to find the optimum results will be tried as well.

8. ACJNOLDGMENT

This work is done under help and Supervision of Dr. M. Matin, a Professor at the University of Denver, Electrical and Computer Engineering Department, Colorado, USA.

9. REFRENCES

1- S.S Shema, I. Daut, Syafwati A.N, M. Irwanto, Shwatri C " Simulation of Push-Pull Inverter for Photovoltaic application via Multisim, The 5th International power Engineering and optimization Conference (PEOC2011), Shah Alam, Selangor, Malaysia:6-7 June 2011.

2- Rajenrda Pratap, R.K Singh, Vineeta Agrwal, " Spice Model Development for SiC power MOSFET" ,2012 IEEE International conference on power electronics, Drives and Energy systems December 16-19, 2012 Bengaluru, India.

3- Multisim Component Reference guide by NI Multisim

4- Hsin-JU Chen, "Power losses of Silicon Carbide MOSFET in HDVC Application".

5- IRFP260n data sheet http://www.infineon.com/dgdl/irfp260n.pdf?fileId=5546d462533600a4015356289dcf1fe2 (accessed in 5/12/2016)

6- SiC power MOSFET datasheet http://www.wolfspeed.com/media/downloads/165/C2M0040120D.pdf (accessed in 5/18/2016)

7- B. Ozpineci and L.M. Tolbert, "Comparison of Wide-Bandgap Semiconductors for Power Electronics Application".

8- US Department of Energy Brochure in Energy Efficiency& Renewable Energy/ Advance Manufacturing office.

9- Jose Millan and Philippe Godignon, "Wide BandGap Power Semiconductor Devices". IBM-CNM-CSIC

10- Yustin Cui, Madhu Chinthavali, Leon M. Tolbert, "Temperature Dependent Pspice Model of Silicon Carbide Power MOSFET".

11- Nando Kaminski, Oliver Hilt, " SiC and GaN Devices-Wide Bandgap is not all the same".

12- K.H Edelmoser , L.L Erhartt, " Simulation of Multiphase DC-to-AC Power Inverter System".