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Evaluation of Losses in HID Electronic Ballast Using Silicon Carbide MOSFETs

Thesis

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Master of Science Degree

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Lakshmi Reddy Gopi Reddy

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Abstract

HID lamps are used in applications where high luminous intensity is desired. They are used in a wide range of applications from gymnasiums to movie theatres, from parking lots to indoor aquaria, from vehicle headlights to indoor gardening. They require ballasts during start-up and also during operation to regulate the voltage and current levels. Electronic ballasts have advantages of less weight, smooth operation, and less noisy over electromagnetic ballasts. A number of topologies are available for the electronic ballast where control of power electronic devices is exploited to achieve the performance of a ballast for lighting. A typical electronic ballast consists of a rectifier, power factor control unit, and the resonant converter unit. Power factor correction (PFC) was achieved using a boost converter topology and average current mode control for gate control of the boost MOSFET operating at a frequency of 70 kHz. The PFC was tested with Si and SiC MOSFET at 250 W resistive load for varying input from 90 V to 264 V. An efficiency as high as 97.4% was achieved by Si MOSFET based PFC unit. However, for SiC MOSFET, the efficiency decreased and was lower than expected. A maximum efficiency of 97.2% was achieved with the SiC based PFC. A simulation model was developed for both Si and SiC MOSFET based ballasts. The efficiency plots are presented. A faster gate drive for SiC MOSFET could improve the efficiency of the SiC based systems.

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Chapter 1

Introduction

Direct lighting is one of the largest users of electricity. It amounts to 8.2quads or 22% of all the electrical energy in the US. In addition, it is one of the growing users of electrical energy. The cost of lighting is over $12 billion a year. This is the cost to individuals, families, businesses, and government agencies to light homes, offices, factories, sporting stadiums, roadways, streets, and airports. The total US site lighting consumption is 765 Terawatt-hours/year. Figure 1.1 is a pie diagram indicating US lighting energy usage in 2001. The commercial sector uses the largest part of lighting which is about one half (51%) of the lighting energy. The second largest sector is the residential housing sector using over a quarter (27%) of the lighting energy. The industrial sector uses about 14%, while outdoor stations use the remaining 8% of the lighting energy.

Lighting electricity generation incurs huge indirect environmental and direct costs. Indirect environmental costs include environmental pollution due to smog, particulate emissions, acid rains, global warming, waste disposal, and health related illnesses.

A significant amount of energy is spent on lighting in buildings, commercial places, and street lighting. A good lighting system should ensure comfort, economy, and innovation. The design of a building depends on the lighting to achieve the desired effect and function, both inside and outside. Lighting can be classified based on the purpose of its use into four types-commercial lighting, industrial lighting, architectural lighting, and decorative lighting.

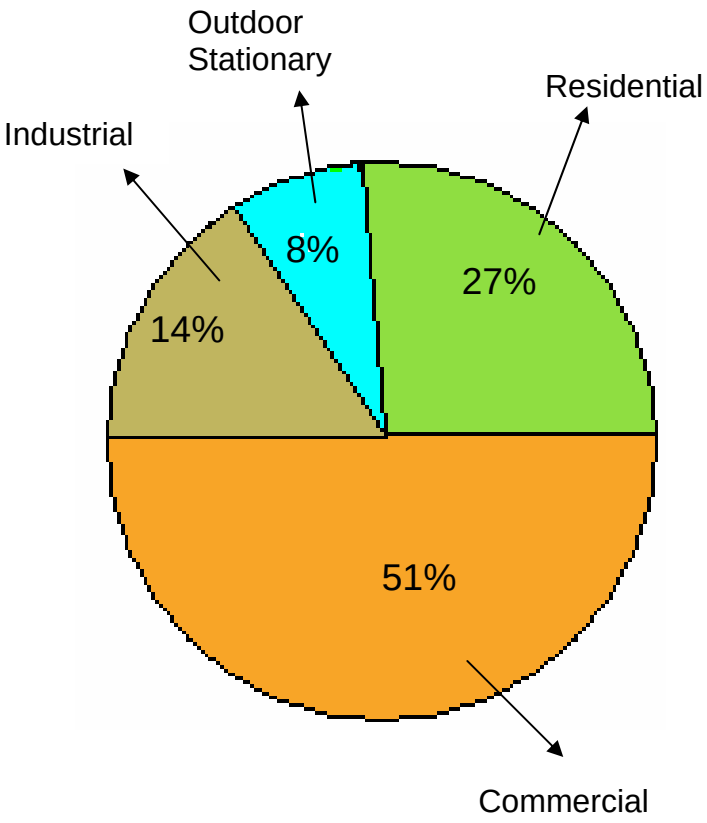


Figure 1.1 US lighting energy used by sector in 2001

1.1 Types of lamps

There are four types of lamps which are described below.

Incandescent lamps: They are the most common lamps with numerous applications as light sources in homes, shops, and other commercial environments. A thin filament, most commonly tungsten, glows when current is passed through it producing heat and light. They have many advantages: low initial cost, excellent color reproduction qualities, and good optical central over spread and direction of light, flexibility and versatility, with no need for electronic starting or control systems. However, incandescent lamps are wrought with short life (around 1000 hours) and less luminous efficiency- only 5% of the energy is illuminated as light the remaining 95% as heat.

Halogen lamps: They are high output light sources. They use halogen gas to improve life of the lamp and also burn brightly. Advantages of Halogen lamps include longer life (about six times of life expectancy of incandescent lamps), whiter light, and better beam control, direction of light, and compact.

Fluorescent lamps: Fluorescent light is produced when the phosphor coating converts UV light to visible light when a gas discharge is created in the tube. Advantages are due to large surface area that ensures more diffused and directional light. Proper choice of coatings is necessary to obtain low initial cost, improved color rendering, and energy savings.

High Intensity Discharge lamps: HID lamps produce light when an electric arc is produced across tungsten electrodes inside fused quartz or alumina tube filled with gas

and metals. The gas helps in starting while the metals produce light when heated to evaporation forming plasma.

Ballasts are required to start HID lamps. While some of the lamps are started using high voltage pulses, mercury vapor and metal halide lamps are started using another electrode near one of the main electrodes.

Applications: When high lighting over large areas, high efficiency and luminous intensity are desired, HID lamps find their use. Gymnasiums, large public areas, warehouses, movie theaters, outdoor activity areas, roadways, parking lots, residential areas, indoor aquaria, indoor gardening, etc. are some of the places where HID lamps are used.

HID lamps are being used as vehicle headlamps. They are also being used on Airbus and other aircraft for landing and taxi lights.

Types of HID lamps:

1) Metal Halide lamps: Offers high energy efficiency, white light, and excellent color reproduction.

   Applications: retail displays, high bay industrial areas, sports lighting, and flood lighting.

   Advantages: efficient compared to mercury and incandescent lamps.

   Disadvantages: Specially designed ballasts used, short life among HID lamps, horizontal operation reduces lamp life.

2) High pressure sodium lamps: long term economics, efficient.

   Applications: large parks, shopping centers, roadways and amenity areas.

Advantages: most efficient among HID lamps, warm-up time is the shortest, long lamp life.

Disadvantages: requires ballast, time taken to reach full output is considerably high (five to ten minutes). Ballast maintenance problems might limit life.

3) Low pressure sodium lamps: extremely efficient, economic operation over long periods.

Applications: best suited for street lighting.

Advantages: the most energy efficient, restart immediate, uniformity of light distribution.

Disadvantages: poorest color rending, expensive to install, wattage increases during lifetime.

4) Mercury Vapor: Produces light when current passes through mercury vapor

Applications: Industrial applications and outdoor lighting.

Advantages: more efficient than incandescent lamps, wide range of ratings, colors and sizes, low unit cost, high average life.

Disadvantages: least efficient among HID, special ballast for dimming required, maximum warm-up time, restart time.

1.1.1 Lighting System in US and HID Lamps

HID lights find their applications mainly in industrial lighting which form, as already mentioned, about 14% of the total lighting in US in 2001, as high bay warehouse lighting. In outdoor stationary sector (8% of total lighting in 2001), HID lamps account for 87% of electricity of which 54% is used by roadway lighting and parking lots use

39%. Well lit parking areas create a sense of personal safety, attract customers, and facilitate better traffic flow, improving economic development and deterring crime and vandalism.

1.2 Ballast

The ballast is used to control the starting and operating voltages for the lamp. It is usually required for gas discharge lights: fluorescent, neon lights and High Intensity Discharge lamps. It can be as simple as a resistor or as complex as power electronic circuit.

The discharge lights have negative resistance i.e., as temperature increases, their resistance decreases thereby increasing the current flow through them. Hence, a ballast is used to control the flow of current and protect the light. Small lights use passive components which are run by less or almost no power.

During the starting of the lamp, high voltage is required to establish an arc between the two electrodes and as the arc is established, the voltage should be reduced and current regulated to produce steady light output. These functions are achieved with the help of a ballast.

The life of a lamp is dependent on the electrode temperature, and maintaining an optimum temperature ensures that the lamp lasts long. This can be achieved by using a separate unit to provide low voltage during starting and typical voltage during the normal operation.

For maximum utilization of the lamp at rated output and life, it is advisable to match the electrical characteristics of the lamp with that of the ballast. Conventionally, to

ensure maximum utilization, ballasts are designed to operate at a specific voltage, for a specific lamp type, and specific number of lamps.

For efficient lamp-ballast system, the efficiency of the ballast has to be increased by decreasing the losses. The ballasts for fluorescent lamps include the features of preheating, instant start, and rapid restart. In a preheat ballast, a starter preheats the lamp filament before starting voltage to arc the lamp is provided. During operation, the power from the filaments is removed to minimize losses. Instant start ballasts do not need filament power, but instead need high starting voltages to start the lamp instantly. In rapid start ballasts, the filament is heated continuously as the lamp is started and operated. A separate starter is not required for instant and rapid start ballasts.

1.2.1 Types of Ballasts

Ballasts can be classified into three types: resistive ballasts, electromagnetic ballasts, and electronic ballasts.

Resistive ballasts are the most primitive and simplest of ballast types. Earlier automobile ignition systems used resistors as ballasts to regulate the ignition voltage. The resistor can be fixed or variable. A fixed resistor is used for simple, low-powered loads such as a neon lamp. The large ballast resistance dominates the resistance of the lamp even during its operation in negative resistance and limits the current flow through the lamp. Self variable resistors act like positive resistances to compensate for the negative resistance of the lamp.

Advantages: simple.

Disadvantages: high power losses (for lamps, no precise control).

Electromagnetic ballasts use the principle of electromagnetic induction to provide starting and operating voltages. An inductor is used to generate the necessary electromagnetism. In an ideal or theoretically perfect reactance, no power would be lost while limiting the current flow; realistically, losses due to resistance can only be minimized, not eliminated entirely. Usually, these ballasts are used to power fluorescent lamps, neon lamps, and HID lamps. For high power applications, the ballast can include an igniter also.

Electromagnetic ballasts limit the flow of current to the light but do not change the frequency of the input power. Hence a flicker is introduced in the light. The rate of flicker is twice the frequency of the power source at 100Hz or 120Hz. A lead-lag lighting ballast can minimize flicker when connected to two lamps by alternating the flow of current to them: one leading the frequency of the input power and the other lagging behind it.

Advantages: Minimal losses in the inductor; the sudden change in current produces a voltage spike which can be used to strike an arc to light the lamp; longer ballast life.

Disadvantages: phase difference between current and voltage introduced resulting in poor power factor, bulky, low efficiency, high starting current, flickering, noisy and single use restriction.

Electronic ballasts start and regulate fluorescent lamps with solid state electronic circuitry rather than the traditional core and coil assembly. They can alter frequency as high as 20 kHz -1MHz. Operation at high frequency has two advantages: improved efficiency and elimination of flickering in the lamps completely. Due to the absence of

magnetic coils, losses are reduced and hence higher efficiency and cooler operation as compared to electromagnetic ballasts is achieved.

Advantages: higher efficiency, high frequency operation, cooler operation, less weight, less noise, no flicker.

Disadvantage: complex circuitry.

1.2.2 Electronic Ballasts for HID Lights

HID lamps make a major impact on lighting and energy consumed in lighting. The HID lighting systems can be made more efficient by improving the ballast energy efficiency and by providing flexible energy saving service features. Therefore an opportunity to provide an impact on the illumination efficiency of the mentioned lighting sectors is significant. Innovative power electronics technology and optimum circuit design are considered to improve efficiency of the ballast in the power range of HID wattage.

1.3 Semiconductor Materials

Silicon is the most commonly used material for making semiconductor devices because it is freely available in pure form. There are materials that exhibit superior properties than Silicon. Gallium Arsenide (GaAs), Silicon Carbide (SiC), and diamond are some of those materials that are being tested for different characteristics superior to Silicon.

Disadvantages of Silicon based semiconductor devices acting as switches are:

- They are thwarted with limited breakdown voltage and power ratings.

- Limited junction temperature
- Limited switching frequency for power ratings more than a few tens of kilowatts.

1.3.1 Wide Band Gap Materials

The present day Silicon technology cannot meet all the application requirements (especially high voltage and temperature). Wide band gap semiconductors have several advantages.

- The potential difference between the valence band and the conduction band in wide band gap semiconductors is greater than that of Silicon; this allows the device to withstand higher electric field than that of Silicon.
- Higher breakdown electric field allows higher doping levels which in turn results in
    a) lower conduction on-resistance, thereby higher efficiency
    b) Less number of devices required in series to achieve high breakdown voltage.
    c) Thin wafers that occupy less space.
- Wide band gap materials have higher thermal conductivity as compared to Silicon. It means it is easier to remove heat from these materials in high temperature applications.
- Forward and reverse characteristics vary slightly with temperature, therefore are more reliable.
- High temperature operation capability as high as 10 times that of Silicon.

However, wideband gap semiconductors also have disadvantages.

- The manufacturing processes are less efficient. Low yield is obtained because of defects such as micropipes.

  Micropipes are defects in the crystalline structure that cannot block voltage and leads eventually to short circuit. Defect density presently is in the range of 1 to 10/cm^2.

- Expensive because of low yield and limited availability.
- High temperature packaging techniques are required to take advantage of high junction temperature rating. Such packaging techniques are not yet available.

Table 1.1 shows the properties of different semiconductor materials potential for power devices.

Table 1.1 Comparison of properties of different semiconductor materials

Property	Si	GaAs	3C-SiC	6H-SiC	Diamond
Band gap at 300K (eV)	1.12	1.43	2.2	2.9	5.5
Relative Dielectric constant	11.8	12.8	9.7	10	5.5
Breakdown electric field(V/cm)	3×10^5	4×10^5	4×10^6	4×10^6	1×10^7
Thermal conductivity (W/cm-^oC)	1.5	0.5	5.0	5.0	20
Maximum operating temperature(K)	300	460	873	1240	1100
Melting temperature(^oC)	1415	1238	Sublime >1800	Sublime >1800	Phase change 2200
Electron mobility at 300K(cm^2/V-s)	1400	8500	1000	600	2200
Specific drift resistance (ohm/cm^2)	1	6.4×10^{-2}	9.6×10^{-3}	9.6×10^{-3}	3.7×10^{-5}
Drift region doping density for 1000V step junction	1.3×10^{14}	5.7×10^{14}	1.1×10^{16}	1.1×10^{16}	1.5×10^{17}

1.3.2 Silicon Carbide

Rapid advance in Silicon Carbide technology and better performance of SiC as compared to GaAs for power devices makes it more viable for power applications. SiC Schottky diodes, JFETs and MOSFETs are being experimentally tested for their superior characteristics.

Silicon carbide is the most mature of wide band gap semiconductors. Its advantages over Silicon are listed below.

- The specific drift region resistance of SiC based devices is 0.001 times that of Silicon.
- For a 1000V step junction fabricated in Si and SiC materials, the drift region doping density of SiC is 100 times that of Silicon, the width of the drift region is reduced to 1/10 th that of Silicon.
- SiC can operate at temperatures as high as 600^{o}C while silicon devices can withstand temperatures as high as 150^{o}C.
- SiC devices have higher breakdown voltages of about 5 to 30 times that of Silicon.
- They have higher thermal conductivity and thus lower junction to case thermal resistance.
- SiC devices are thinner, have lower on-resistances. Higher concentration of doping results in lower series resistance. Unipolar SiC devices have on-resistances almost 100 times lower for low breakdown voltages and for high breakdown

voltages, on-resistance is around 300 times lower. With lower on-resistance, SiC unipolar devices have lower conduction losses and hence high overall efficiency.

With these advantages of Silicon Carbide devices, the use of SiC devices in the ballast circuit is being considered for improved efficiency.

This project explores the possible effect on efficiency by using Silicon Carbide devices in the electronic ballast system. An electronic ballast circuit using special material components to reduce losses for HID lamps is proposed to achieve an "ultra" high efficiency of 96 %. The first stage of the ballast which is the power factor correction boost converter has demonstrated an efficiency of 98% using Si MOSFET as the switch. Efficiency of the ballast using SiC MOSFETs has been studied. The second stage of the ballast, a DC to high frequency inverter is being designed by Epic Systems Inc. to achieve 98% efficiency. Thus the overall efficiency of the ballast is expected to be 96%.

1.4. Chapters' Description

Chapter 2 describes the basic topology of an electronic ballast. It presents the various types of ballasts and presents the literature review on the various methods proposed.

Chapter 3 presents the overview of the project. It also describes the mathematical modeling of the loss system and describes the simulation methodology. The simulations in PSIM and MATLAB are discussed in detail.

Chapter 4 presents the experimental setup. The simulation and experimental results are compared and analyzed.

Chapter 5 comprises the conclusion and the prospective future work in the design of the ballast system.

1.5. Summary

This chapter briefly introduces the various lighting systems. It discusses the basics of a ballast, different types of ballasts, and the advantages of electronic ballast. It also presents an overview of the various semiconductor materials and some advantages of Silicon Carbide over Silicon. Finally it presents a preliminary overview of the project. The overview of the chapters to follow is also presented.

Chapter 2

Literature Review

This chapter describes the main components of the ballast circuit in detail. Section 2.1 is an introduction about the components of the electronic ballast. Section 2.2 describes briefly the electromagnetic interference (EMI) filter, while section 2.3.describes the basic Power Factor Corrector (PFC) design and also the simulation modeling of PFC and the different types of power factor correction methods. Sections 2.4 and 2.5 briefly outline inverter and resonant filter functioning in the electronic ballast. Previous literature is summarized in section 2.6, and section 2.7 presents the SiC technology used in electronic ballasts.

2.1. Introduction to Electronic ballasts for HID lamps

High starting voltage is required to strike a lamp, and it is necessary to regulate the arc currents during steady state operation. These functions are provided by a ballast. Electronic ballasts are widely used because of their light weight, small size, and higher efficiency.

Electronic ballasts can be divided based on the output wave shape and frequency as:

Direct current ballast: These are used with lamps operating with direct current.

Low frequency ballast: These are used with lamps operating at square wave output with a frequency between 50 Hz and 400 Hz.

High frequency ballast: These are used for lamps operating at high frequencies of 19 kHz to 100 kHz.

Very high frequency ballast: For frequencies above 100 kHz, these ballasts are used. The lamps are known to operate until 1000 kHz.

The basic electronic ballast circuitry can be divided into sections based on the function each section does. Figure 2.1 demonstrates the block diagram that can be used to describe an electronic ballast system. The components of the ballast include:

1) AC/DC converter

2) EMI filter

3) Power factor correction converter

4) Inverter

5) Passive filter.

AC-DC power converters are used increasingly due to high efficiency and smaller size and weight. The diode bridge rectifier is the most popular AC/DC converter whereby the input sinusoidal voltage is converted to dc voltage. The ripple in the output voltage is

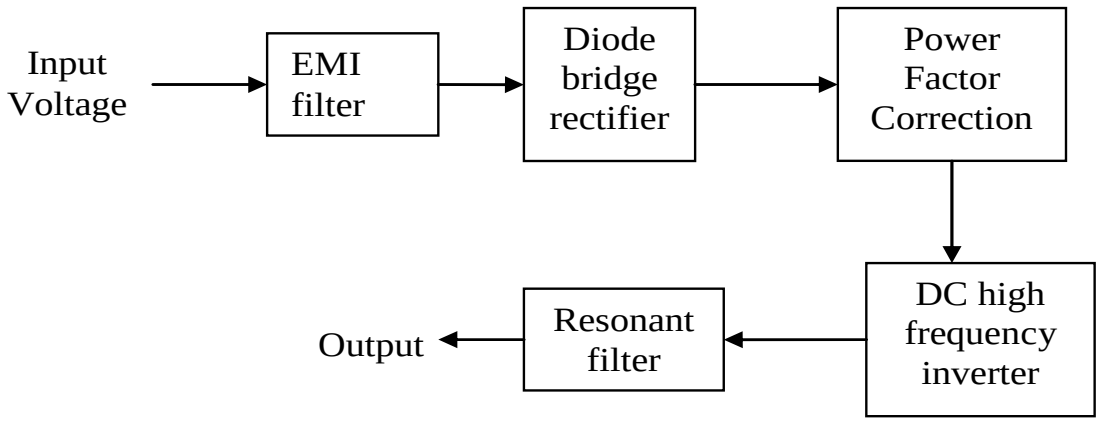


Figure 2.1 Basic block diagram of an electronic ballast for lamps

reduced by a large filter capacitor at the rectifier output. Because of this large capacitor, the current drawn by the converter is rich with lower order harmonics. With proliferation of converters, pulsating input current is drawn from the input line. To limit low order harmonics and low power factor (current distortion), utilities enforce regulations to maintain power quality [3]. So, the design of the converter should be such that the power factor is closer to unity and the input current distortion is minimal.

2.2. EMI filter

Electromagnetic interference filter plays an important role in reducing the total harmonic distortion and hence improving the efficiency. This filter can prevent the radio frequency interference of the circuit with other adjacent circuits.

It comprises of two small inductors of the order of milliHenry, a toroidal ferrite, capacitance of the order of 0.1 microFarads, and two capacitors of the order of nanoFarads, a huge resistance of the order of megaohms and a varistor to protect from over voltage. Figure 2.2 shows the basic structure of an EMI filter.

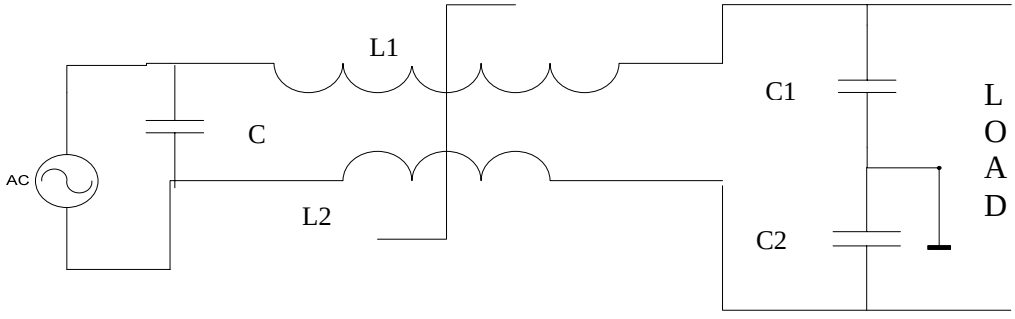


Figure 2.2 EMI filter

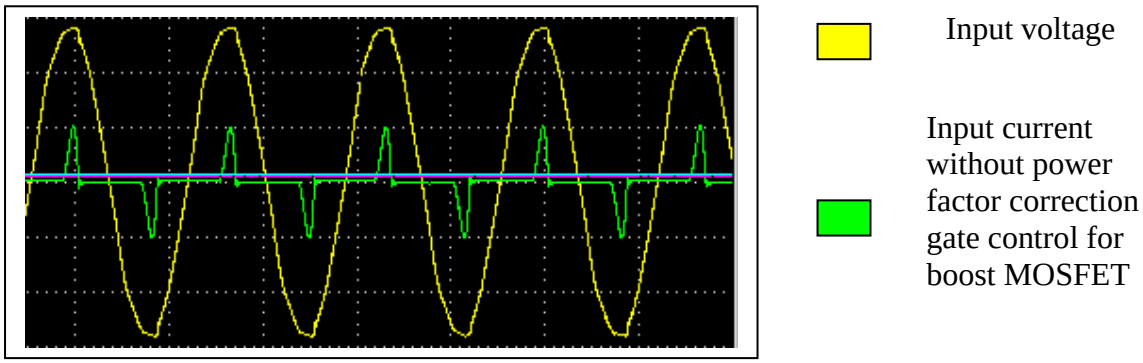


Figure 2.3 Current and voltage waveforms without PFC gate control for boost MOSFET

2.3. Power Factor Correction

The simplest AC-DC converter is a diode bridge rectifier with a capacitor filter. Some of the single phase switch mode power supply units use this conversion unit. However, this is thwarted by limitations-

(i)The output voltage cannot be controlled due to the output capacitor and changes with output current.

(ii)The power factor is very low in the range of 0.6-0.8. High line current distortion is the main drawback of this scheme.

To improve power quality, Power Factor Correction (PFC) schemes are proposed. As the name suggests the PFC circuit ensures that input current follows the input voltage thereby correcting the power factor, and maintaining unity power factor. Figure 2.3 demonstrates the input waveforms in the absence of PFC control of gate to boost MOSFET. The operation of the PFC circuit is better explained based on the type of circuit it is made of. Based on the type of components used, PFC circuits can be classified as [3]:

a) Passive power factor correction technique

b) Active power factor correction technique

Passive power factor correction circuitry realizes power factor correction with the help of passive components, inductor and capacitor. It is usually an LC filter inserted between the AC input mains and the input of the diode bridge rectifier. Figure 2.4 shows the basic circuit design of a passive PFC circuit.

Advantages: Passive PFC technique is simple, rugged and robust.

Disadvantages: They are bulky and heavy. The power factor cannot be very high.

In active power factor correction, at least a single switch i.e., switched mode power supply technique, is used to shape the input current in phase with the input voltage. It is usually a dc-dc converter inserted between the output of the diode bridge rectifier and the load. Figure 2.5 shows the basic circuit design of a passive PFC circuit.

Advantages: It is smaller in size, light weight. Reduced harmonics and higher power factor are achieved as compared to passive PFC technique.

Disadvantages: The switching losses reduce the overall efficiency. The switching control scheme is complex and also consumes significant amount of power. Relatively high cost is another drawback of this technique.

The DC-DC converters are classified depending on the output as

1) Buck

2) Flyback

3) Boost

4) Cuk

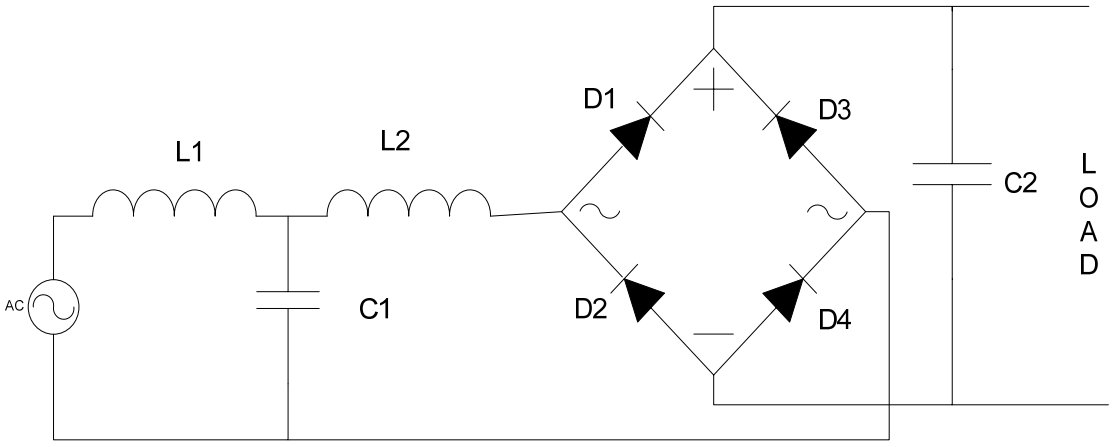


Figure 2.4 Passive Power factor correction circuit

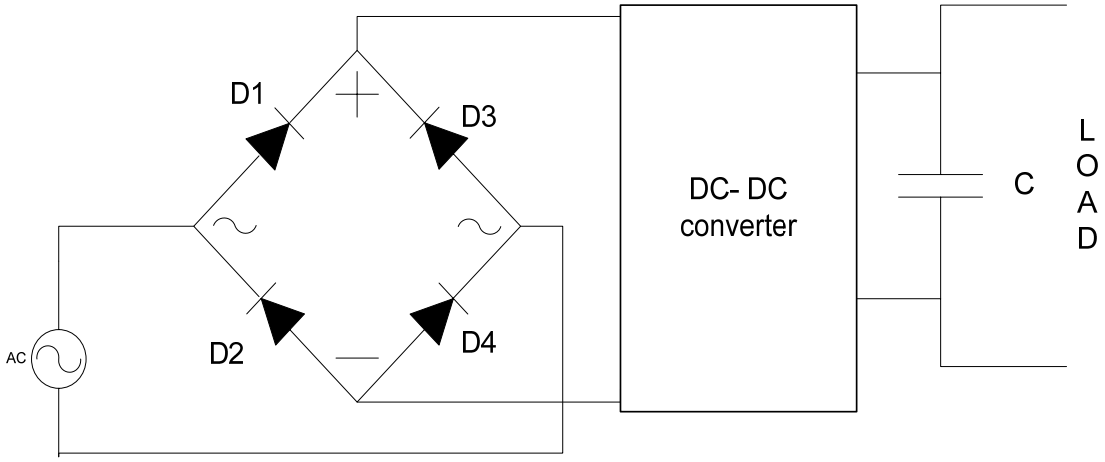


Figure 2.5 Active power factor correction circuit.

Buck converter is used when output voltage lower than the input is desired. Higher EMI is produced due to discontinuous input current. It is not efficient for power factor correction. Flyback topology is used in applications where the output voltage can be isolated and be higher or lower than input voltage. But higher switching voltage and discontinuous input current limit its use as PFC topology.

The boost converter topology is the most commonly used topology for power factor correction. It is used when the output voltage is higher than the input voltage. Current mode control is easy and less EMI is generated. However, isolation of input and output is not achieved.

Cuk type of topology ensures that the input current is continuous even though it operates in discontinuous conduction mode. However, it is limited by increased voltage and current stress.

Based on the switching technique for maintaining the power factor, the active power factor correction can be classified further into

a) Pulse Width Modulation (PWM) PFC

b) Resonant PFC and

c) Soft switching PFC.

In PWM PFC technique, the device is switched based on pulse width modulation. The switching frequency is constant, but the turn-on and turn-off times are variable.

Advantages: simple, easy to control and low current and voltage stresses.

Disadvantages: significant switching losses.

In a resonant converter, as the name suggests, the resonance of the inductor and capacitor determines the time of switching on and off. Gain-boosting characteristic

ensures power factor correction. Variable switching frequency can be obtained using resonant converter topology. However, they have higher voltage and current stresses as compared to PWM mode.

Soft switching PFC is a combination of both resonant and PWM mode with additional resonant tank circuit and a switch. The converter operates in PWM mode for most of the time and in resonant mode during switching on and off intervals. It operates at constant frequency. Improved efficiency and power factor is obtained by this technique. Figure 2.6 demonstrates the various types of PFC design [4].

2.3.1. PFC Design for Simulation

For 50-60Hz, passive and active techniques have been proposed. The active power factor correction technique wherein DC-DC converters between diode Bridge and capacitor is efficient. The input voltage and the average input current have same waveforms (sinusoidal). The ripple in the current can be removed by a filter. [22, 23]

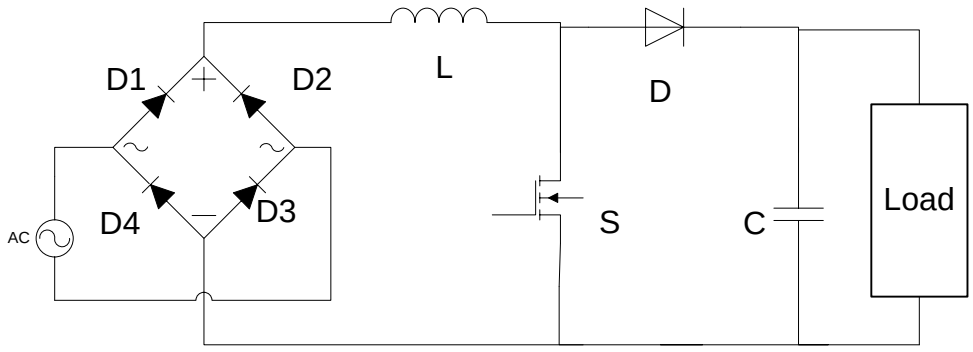
A diode rectifier converts AC to DC while the gate controller switches the MOSFET so as to maintain input power factor. For the control strategy, the two important considerations are

a) the output voltage should be constant and

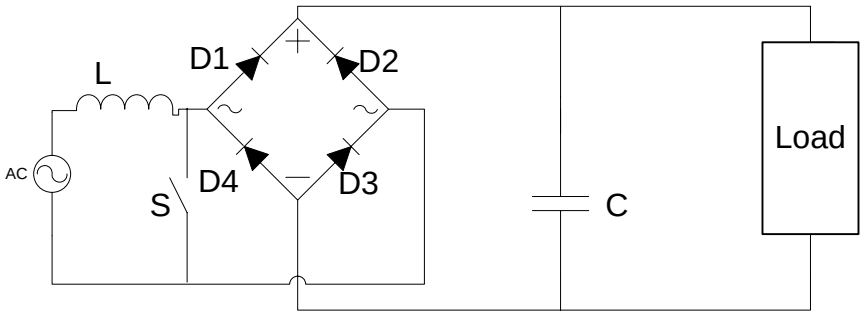
b) the input current must follow the input voltage.

Thus an output feedback loop to control and maintain constant output voltage is required. For maintaining power factor, either multiplier approach or voltage follower approach can be used. In the multiplier approach, the input current feedback loop is programmed from the input voltage so that DC-DC converter operates as a current sink.

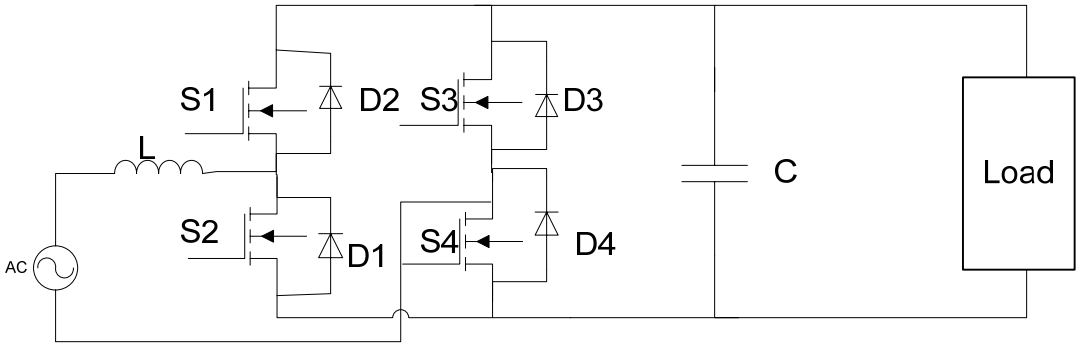
Figure 2.6 General circuit topologies of a single phase PFC with (a) boost, (b) with ac power switch, (c) full bridge type, (d) Zeta type, (e) Sepic type, (f) Cuk type, (g) buck-boost type, (h) semiconductor type, (i) half bridge type, (j) semiconverter type 1


D1
D2
L
D
AC
D4
D3
S
C
Load

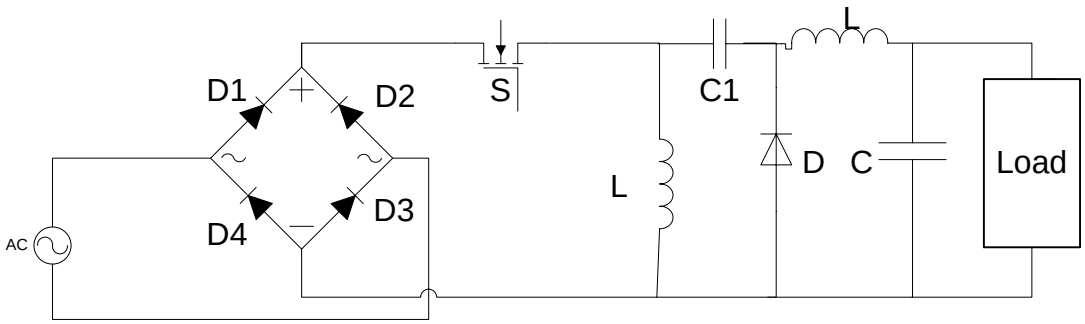
(a)


L
D1
D2
AC
S
D4
D3
C
Load

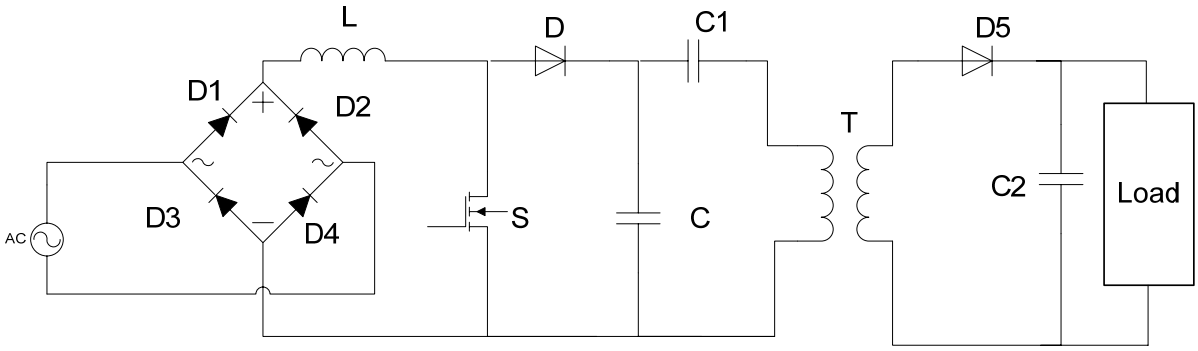
(b)


S1
D2
S3
D3
L
C
Load
S2
D1
S4
D4
AC

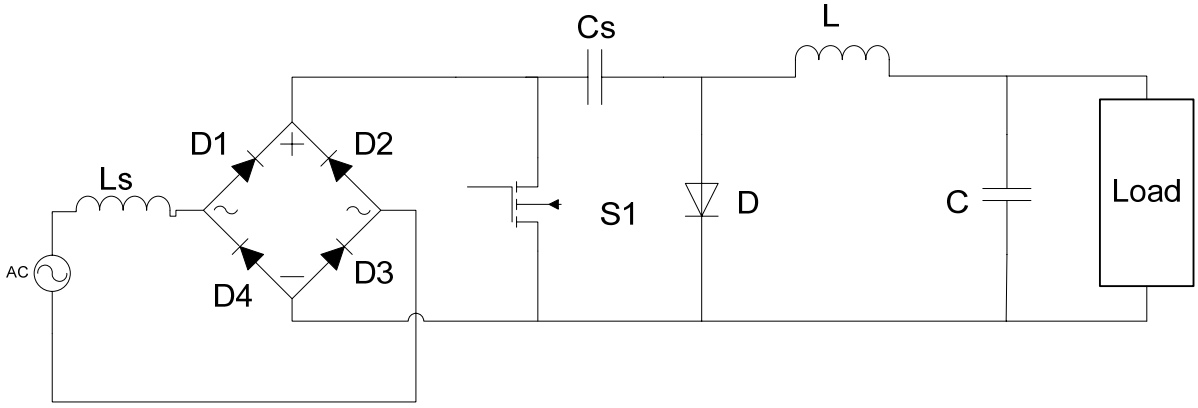
(c)



(d)

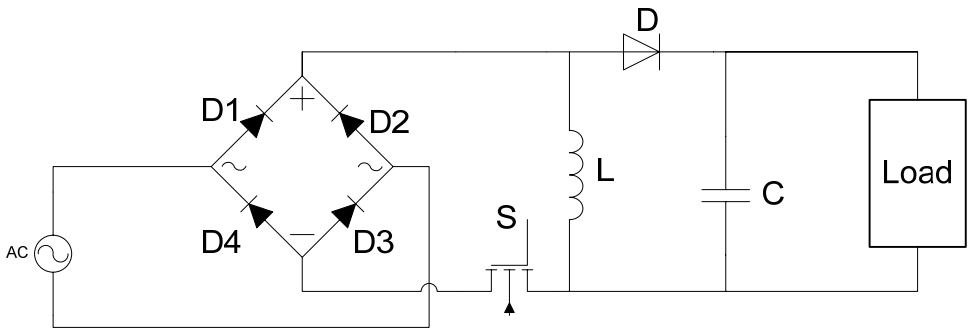


(e)

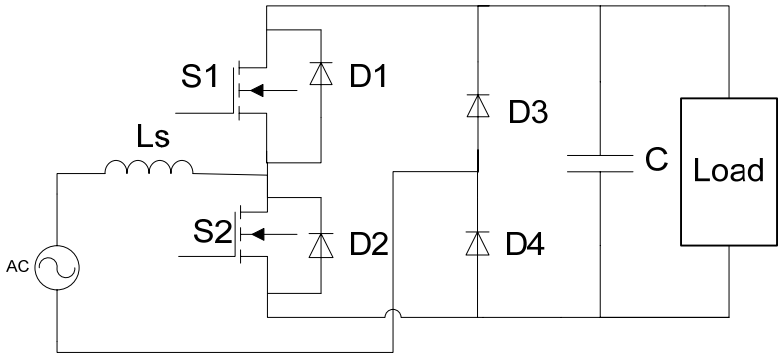


(f)

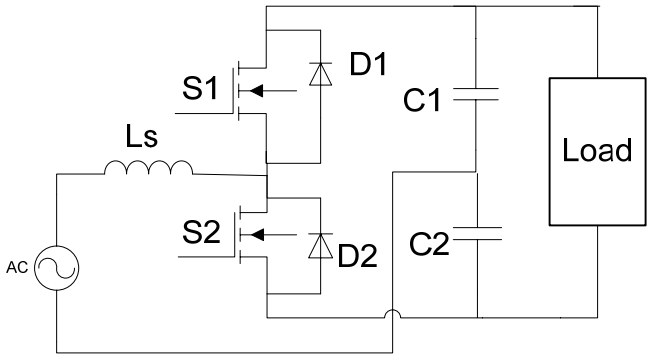
Figure 2.6, continued



(g)

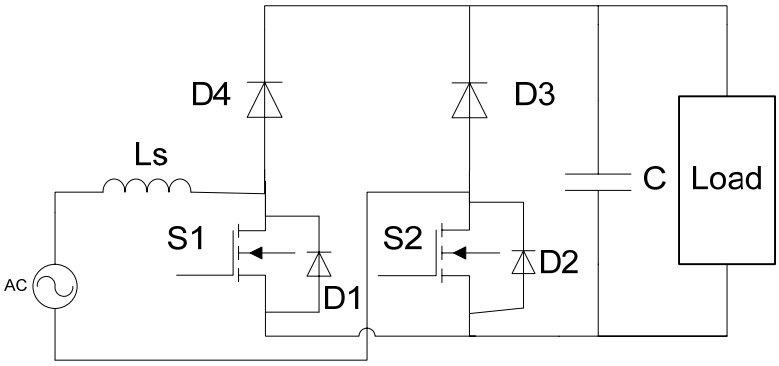


(h)



(i)

Figure 2.6, continued



(j)

Figure 2.6, continued

In the voltage follower mode, the DC-DC converter is operated in discontinuous conduction mode or in critical conduction mode. The average input current is proportional to the input voltage when operating in DCM (buck-Boost, SEPIC, Cuk and flyback). Both techniques require a low pass filter into voltage feedback so as to keep the output of the error amplifier constant during each line half-cycle [22, 23].

Multiplier approach can be divided into

(a) Average current control

(b) Peak current control

(c) Variable hysteresis control

Average current control: The inductor current is sensed. It is then filtered by a current error amplifier which drives the PWM. Thus, in the inner current loop, the average input current tends to approach the reference. The converter works in CCM (continuous conduction mode).

Advantages: a) Less sensitive to switching noise as there is current filtering.

b) Better input current waveforms than peak current control method because near the zero voltage crossing the duty cycle is unity (no dead angle in the input current).

Disadvantages: Current sensing complexity.

Peak current control: In this method, the switch is turned on at constant frequency by a clock signal and turned off when the sum of the ramp of the inductor and external ramp equals the reference sine current. The converter operates in CCM.

Advantages: The switch current is sensed. It can be accomplished by a current transformer.

No current error amplifier

Disadvantages: Sub-harmonic oscillations are present at duty cycle greater than 0.5. Compensation ramp is required.

Control is more sensitive to communication noises.

Hysteresis control: In this method, two current references are produced: one for peak and the other for valley of the inductor current. Switch is turned on when the inductor current is below the valley reference and is turned off when the inductor current is above the peak reference. This also operates in CCM mode.

Advantage: Low distorted input current waveform

Disadvantage: Variable switching frequency

Control sensitive to noises.

These three control methods basically define the type of PFC controller being used for simulation. The average current control mode has been simulated using PSIM.

2.4. Inverter

The output of the PFC circuit is fed into an inverter to obtain high frequency pulses to the output. The topologies are implemented with one, two or four switches [6]. Most of the electronic ballasts use a half-bridge inverter.

2.5. Resonant filter

The output of the inverter is passed through a passive filter to obtain more sinusoidal output. Types of resonant filters:

(a) LC series resonant

(b) LCC series resonant

(c) LC parallel resonant

Figure 2.7 demonstrates the various resonant inverter topologies for a lamp load.

2.6. Previous work

Different types of HID electronic ballasts have been proposed in the literature and their efficiencies modeled [1-15].

Typical electronic ballast with half wave inverter is described in [2]. The core coil type ballast and the electronic ballast with and with out PFC section and EMI section are compared for studying in Tables 1, 2, and 3 of [2]. The newly developed topology in [2] with an igniter circuit ensures lower losses in the ballast and hence better system efficiency. However, the main disadvantage is that the total harmonic distortion is high.

The single stage topology is best suited for low power applications. However, at light loads, there would be high voltage rise which is a limitation to this scheme. Direct transfer topology (DPT) was proposed in which a part of the power is processed once and directly connected to the output while the remaining power is processed twice, one by the PFC and the other by the DC-DC converter before being connected to the output. Thus the system operates in two modes- as flyback transformer at low input voltages and as boost converter at high input voltages. DPT is an effective way of controlling high DC

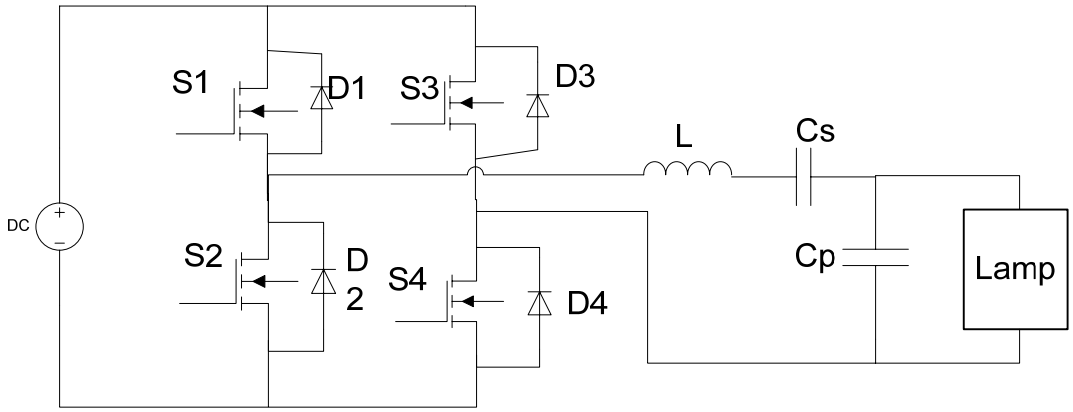


Figure 2.7. (a)

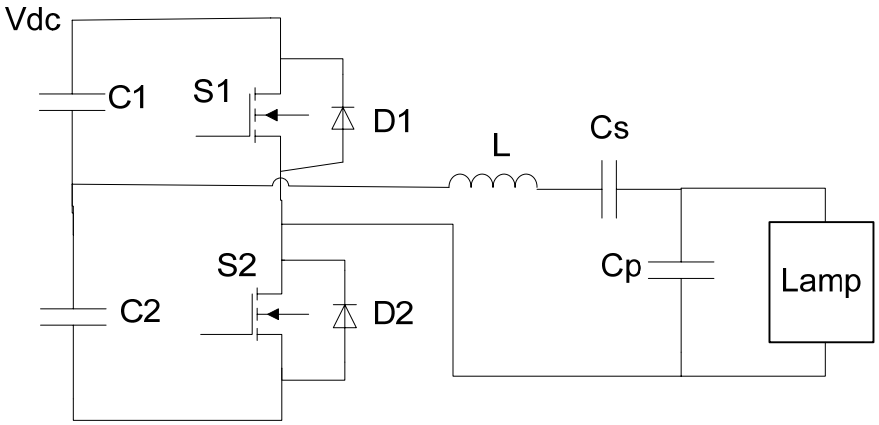


Figure 2.7 (b)

Figure 2.7 The general resonant inverter topologies with lamp load (a) LCC type with full-bridge series resonant inverter, (b) half bridge inverter with LCC type resonance, (c) full bridge inverter with LC type series resonance parallel-loaded inverter (d) LC type with half-bridge parallel resonant inverter, (e) single-ended resonant typed inverter.

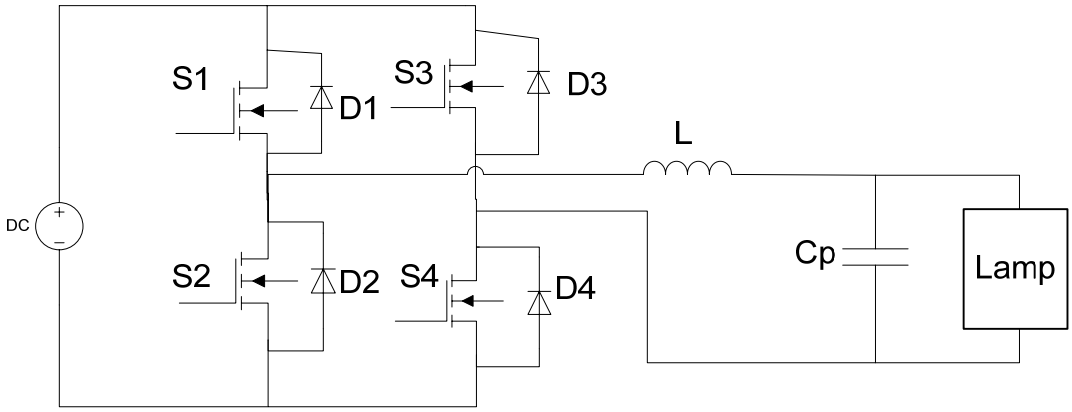


Figure 2.7 (c)

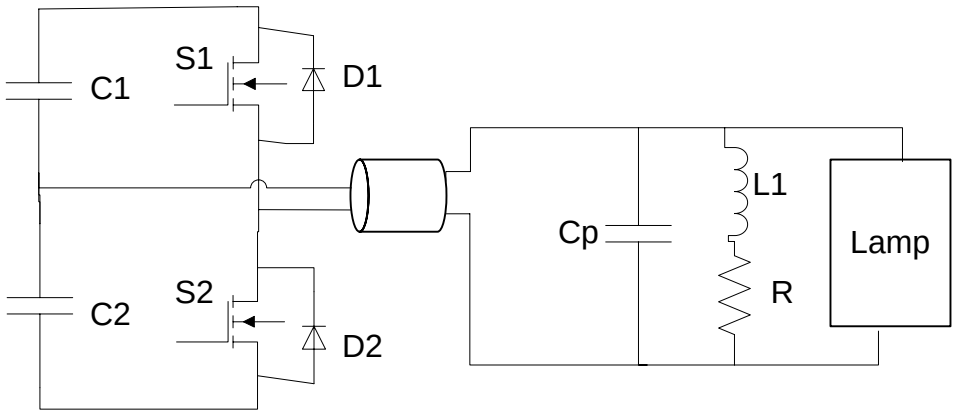


Figure 2.7 (d)

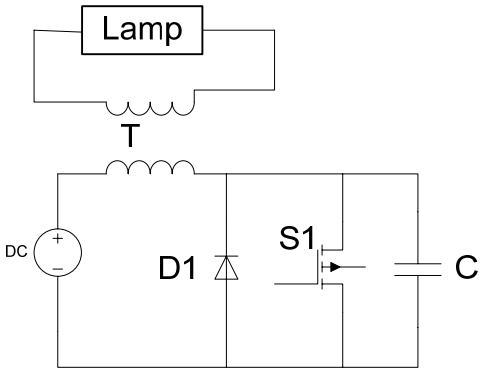


Figure 2.7 (e)

Figure 2.7, continued

link voltage by maintaining high power factor without compromising with high DC bus voltage [3].

A dimming control PFC scheme was achieved in [4] by using a phase shifted PWM for the full bridge inverter of ballast system, wherein variable duty cycle with constant frequency ensures dimming control.

Two common ways to control dimming is to vary duty cycle or switching frequencies. A new method of control was proposed by varying the DC output voltage of the converter. However, the proposed design is for fluorescent lamps [7].

Variable frequency control was used in a new topology with shortened lamp start-up time which resulted in improved efficiency [9].

A PFC ballast for xenon short arc lamps has been proposed wherein the two stage structure with flyback converter coupled to buck converter are used for power factor correction. However, the stress due to the flyback converter and transformer is high and hence a PWM technique for continuous mode operation is being explored [11].

A microcontroller to control the various tasks in the ballast system simplifies circuitry and offers better control. Further, it reduces the warm-up and re-ignition time [12].

The unity power factor parallel resonant electronic ballast suggested in [14] demonstrates the following advantages for 175 Watt metal halide lamp.

(a) Unity power factor and low harmonics

(b) Minimum number of switches

(c) High frequency operation

(d) Low acoustic noise

(e) Improved luminous efficacy.

For higher efficiency, the proposed circuit [14] adopts zero voltage switching. The predominant losses are due to transistor switching losses.

A new type of ballast with a series resonant circuit is described in [13]. In this circuit, the series capacitor is switched into the circuit after the lamp has started. The circuit ensures a sinusoidal turn-on current waveform thereby reducing the switching losses. The lamp current is regulated by controlling the switching frequency of the inverter.

2.7. Benefits of SiC Schottky Diodes

Fast rectifiers allow higher switching frequencies, smaller sizes of the passives and switches, and also limit the need for cooling [15]. Schottky silicon rectifiers are not efficient above 150-200V [15] as they are temperature and high voltage sensitive. Recent advances in semiconductor materials have lead to the fabrication of high voltage Schottky rectifiers.

Higher frequencies ensure reduced size of the passive components, inductor and capacitors; however, this results in higher switching losses. CCM limits peak current stress, and is easy to filter, but the diodes will have higher losses and larger EMI associated with the turn-off boost diode.

The reverse recovery in the diode also shows up in the MOSFET drain current. The reverse recovery current increases with increase in temperature and may lead to thermal runaway. Schottky Diodes have following benefits

- Lack of reverse recovery currents.

- Small stored capacitive charge.

1 MHz switching frequency was chosen because the passive components size is significantly reduced at frequencies less than 150 kHz and the EMI is reduced at 150 kHz. The reverse recovery current in Schottky SiC diode is reduced and the losses in the MOSFET are reduced. Figure 5 of [15] illustrates the losses versus SiC dielectric area.

Air core inductance would result in reduced losses as the core losses are absent, reduced cost, and reduced stray capacitances between cores and wires but it is limited by volume increase, low frequency operation, and oscillations during switching. Two air inductances have been evaluated- one layer and double layer inductances. Single layer inductance had losses, mainly copper losses (~2.48W theoretical) until 15 MHz. However, the volume was 120 cm^3. With double layer, the volume is reduced and so also the losses due to reduction in the length of wires. Magnetic cores had a little higher loss but the size is significantly reduced, and the range of frequencies available is also very high. Experimental results demonstrated efficiencies of 88% to 92% for PFC with 3F3 ferrite material for inductance and with input voltage varying from 90 to 260V for 300W power as shown in Figure 6 of [15].

Two tests were conducted: one to compare ultra fast silicon rectifiers and SiC Schottky diodes, and the other test to evaluate the effect of higher switching frequency. The efficiency improvement for an 80 kHz converter at low line input voltage was about 2% with SiC Schottky diodes. The energy losses in SiC diode is almost 8 times less than that of that of Si diode loss. With high switching frequency, the input EMI filter size is reduced. At low frequencies [50 to 400 Hz], an additional inductance is required to

attenuate below switching frequencies. Table 2 of [16] demonstrates the comparison of EMI filter sizes at 80 kHz and 200 kHz.

The performance of a single phase PFC with SiC MOSFET and BJT in combination with SiC diode was tested in [24]. At 80 kHz, the efficiency for SiC MOSFET and SiC Schottky diode was found to be highest (96.7%) at 150W output power than SiC BJT and SiC Schottky diode combination, and Si CoolMOS and SiC Schottky diode combination. Better thermal capability of SiC power devices was observed as they were tested at frequency of 1MHz, 250W output. Hence the heat sink volume was reduced by 33% with the use of SiC devices. The efficiency of 91.5% for SiC MOSFET and SiC Schottky diode combination was obtained at frequency of 1MHz and 250 W output power.

2.8 Summary

This chapter describes the various types of electronic ballasts. It describes the various sections in the ballast in detail and also presents the previous work done in the design of electronic ballasts. The relevance of this work to the present project will be discussed in the next chapter.

With this background, a new design of the ballast has been proposed. The PFC stage consists of boost converter. Different devices for each section were tested to make sure an efficient system is obtained. Epic Systems Inc. has done several tests to optimize the system. The optimization developed shall be discussed in detail in the next chapter.

Chapter 3

Simulation Model

In this chapter the simulation models to evaluate losses in the electronic ballast are discussed. Two models are used for modeling losses in the ballast –the PSIM model and the mathematical model in Simulink. Section 3.1 briefly describes the model of the ballast that has been designed. Section 3.2 describes the PSIM model that generates the values of current and voltage used in the mathematical model in Simulink described in section 3.3.

3.1. Introduction to PFC Design

The main objective of the project is to design and test an electronic ballast with efficiency as high as 96%. The ballast design has been accomplished in 2 stages. The first stage included the design of the front-end power factor correction (PFC) circuit while the second stage included the design of DC to high frequency (HF) output lamp driver. The PFC stage has been optimized with different design materials and also using SiC devices. The efficiency of the PFC system with Si MOSFET and SiC diode in the boost converter has achieved efficiency as high as 97.6% for different operating input voltages. The second stage DC to HF lamp driver is designed to obtain efficiency as high as 98%. Thus the overall efficiency is about 96%.

Each element in PFC circuit has been optimized to reduce losses. As already discussed, the ballast system consists of an EMI filter, diode bridge rectifier, PFC boost

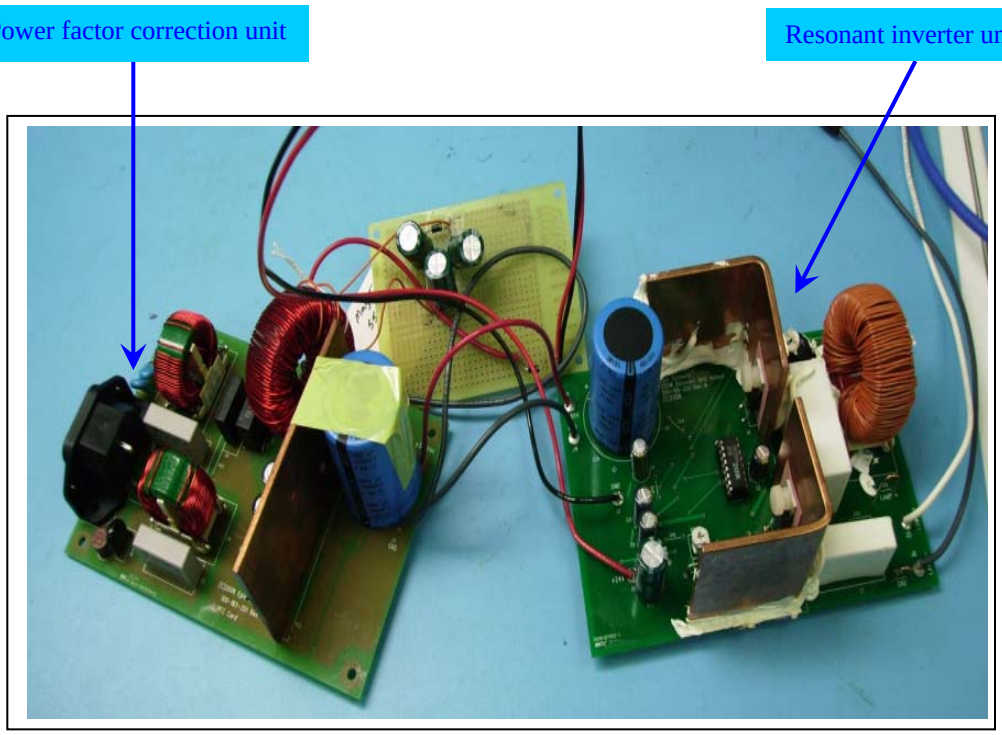


Figure 3.1 Experimental design of the ballast

converter, and inverter with resonant filter. Figure 3.1 demonstrates the design of the ballast assembled by EPIC Systems Inc.

3.2. Simulation Model in PSIM

The input is sinusoidal voltage varying from 90 V to 265 V at line frequency of 60 Hz. The input is fed into a diode bridge rectifier where the ac voltage is rectified to DC. This DC voltage is fed into the boost converter to get a higher output voltage of 385-400V. The PFC control circuit is basically achieved by controlling the gate pulses and duty cycle. For this, the gate signal generating IC is modeled to vary duty cycle so as to maintain constant output voltage and also maintain input power factor. The frequency of operation of the PFC is maintained at 70 kHz. It was loaded with a 250 W resistive load.

The output voltage across the bulk capacitor is sensed and compared with the reference output voltage, and the resulting error voltage is multiplied with a multiplier and input voltage to give the reference input current. The error between the reference and the input current determines the switching of the MOSFET. The values of the divider and the multiplier constants vary with the input voltage. Figure 3.2 is the PSIM model of the power factor correction circuit.

3.3. Mathematical Loss Modeling in Simulink

The known parameters are input voltage, output voltage, output power, switching frequency. The loss model includes losses in various components of the PFC system.

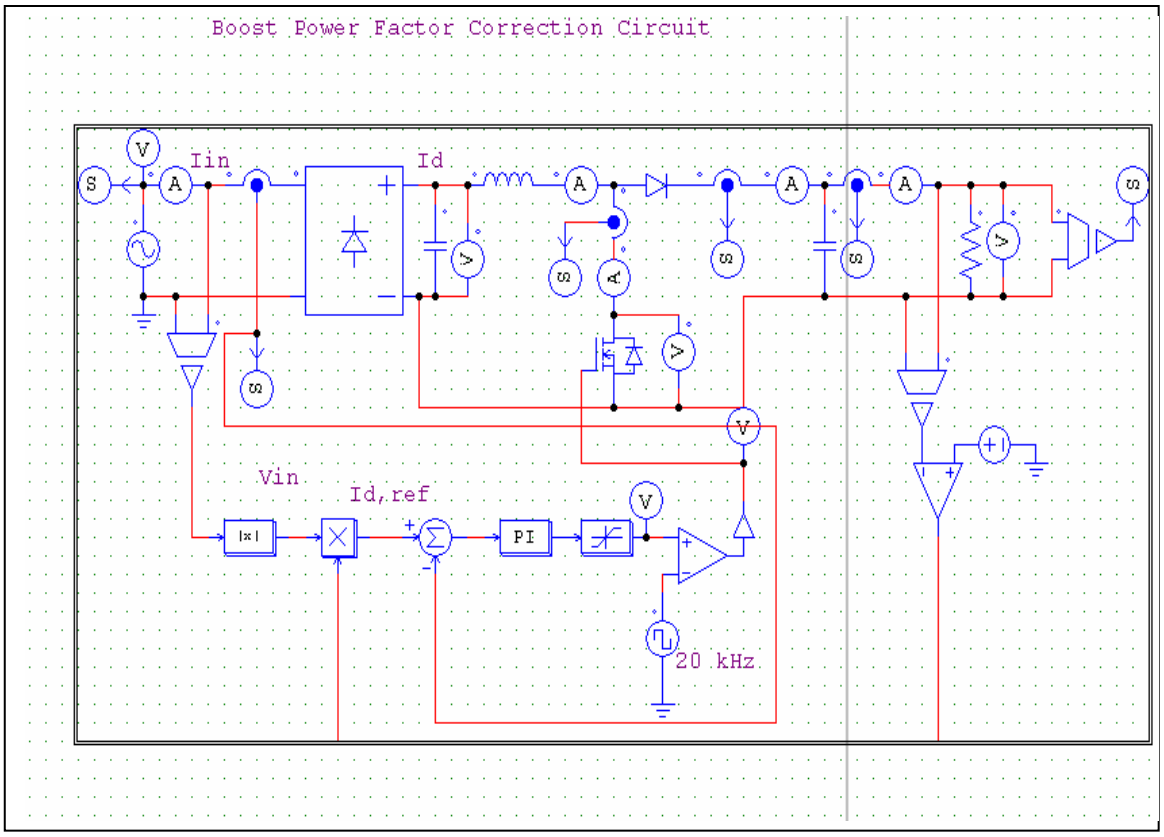


Figure 3.2 PSIM model for power factor correction circuit

They can be classified as: a) Rectifier losses b) Inductor losses c) Boost switch looses and d) Boost diode losses.

Rectifier losses: The losses in the diode rectifier are due to forward diode drop when the diode is conducting and also the conduction losses due to on-resistance.

$$P_{rec} = 2 \times I_{in} \times V_{on} + 2 \times I_{in}^2 \times R_{on} \quad (3.1)$$

From the operation of a diode bridge rectifier, two diodes conduct during positive half cycle and the other two diodes conduct during negative half cycle. Hence the loss equation is twice that of the conduction losses in a single diode. The switching losses are very small compared to the conduction losses and therefore are neglected.

Inductor losses: The inductor is basically an electrical wire wound over a magnetic core. The losses include the inductor core and copper losses. The magnetic intensity H is the product of number turns and current through the winding:

$$H = n \times I_L \quad (3.2)$$

where n is the number of turns, and I_L is the inductor current.

On obtaining the magnetic intensity using (3.2) for different values of current through the inductor, the magnetic field intensity B was obtained from the B-H curve of the inductor from the data sheets. Substituting B in (3.3), the core losses were calculated.

$$P_{core} = K \times B^{2.24} \times f^{1.41} \quad (3.3)$$

where K is the core constant with a value of 0.625 for the inductor core used,

B is the magnetic field intensity obtained from B-H curve,

f is the frequency of operation, 67 kHz.

The copper losses in the inductor is dependent on the resistance of the inductor given by

$$P_{copper} = I_{Lrms}^2 \times R_{dc} \qquad (3.4)$$

The copper losses are predominant as the inductor core chosen is operated in the region with minimum core losses.

Boost switch losses: A MOSFET is used as a switch in the boost converter circuit. The losses in the diodes and MOSFETs are divided into conduction and switching losses. The switching losses are dependent on the switching frequency; switching losses in the MOSFET and the diode have to account for removal of the stored charge in the junction capacitances also. The conduction losses are the losses in the drift region, channel, and contacts when the device is conducting. It is dependent on the resistance and the square of the current through it. The equations for calculating these losses are given in [15]. The switching losses in the MOSFET are given by

$$P_{sw} = \left(\frac{1}{2} \times V \times_o I_{Lrms} \times 0.9 \times t_{sw} \times f\right) + \left(\frac{1}{2} \times C_{oss} \times V_o^2 \times f\right) \qquad (3.5)$$

where V_o is the output voltage,

I_{Lrms} is the rms inductor current,

t_{sw} is the switching time,

f is frequency of operation,

C_{oss} is the output MOSFET capacitance.

The first part of the switching loss is obtained by averaging the area under the transition waves of voltage and current during turn-on and turn-off switching times. The switching time t_{sw} is the sum of rise and fall times of the current. The second part of the

switching loss in the MOSFET is due to the output capacitance C_{oss} measured between the drain and source with the gate- source voltage, V_{gs}, zero for AC voltages. C_{oss} is given by the drain to source capacitance C_{ds} in parallel with the gate to drain capacitance C_{gd}. The output capacitance decreases with voltage hyperbolically. For high voltages across the MOSFET and high switching frequency, this loss becomes significant. The output capacitance of the SiC MOSFET is 21pF and that of Si MOSFET is 48 pF at 400V.

The conduction loss when the MOSFET is conducting is mainly an I^2 R loss due to the on-state resistance of the MOSFET. Equation 3.6 gives the conduction losses in the MOSFET.

$$P_{MOS_con} = \left(I_{MOSrms}\right)^2 \times R_{ds} \qquad (3.6)$$

where R_{ds} is the on-resistance of MOSFET, and

I_{MOSrms} is the rms current through the MOSFET.

The values of R_{ds} for Si and SiC are 0.19 and 0.25 at 25^0 C from Fig. 4.4. This implies there is an higher conduction loss in SiC MOSFET than that of Si MOSFET at room temperature.

Boost diode losses: The boost diode losses are similar to that of the MOSFET losses i.e., they attribute most of the losses to conduction and switching losses. The conduction losses in the diode are given by

$$P_{D_con} = \left(I_{Drms}\right)^2 \times R_{on} + V_{on} \times I_{Drms} \qquad (3.7)$$

where R_{on} is the on resistance of the diode,

V_{on} is the on-state forward voltage drop of the diode,

I_{Drms} is the rms current through the diode.

The conduction loss in the Schottky diode is due to the on-state resistance and the diode forward voltage drop V_{on}. The equation for calculating the switching losses in the diode is given by

$$P_{D_sw} = Q_c \times V_o \times f \qquad (3.8)$$

where V_o is the output current of the PFC converter, and

Q_c is the reverse recovery charge of the diode.

The switching loss in the diode is mainly due to the reverse recovery charge that has to be removed before the diode is to be turned on. The reverse recovery charge for a SiC diode is only 1/5th that of a Si diode which results in significant efficiency improvement with the use of SiC Schottky diode.

The mathematical model had been developed in MATLAB with the parameter values obtained from PSIM as shown in Figure 3.3. SIMCoupler was used to couple PSIM with MATLAB. The rms values of the voltages and currents obtained from PSIM are used in the mathematical model in Simulink which generate the losses. For varying input, the losses are calculated to plot the efficiency versus input graphs for both Si and SiC MOSFET based systems.

3.4 Summary

This chapter outlines the simulation models used to evaluate losses in the ballast. The simulation model in PSIM is described and the values thus obtained from PSIM are coupled to the loss model in Simulink through SIMCOUPLER. The results thus obtained are used to plot efficiency plots which are demonstrated in the next chapter.

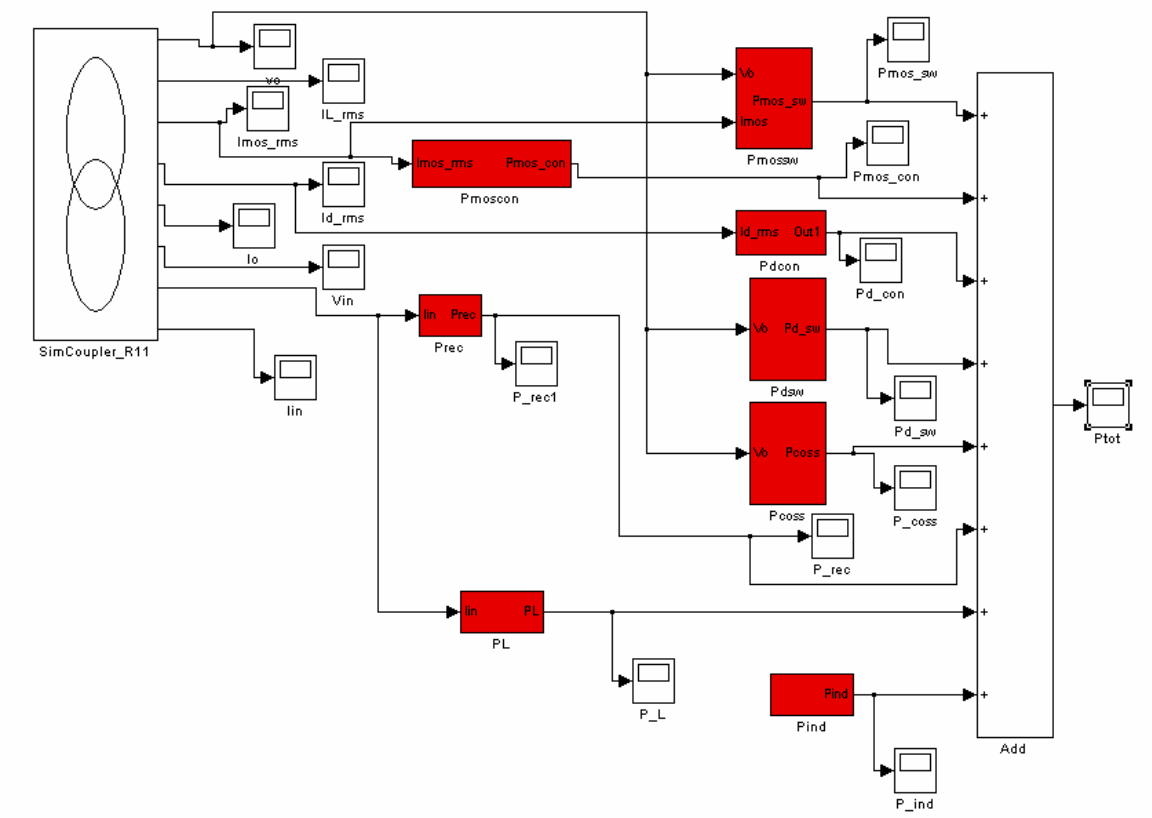


Figure 3.3 MATLAB Simulink model of the losses in the PFC circuit.

Chapter 4

Simulation and Experimental Results

This chapter presents the simulation results obtained from the simulation models in PSIM and Simulink which were described in chapter 3. The experimental results obtained from the PFC unit are used to compare with the results obtained from the simulation model. The simulation models of the ballast for Si and SiC MOSFETs are compared.

4.1 Si and SiC characteristics

Static and switching tests required to characterize the MOSFET devices have been conducted. The I-V curves indicate the temperature variation of the on-resistance for an 800 V, 10 A SiC MOSFET from Cree as shown in Figure 4.1. The resistance of the SiC MOSFET decreases with increase in temperature from 25^{o} C to 150^{o} C

The I-V characteristics for a Si MOSFET rated at 600 V, 10 A indicate an increase in resistance with temperature as shown in Figure 4.2. The threshold voltage decreases with temperature in both Si and SiC as shown in Figure 4.3.

To determine switching characteristics, a double-pulse gate signal was used to drive the MOSFET, and the applied voltage was 200 Vdc. An inductive load of 8mH was used, and the current was varied from 2 to 10 A. The temperature of the device was varied from 25 to 150 °C for the testing. The switching energy losses for the device during turn-on and turn-off as a function of temperature are plotted.

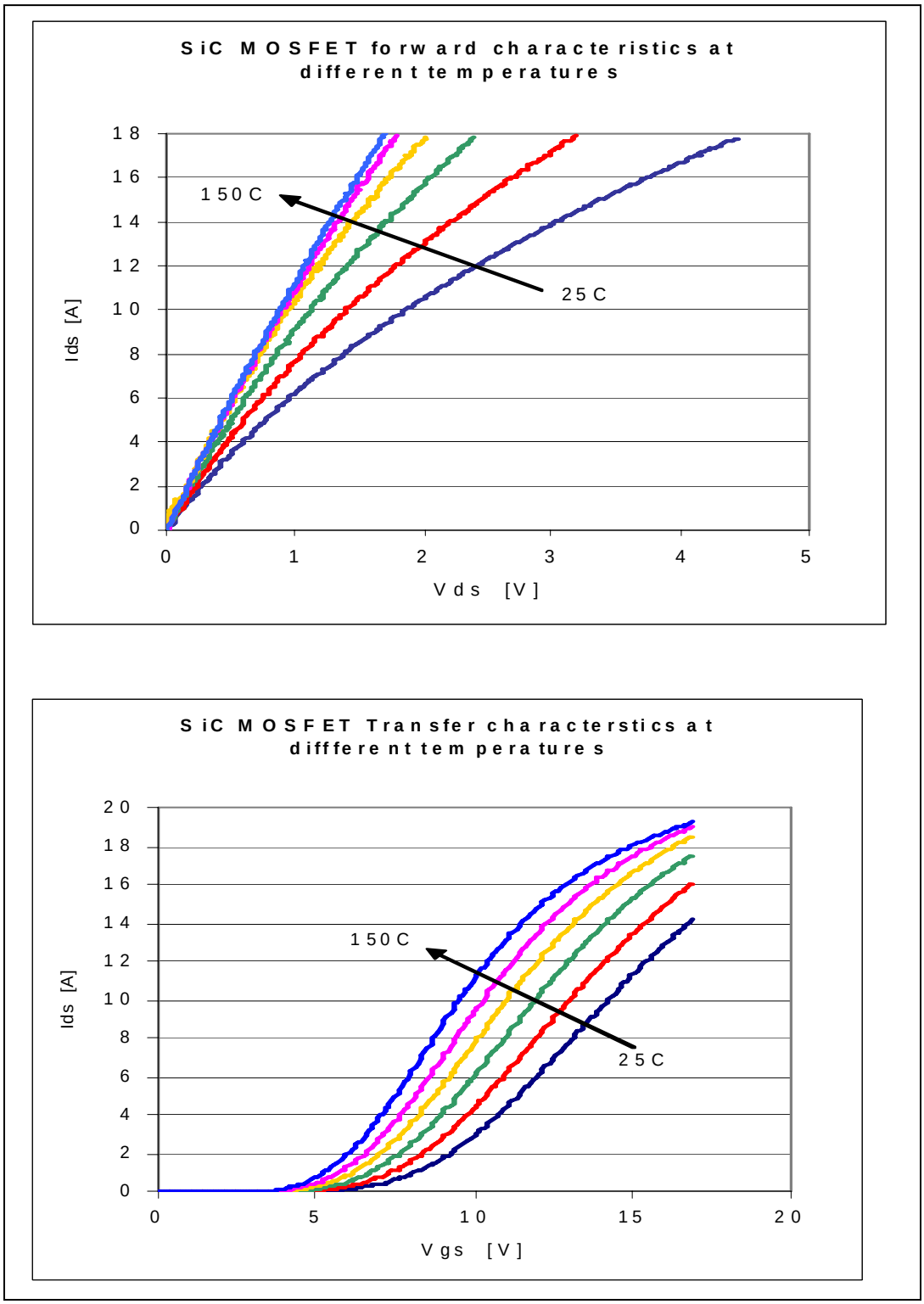


Figure 4.1 Forward and transfer characteristics of SiC from experimental tests.

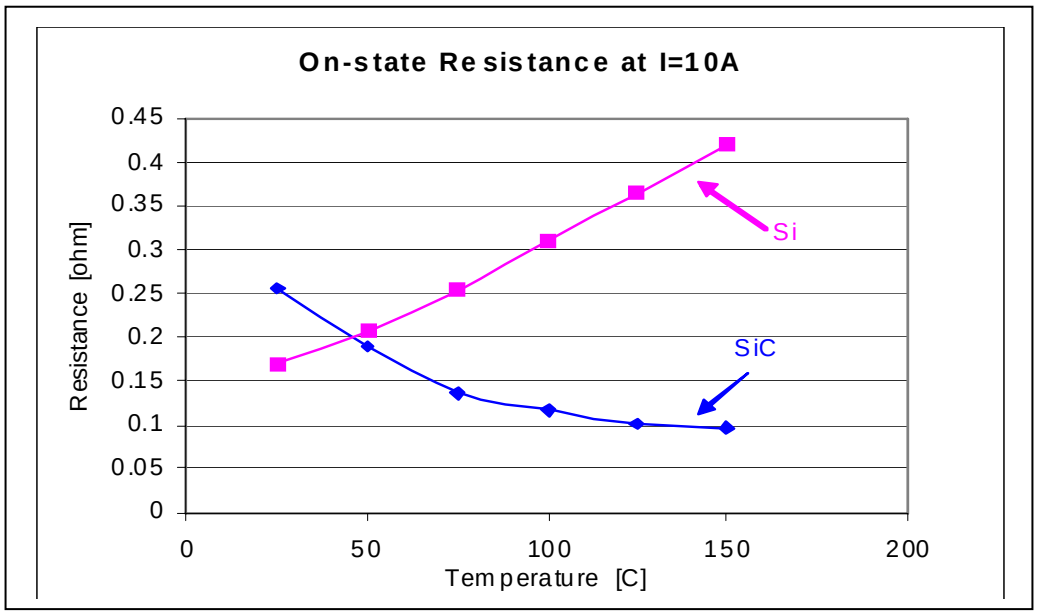


Figure 4.2. Variation of on-resistance with temperature for Si and SiC MOSFETs.

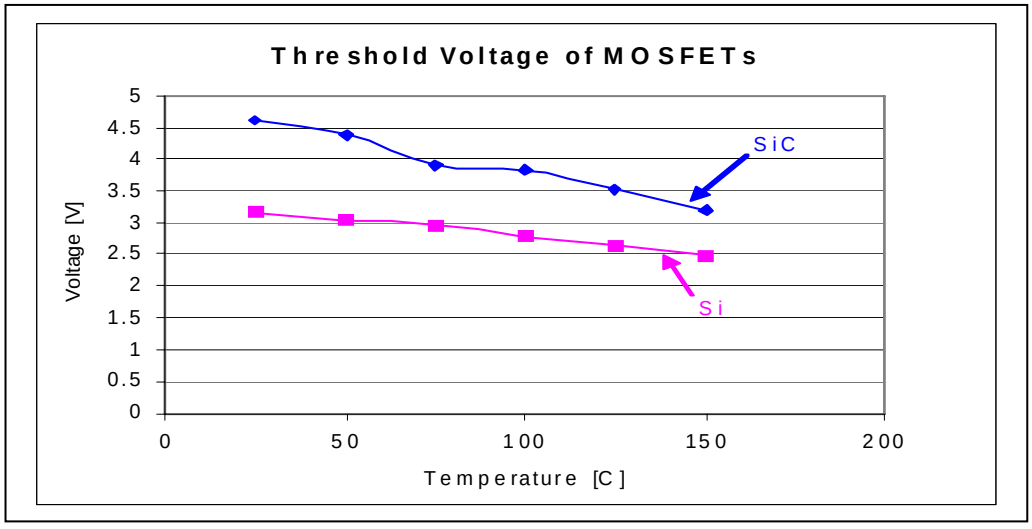


Figure 4.3. Variation of threshold voltage with temperature in Si and SiC MOSFETs.

Figure 4.4 shows that for the SiC MOSFET the energy losses increase with increase in current and decrease with temperature. At lower currents, the change in temperature has no significant effect on the losses; however, for higher currents the decrease in losses with temperature is more significant in turn-on losses than in turn-off losses.

The forward voltage drop across the diode is higher for the SiC diode than that for Si. The reverse recovery time is reduced in Si; it is considered to have near-zero reverse recovery charge because it is a Schottky device and hence results in a significant reduction in recovery time compared to the Si pn diode.

4.2 Simulation and Experimental results of PFC

The PFC section of the ballast was loaded with a 250 W resistive load for testing. The output voltage varies between 370V to 385V. Typical wave shapes obtained from the PFC (power factor correction) unit with Si and SiC MOSFET are demonstrated in Figures 4.5 and 4.6 at input voltage of 120V for a 250 W load.

The power factor is maintained around 0.998 and decreases to as low as 0.985 as input voltage increases implying the power factor correction decreases slightly as input voltage increases. The power factor correction is almost the same for the Si and SiC based PFC unit.

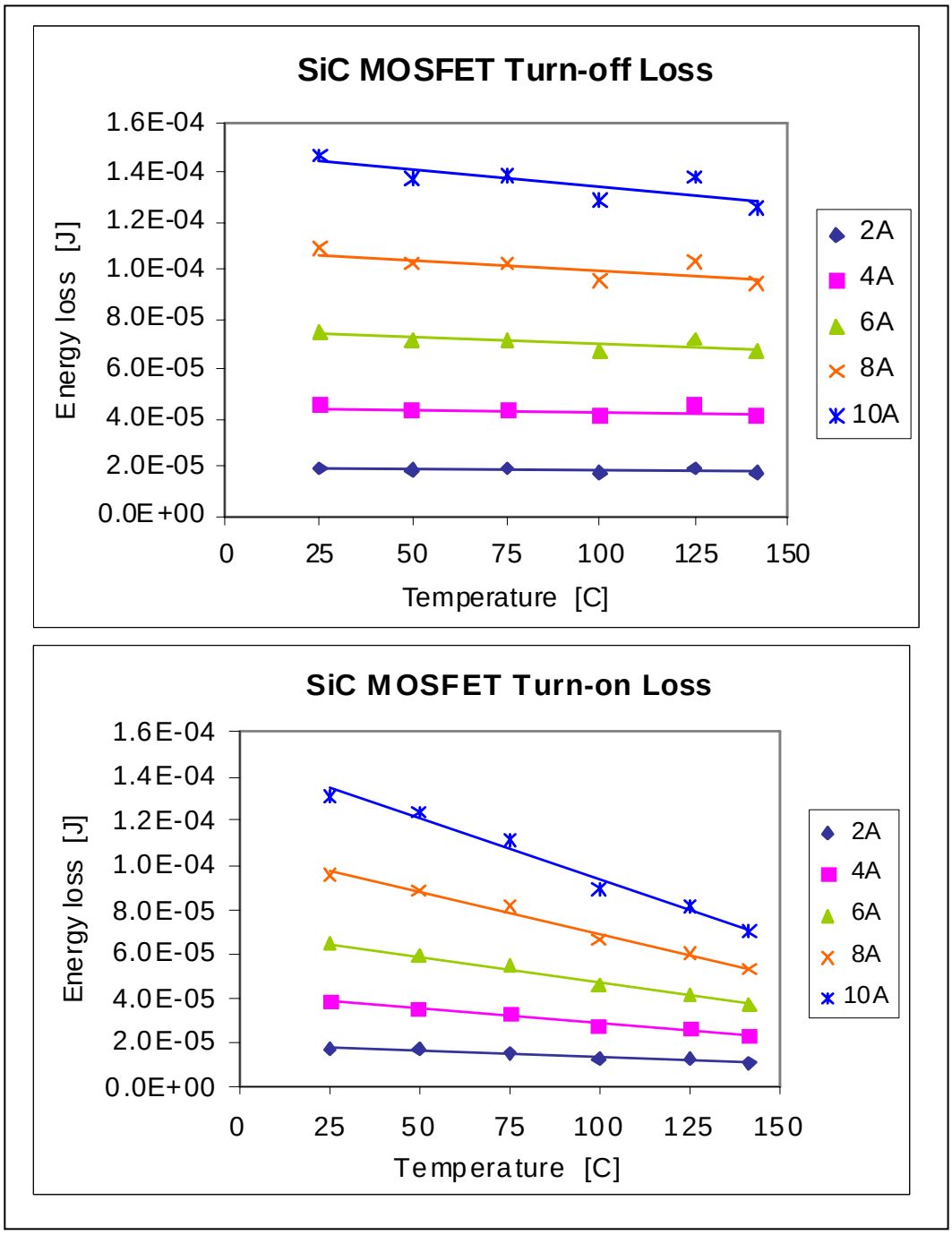


Figure 4.4 Variation of turn-on and turn-off losses in SiC MOSFET with temperature.

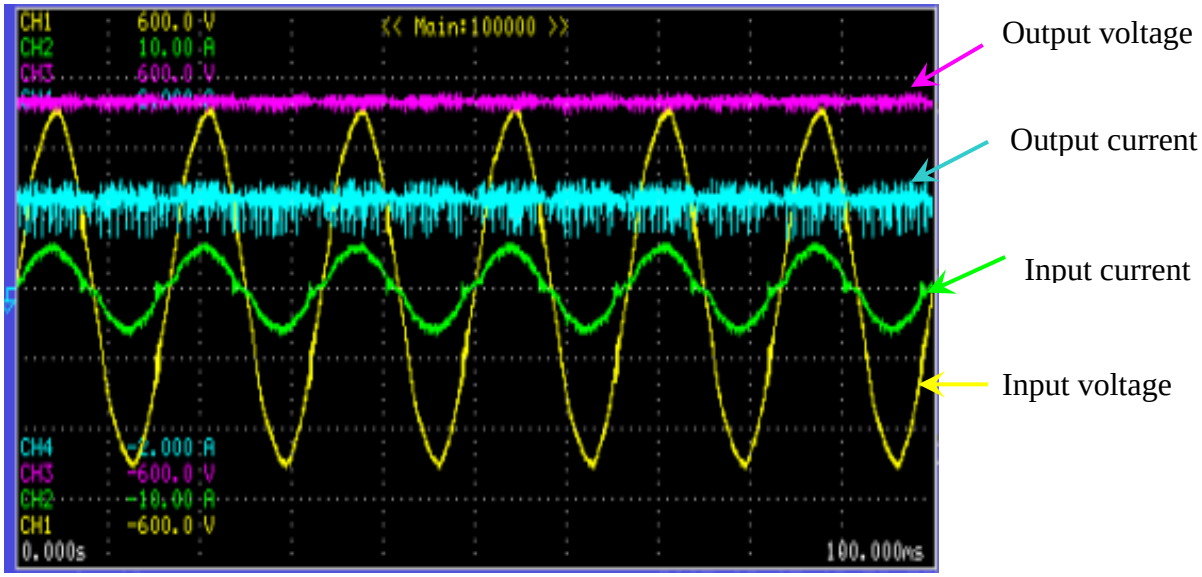


Figure 4.5 Input and output waveforms of current and voltage of the Si MOSFET based PFC circuit at input voltage of 264V and output power of 250 W.

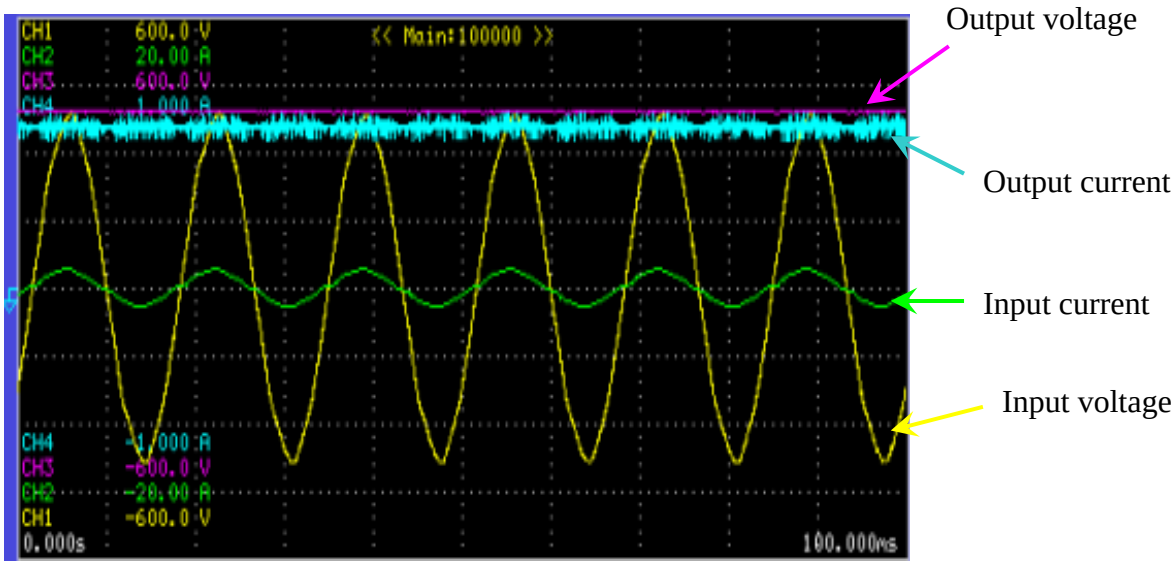


Figure 4.6 Input and output waveforms of current and voltage of the SiC MOSFET based PFC circuit at input voltage of 120V and output power of 250 W.

The PFC was subjected to testing for efficiency calculations at a constant load of 250 W. The PFC boost converter in literature has at most reached an efficiency of 96% [1-3, 16, 17, 19, 20]. The simulation and experimental results of efficiency of the PFC unit with Si MOSFET with varying input voltage is shown in Figure 4.7. Using the design by Epic Systems, Inc. the efficiency of the PFC circuit varies from 93.5 to 97.4 % for input voltage range of 90V to 264V. Thus at high input voltage, the efficiency obtained experimentally is high with a maximum of 97.4%. The simulation results show a maximum efficiency of 97.8% at 264 V input voltage.

The simulation and experimental results of efficiency of PFC unit with SiC MOSFET with varying input voltage is shown in Figure 4.8. It can be observed that the simulation result is close to the experimental result verifying the accuracy of simulation model. Figure 4.9 compares the experimental results of the PFC circuit with Si and SiC MOSFETs. It can be observed that the efficiency of the PFC circuit decreases as Si is replaced with a SiC MOSFET. The reason for decrease in efficiency and hence the increase in losses is mainly due to increase in the switching times of SiC MOSFET with the same gate drive. This indicates that a faster gate drive is needed with SiC MOSFET.

Figure 4.10 compares the simulation results of the ballast with Si and SiC MOSFETs. The ballast circuit includes PFC unit and the resonant inverter unit. In both units, the Si MOSFETs are replaced with SiC MOSFETs in the simulation model. The results are as shown in Figure 4.10. The efficiency of the ballast with SiC MOSFETs is less than that with Si MOSFETs owing to increased switching times in SiC MOSFETs with the same gate drive circuit.

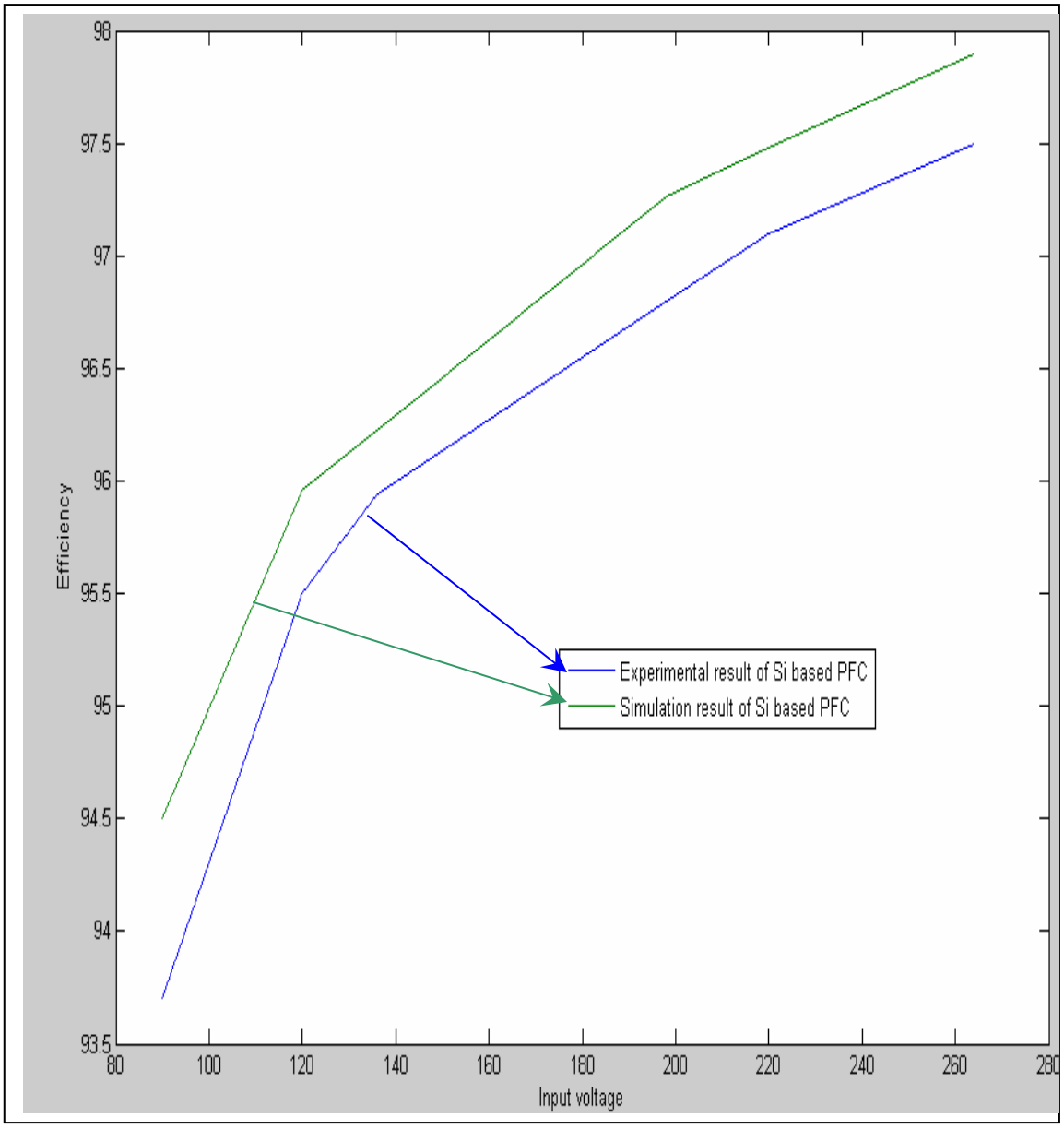


Figure 4.7 Efficiency versus input voltage obtained by plotting experimental and simulation results of 250W Si based PFC.

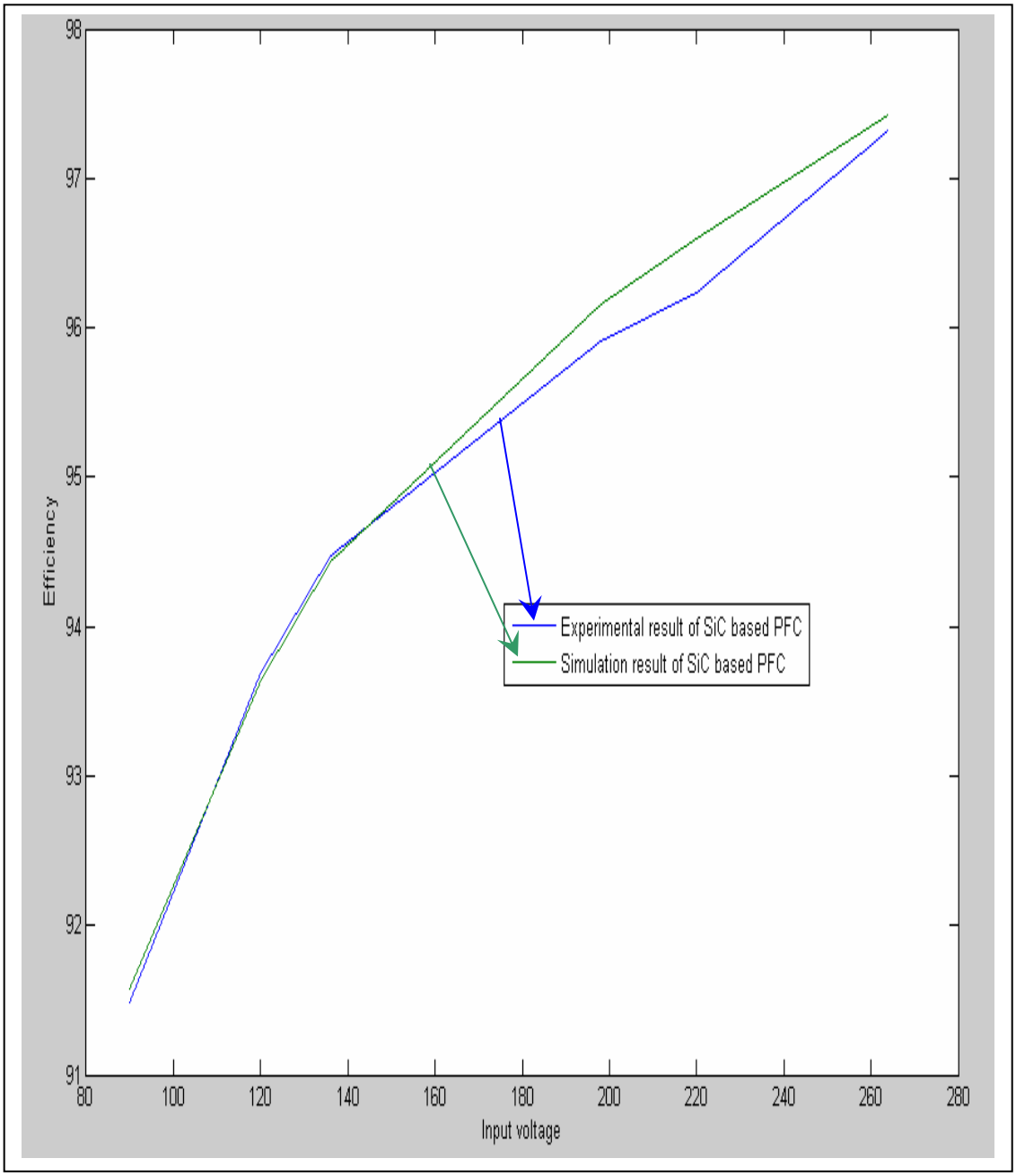


Figure 4.8 Efficiency versus input voltage obtained by plotting experimental and simulation results of 250 W SiC based PFC.

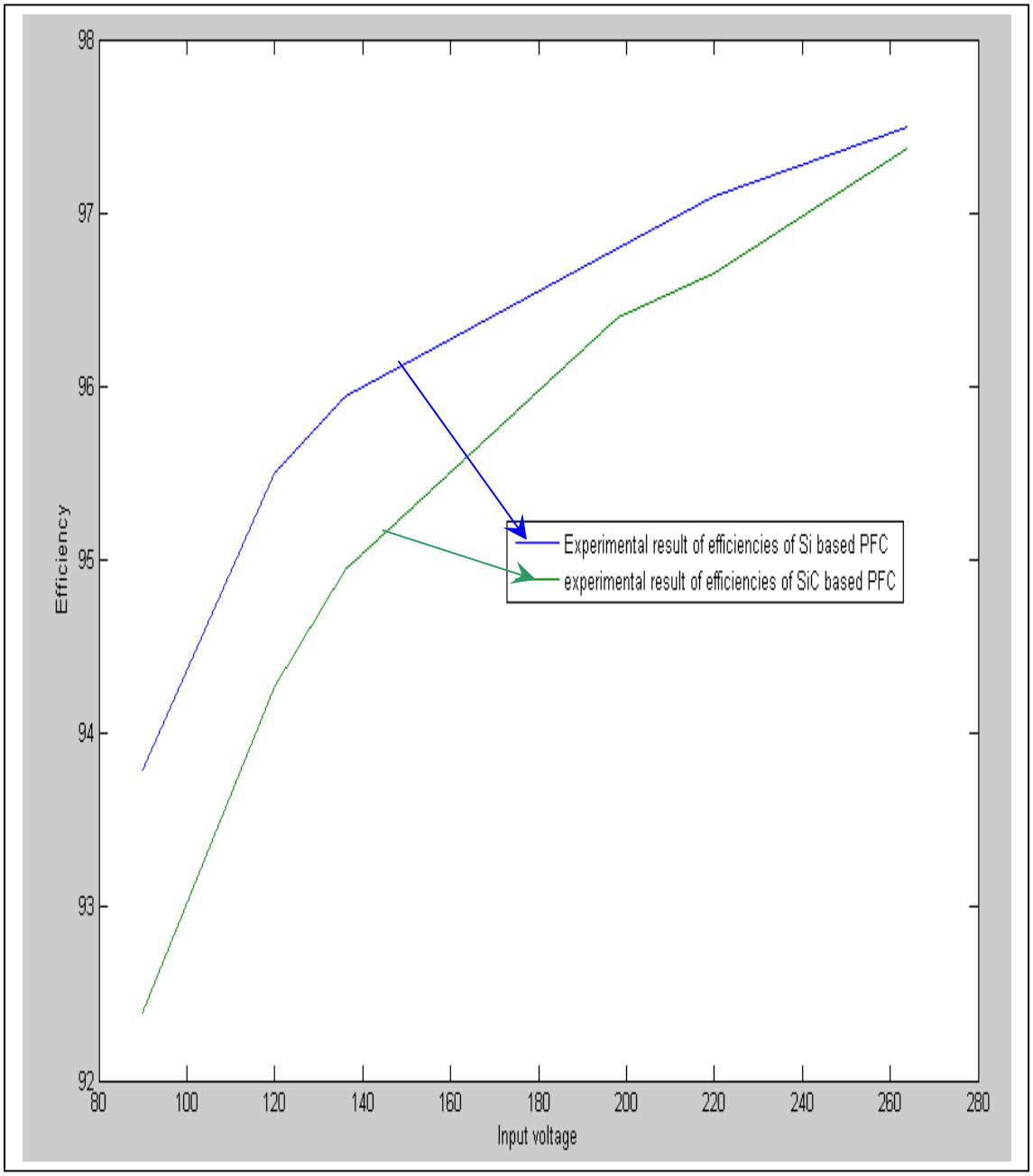


Figure 4.9 Comparison of experimental results of 250 W Si and SiC based PFC units.

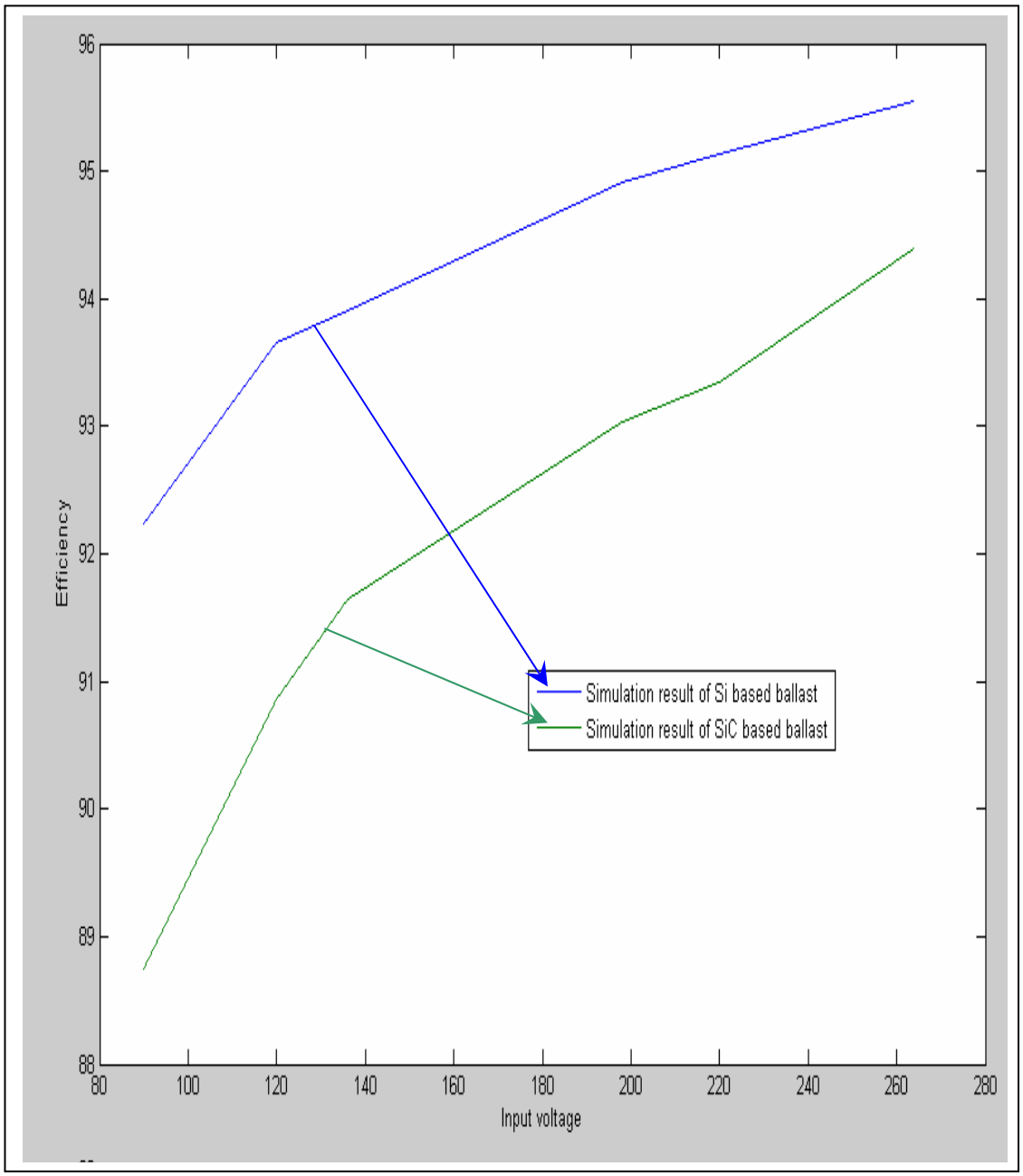


Figure 4.10 Comparison of simulation results of 250 W Si and SiC based ballast.

Table 2. Simulation results of various losses for varying input in Si MOSFET based PFC

Vin	Ilrms	Id_rms	Imos_rms	P_dcon	P_moscon	P_MOSsw	Pcoss	Prect	PL	Ptot	efficiency
90	2.54	1.21	2.22	1.6	1.1	5.206	0.336	4.15	1.87	14.32	94.58
120	1.97	1.1	1.645	1.426	0.62	3.91	0.336	2.94	1.39	10.75	95.87
136	1.78	1.05	1.435	1.375	0.45	3.43	0.336	2.57	1.27	9.62	96.294
198	1.276	0.928	0.876	1.2	0.19	2.12	0.336	1.68	1.03	6.73	97.37
220	1.165	0.9	0.736	1.16	0.12	1.8	0.336	1.51	0.98	6.2	97.58
264	0.974	0.857	0.463	1.1	0.05	1.1	0.336	1.21	0.92	4.92	98.06

Table 3 Simulation results of various losses for varying input in SiC based PFC

Vin	Ilrms	Id_rms	Imos_rms	P_dcon	P_moscon	P_MOSsw	Pcoss	Prect	PL	Ptot	efficiency
90	2.54	1.21	2.22	1.6	1.1	11.25	0.159	4.15	1.87	20.4	92.45
120	1.97	1.1	1.645	1.426	0.62	8.5	0.159	2.94	1.39	15.3	94.2
136	1.78	1.05	1.435	1.375	0.45	7.4	0.159	2.57	1.27	13.6	94.84
198	1.27	0.928	0.876	1.2	0.19	4.6	0.159	1.68	1.03	9.15	96.469
220	1.16	0.9	0.736	1.16	0.12	3.87	0.159	1.51	0.98	8.18	96.83
264	0.97	0.857	0.463	1.1	0.05	2.38	0.159	1.21	0.92	6.48	97.47

Tables 2 and 3 show the simulation results of the various losses calculated in Si and SiC based PFCs. As the input voltage increases, the input current decreases as the power is constant. Most of the losses are dependent on current through the device and output voltage. The output voltage being constant, the losses vary with the current through the device. The losses due to output capacitance of the MOSFET is constant for any input voltage as it is a function of output voltage and the material of the MOSFET.

In Si and SiC based PFCs, SiC Schottky diode was used. Hence the diode losses are same in both the units. The losses due to MOSFETs vary with the material. The switching times of the SiC MOSFET is higher than that of Si MOSFET for the same gate

drive circuit. Hence the MOSFET losses especially the switching losses of SiC MOSFET are higher than that of Si MOSFET.

A considerable fraction of losses is due to diode bridge rectifier and the MOSFET switching losses. To improve the efficiency of the ballast further, designs to reduce these losses would be beneficial.

4.3 Summary

This chapter demonstrated the experimental results obtained when testing the PFC unit. The simulation results are also presented and compared with the experimental results. It has been observed that with the same gate driver circuit used, the efficiency of SiC MOSFET based PFC unit was less than that of Si MOSFET based PFC unit. The overall performance of the ballast according to the simulation model showed a decrease in efficiency by around 2%. The next chapter presents the future work of this project to enhance the performance of the ballast so as to exploit SiC advantages.

Chapter 5

Conclusion and Future work

This chapter presents the conclusions drawn from the project and the possible future work that would enhance the performance of the ballast are presented in section 5.2.

5.1 Conclusions

Lighting forms 22% of all the electrical energy in USA. High intensity discharge lamps are used in applications where high intensity and efficiency, lighting over large areas are desired. High voltage is required to establish an arc between the electrodes during starting of the lamp. Once the arc is established, the voltage should be reduced and current should be regulated to produce steady light output. HID lamps require ballasts to control the starting and operating voltages.

Of the different types of ballasts, electromagnetic ballasts and electronic ballasts are popular. Electronic ballasts have higher efficiencies, higher frequency operation, and ensure cooler operation. They offer less weight, less noise and no flicker when compared to electromagnetic ballasts. Because of these advantages, electronic ballast is being used in wide range of applications.

Better performance and higher efficiencies of ballasts have always been under research. Innovative power electronics and optimum circuit design are considered to improve efficiency of the ballast in the power range of HID wattage. SiC devices because

of their better performance characteristics as compared to Si devices are used to obtain higher efficiencies.

Different ballast topologies have been studied and discussed in chapter 2. The basic topology consists of a power factor correction unit and a resonant converter unit. The considered power factor unit consists of diode bridge rectifier, and dc-dc converter with gate drive controlled to ensure power factor correction. The input ac voltage is rectified by the diode bridge rectifier and the dc-dc converter is used to regulate the voltage at the desired level. Boost converter is the typical dc-dc converter topology used for power factor correction. The boost switch, in this project a Si MOSFET, has been replaced by a SiC MOSFET to test the compatibility of SiC devices for a one to one replacement. Further, other components like the boost inductor, and the boost diode which is a SiC Schottky diode have been optimized to minimize losses and improve efficiency.

The 250 W-PFC circuit is designed to operate at a frequency of 70 kHz, with input voltage varying from 90 V to 264 V. A resistive load of 250 W was applied. The circuit was tested experimentally with Si CoolMOS and SiC MOSFET as the boost MOSFET. The gate drive IC is a current mode operating chip in average current control mode for power factor correction.

The simulation model for the PFC was modeled in PSIM and coupled to the mathematical model in Simulink. The average current control gate drive was simulated in PSIM to obtain power factor correction. The rms values of the currents and voltages are obtained by simulating the PSIM model and are coupled to the mathematical model in Simulink using these values through the SIMCOUPLER.

The resonant converter consists of inverter with resonance filter at the output. The output of the PFC unit which is a DC voltage and current is fed into an inverter and a high frequency ac output is obtained. In this application, a half-bridge inverter with parallel resonance LC filter was used. The simulation model was developed and simulated for Si and SiC devices.

Using the design by Epic Systems, Inc. the efficiency of the PFC circuit varies from 93.5 to 97.4 % for input voltage range of 90V to 264V. Thus at high input voltage, the efficiency obtained experimentally is high (as compared to previous available PFC models) with a maximum of 97.4%. The simulation results show a maximum efficiency of 97.8% at 264 V input voltage.

Efficiency as high as 95% can be achieved from Si MOSFET based ballast from the simulation model. An optimum design for Si MOSFET based PFC has been modeled. The simulation and experimental results show that with a one-to-one replacement of Si and SiC devices, the performance of the SiC MOSFET based system declines from efficiency point of view.

5.2 Future work

To exploit the advantages of SiC devices, the gate control of the SiC MOSFET should be redesigned to ensure faster turn-on and turn-off. An optimum design to maximize efficiency can be designed with considerations on lowering losses in the component devices. The operation of the electronic ballast is usually at high temperatures. High temperature operation of the ballast should be considered and a simulation model should be developed.

5.3 Summary

This chapter presents the overview of the project and the conclusions drawn from the experimental and simulation work. Future work that can be done to enhance the performance of the model has been suggested in section 5.2.

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Vita

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