A STUDY ON PERFORMANCE IMPROVEMENTS BY USING SiC (SILICON CARBIDE) BASED MOSFET AS COMPARED TO Si-IGBT IN STATIC INVERTER OF METRO TRAIN

A DISSERTATION SUBMITTED TOWARDS THE PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF MASTER OF TECHNOLOGY

IN

POWER ELECTRONICS

(2013-2016)

SUBMITTED BY

AJAI KUMAR KESHARVANI
ROLL NO. 2K13/PES/505

Under the esteem guidance of:

Sh. Amritesh Kumar

Department of Electrical Engineering

Delhi Technological University

July 2016

Abstract

In Modern power electronics system, now improvement in system efficiency, lesser weight of components, higher switching frequency and lesser losses are area of research. As far as power electronics devices are concern, almost all conventional silicon based devices like IGBT, MOSFET, GTO has reached at their maximum theoretical limit. So now a new material which is SiC (silicon carbide based) is currently topic of discussion. SiC based power electronics devices has many advantages like lower On state loss, lower switching losses, higher switching frequency, higher breakdown voltage, better thermal stability, less weight with same power rating.

In this project work, effiency improvement by using SiC based MOSFET has been compared with Si based IGBT used for metro train Static inverter. MATLAB simulation also done for above study. 50%, 75% & 100% loading condition of static inverter was considered for above study. As per MATLAB simulation it is concluded that efficiency of system improved in the range of 3-4% at each 50%, 75% & 100% loading condition.

Department of Electrical Engineering

Delhi Technological University

CERTIFICATE

This is to certify that this project titled " **A study on performance improvements by using SiC (Silicon carbide) based MOSFET as compared to Si-IGBT in Static Inverter of Metro Train** “submitted for the partial fulfillment of the requirements for the award of the degree of Master of Technology (Power Electronics System) by Mr. Ajai Kumar Kesharvani, University Roll No. 2K13/PES/505, student of Electrical engineering department from Delhi Technological University is a dissertation work carried out by him under my guidance. Any material borrowed or referred to is duly acknowledged.

Sh. Amritesh Kumar
Project Guide
Delhi Technological University
Electrical Engineering Department

ACKNOWLEDGEMENT

I express my sincere thanks to my project guide **Sh. Amritesh Kumar**, for providing me an opportunity to work under his guidance and tireless support during the course of the project. His continued cooperation, never-ending encouragement, meticulous guidance and uninhibited support at various stages helped me in preparation of this Project. It would never been possible for me take this project to completion without his innovative ideas and relentless support.

I would also like to thank **Professor Dr. Vishal Verma, Dean of PG courses & Controller of Examinations** of Delhi Technological University for their cooperation and dedicated support.
I would also like to thank entire faculty and staff members of the electrical engineering department for their help and co-operation during the entire project work.

I would also like to acknowledge the vital role of my seniors and colleagues from present organization **Delhi Metro Rail Corporation Limited**, in providing me support throughout the project work.

July 2016

Ajai Kumar Kesharvani

2K13/PES/505

M-Tech (Power Electronics System)

Table of Contents

1. **Introduction**

2.2 Review of Literature

List of Figures

CHAPTER 1

INTRODUCTION

1.1 General:

In metro system, static inverter provides the auxiliary power requirements of trains. It provides power to air conditioners, compressors, blowers and different single phase and DC loads. This power requirement is substantial when we are dealing with many numbers of trains in a Transport network. Normally in a 2 car unit it is designed at 180 KW.

In earlier era, conventionally Si based IGBTs were used as power devices in static inverter. But IGBT is having certain limitations with regard to TURN-ON delay, Turn-OFF delay, ON-State losses and switching losses. Due to these limitations these was substantial losses in static Inverter.

To reduce the losses and to improve efficiency of static inverter, SiC based power devices is better option available. SiC based devices is having higher voltage withstanding capability, Low ON-State resistance, lesser turn on delay, lesser turn off delay, higher allowed junction temperature, faster switching and better thermal conductivity as compared to IGBTs. So, by using of SiC devices, losses shall be lesser and the overall efficiency of Static inverter will improve, so a substantial energy can be saved and finally operational cost shall be reduce.

Reverse recovery time in SiC devices is far lesser than conventional Si devices so we operate it at higher frequency and add on to this ripple filtering requirement with SiC devices will be lesser as compared to Si devices due to higher frequency of opeartion.

SiC devices gather lesser space as compared to conventional silicon devices so size and weight of SiC based power unit shall be lesser as compared to Si devices based power unit.

1.2 Switching Characteristics of IGBT

Below figure-1shows switching characteristics of IGBT. In this characteristic, t_{on} is Turn ON delay and t_{off} is turn off delay. In Si-IGBT, these Turn ON delay and turn off delay is more as compared to as that of given in SIC MOSFET.

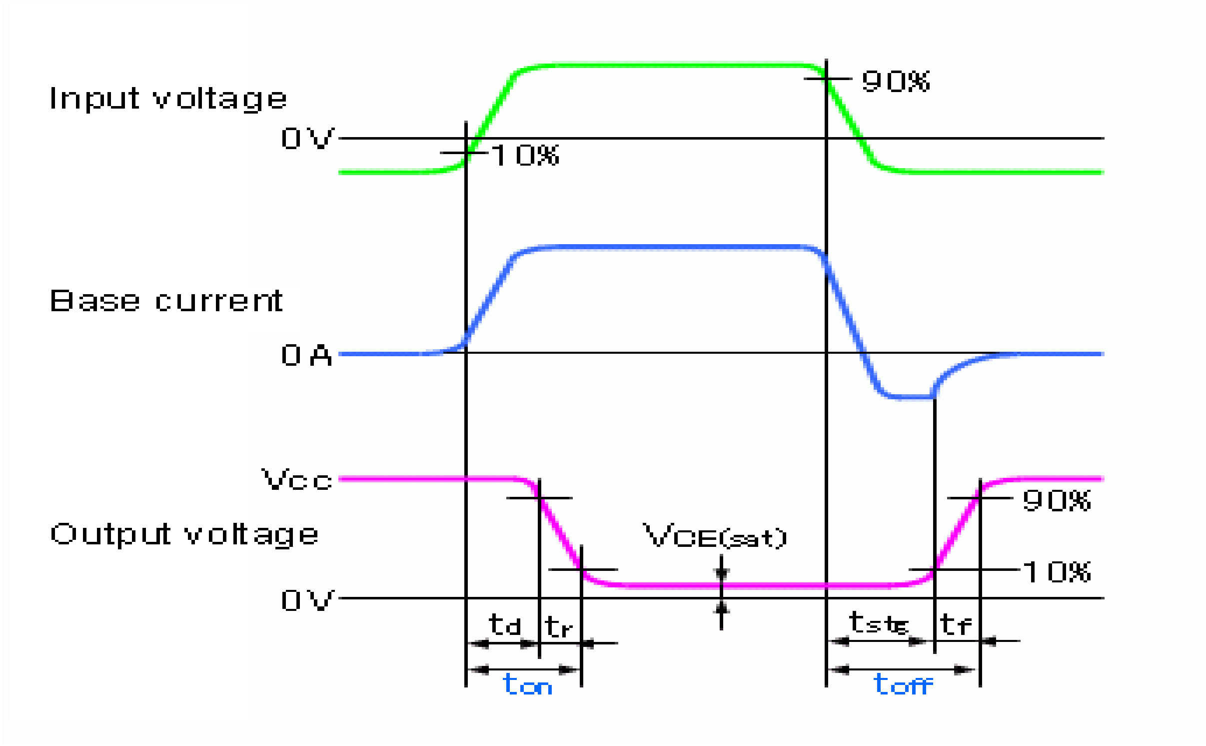


Fig-1 Switching Characteristics of IGBT

1.3 Switching Characteristics of SIC MOSFET

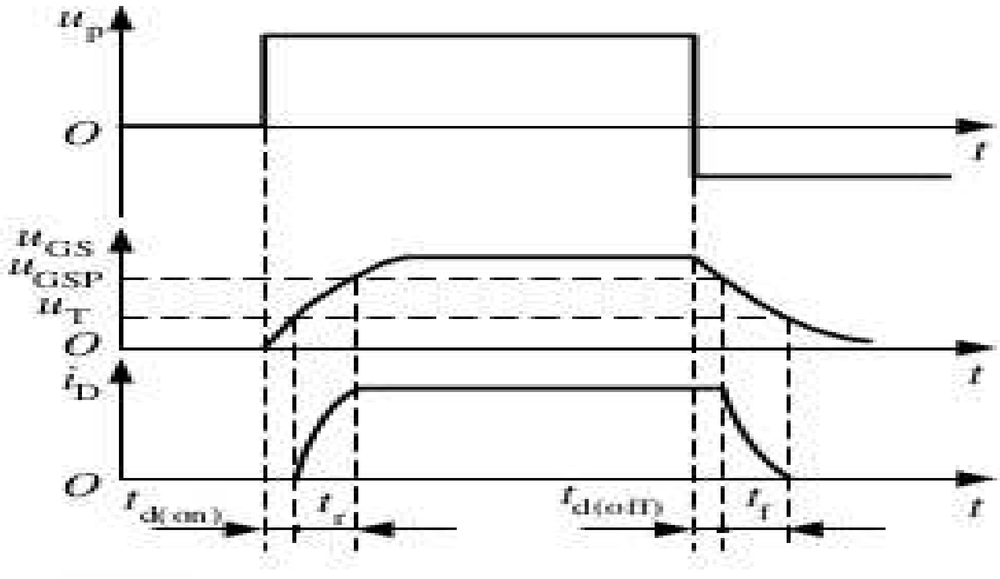


Fig-2 Switching Characteristics of SIC MOSFET

Above figure shows switching characteristics of SiC based MOSFET. By characteristics it is clearly seen that there is some turn-on and turn-off delay in IGBT. $t_{d(ON)}$ is Turn ON delay, t_r is rise time. $t_{d(off)}$

is Turn Off delay, t_f is fall time. These delays normally becomes in the range of nano seconds. Turn ON and Turn Off delays in Si- based IGBT are much more than SiC based MOSFET. In Si based IGBTs these delays normally becomes in the range of micro seconds. So reverse recovery time in SiC based devices is many times lesser than that of conventional Si-based devices.

1.4 Parameter comparisons of devices (SIC Vs Si)

In Metro train, 180 KW Static inverter is used. For the same capacity, comparisons of different parameters are given below:-

Sl. No.	Parameter	Si-IGBT	SiC-MOSFET
1	Turn-On Delay time (td-on)	1.2 micro-s	0.0172 micro-s
2	Turn-on Rise time (tr)	1.5 micro-s	0.0136 micro-s
3	Turn-off delay time (td -off)	2.0 micro-s	0.062 micro-s
4	Turn-Off fall time (tf)	0.6 micro-s	0.0356 micro-s

Note: - From parameter comparison it is concluded that turn on and turn off delay in SiC MOSFET is much lesser than Si- IGBT.

1.5 Rating Comparisons of both devices:-

Sl. No.	Parameter	Si-IGBT	SiC-MOSFET
1	Voltage Rating	1700 V	1200 V
2	Current Rating	1200 A	1200 A
3	Switching Frequency	1.5 KHz	5.5 KHz
4	Size	140 mm x 130 mm	109mm x 56 mm
5	Maximum allowed Junction Temp.	150 Deg C	175 Deg C

Note:- From rating comparison followings are concluded:-

i. Size of SiC MOSFET is much lesser than Si- IGBT.
ii. SiC MOSFET temperature withstanding capacity is more than Si IGBT.
iii. Switching Frequency of SiC MOSFET is more than Si IGBT.

1.6 Advantages of using SIC based devices over Si based devices

SIC devices have following advantages over Si based devices:

1. Higher Switching frequency.
2. Lower Switching Losses
3. Lesser in space for same power rating
4. Higher Temperature of operation.
5. Lesser weight for same power rating
6. Lesser filter requirement for filtering of harmonics and ripples.

1.7 Metro Train Static Inverter

1.7.1. Block Diagram of Static Inverter:-

Figure shows block diagram of Metro Train static inverter.

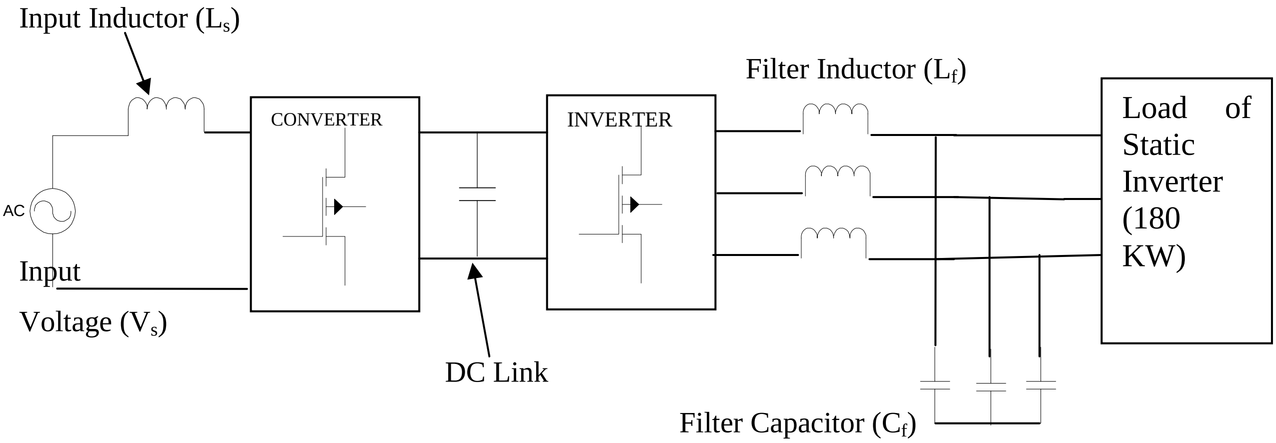


Fig-3 Block Diagram of Static Inverter

Different components of static inverter are shown in block diagram. The Static Inverter has the following functions:-

Input circuit

A 470V AC, single-phase power will be supplied from the OHE through the main transformer. The pre-charging circuit, the line contactor, and input filter reactor will be provided. The function of input filter reactor is to decrease high harmonic current.

Converter Functions:-

The PWM converter will rectify the AC to DC and the DC link voltage will be stabilized in constant at 810 volt under input voltage variations and output load variation. The control method of the converter is of pulse width Modulation (PWM) control using large capacity SiC MOSFET modules.

DC Link Circuit

In order to obtain the stabilized operation of the inverter, the DC voltage will be kept constant against the variation of the input catenary's voltage and output load conditions.

The control will be by the PWM converter.

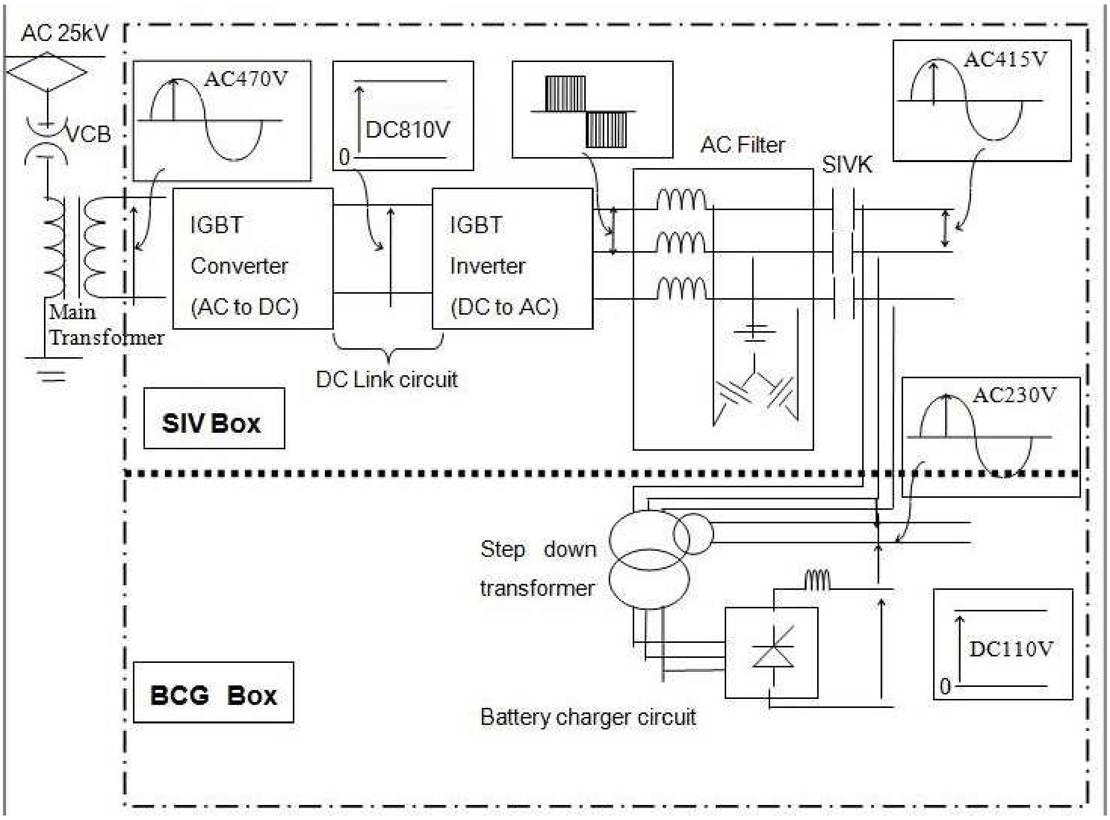


Fig-4 DC Link Circuit

Discharging switch (GS) is used at discharging filter capacitor voltage for safety of maintenance personal.

Constant Voltage, Constant Frequency Inverter

The Constant Voltage and Constant Frequency (CVCF) Inverter has the function to make 3-phase AC power for the on-board equipment, such as air conditions, air compressors, battery chargers. It generates 3 phase, 50 Hz. 415 Volt output.

Output AC Filter Circuit

The output AC filter consists of AC filter capacitors and AC filter reactors. The output AC filter makes output of 3 phase sign wave.

The waveform distortion will be less than as compared to conventional Si-IGBT.

CHAPTER 2

LITERATURE SURVEY

2.1 General

This is a very important issue to improve the efficiency of large capacity converter/inverter system. This will leads to reduce operational cost of the system. Many devices which are basically based on Si material like, IGBT, MOSFET, GTO, Thyristor are being used at present for converter/inverter system but these conventional devices have reached at their maximum theoretical limit so a new Device which is based on SiC material is matter of attraction in this field now a days. SiC based devices have more excellent electrical characteristics than that of conventional power devices.

2.2 Reviews of Literatures

Many literatures, publications and IEEE papers have produced analysis of improvement by using SiC based devices.

By reviewing of these literatures, the research work content and topics which are presently being carried out on SiC based devices are given below:-

2.2.1 Efficiency improvement of Converter/Inverter system :-

By using of SIC based power electronics devices overall efficiency of the system improves. This happens due to switching loss and Turn-ON losses of SIC based power devices is much lower as compared to conventional Si based power electronics devices[1].

SIC based power electronics devices have following characteristics and advantages:-

1. **Wider Energy band Gap: -** Due to wider energy gap, SIC devices can easily withstand higher withstanding Voltage and with this feature it is possible to reduce quantity of series connected power devices [1].
2. **Faster Switching Frequency: -** In SIC based power electronics devices, reverse recovery time is much lesser as compared to conventional Si based power electronics devices, so SIC based devices can operate at higher switching frequency as compared to conventional Si based devices. This is a great advantage for high speed control [1] [3] [10].
3. **Higher Breakdown Electric field: -** SIC based power electronics devices realize Higher Breakdown Electric field [1].

4. **Faster Electron Velocity: -** SIC based power electronics devices realize faster electron velocity as compared to Si based conventional power electronics devices [1].
5. **Better Thermal Conductivity: -** SIC based power electronics devices realize better thermal conductivity and due to this heat dissipation in SIC based power electronics devices is better than Si based conventional power electronics devices [1].
6. **Higher Vaporizing Temperature:** - SIC based power electronics devices realize higher vaporizing temperature as compare to Si based power electronics devices [1].
7. **Higher temperature of Operation: -** SIC based power electronics devices can operate at 300deg centigrade which is approx double as compared to Si based conventional power electronics devices [1].
8. **Low ON state Resistance: -** Due to lesser on state resistance, the ON-state losses of SIC based power electronics devices is much lesser as compared to Si based power electronics devices [1].
9. **Lesser Switching losses: -** Switching losses of SIC based power electronics devices are very less as compared to Si based power electronics devices [1].

Conclusion:-

Based on above features, it can be concluded that total operational losses by using SIC based Power electronics devices are much lesser as compared to Si based power electronics devices. So total efficiency of the system will improve by using SIC based power electronics devices.

2.2.2 Working as PFC converter

For compliance of international standards such as IEC-1000-3-2 and IEEE-519, power factor correction is mandatory for AC-DC SMPS. Conventionally many Power factor corrections circuits have been developed but these circuits also creates losses in system. So to reduce losses and increase system efficiency, power electronics device which can operate at high switching frequency and having low switching losses with lesser size is suitable for design of power factor correction circuit. A lot of efforts have been made in past in this regard but circuits were complex and not reached to desired result [2].

Now SiC based power electronics devices has developed, which has many better characteristics. SiC devices can operate at higher switching frequency and having low switching losses, lesser size for same power rating. So SiC based power electronics device like diode is best suitable for this application [2].

2.2.3 Working as utility interface for a battery system:-

SiC based converter is being used as utility interface in battery system. It acts as interface as it is connected between battery and supply system and support for charging and discharging of battery as per the requirement. Simulation was done to compare performance between SiC based converter and Si devices based converter and following was the findings [4]:-

1. Efficiency of the system was improved with the same heatsink size and ambient temperature in the SiC-based converter
2. Large savings in system weight and volume was observed with same thermal limit of system in SiC based converter.

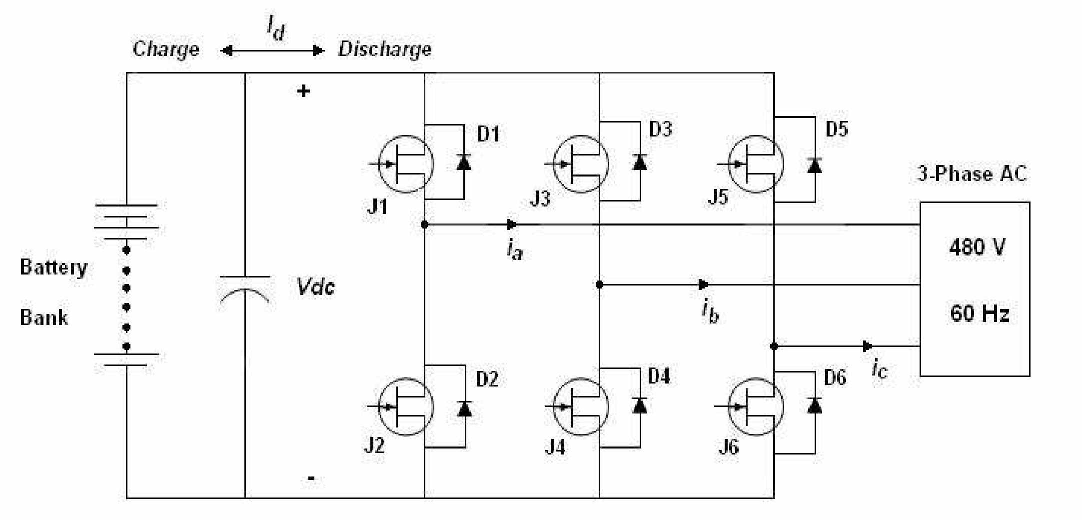


Fig-5 Interface for a battery system

Above figure shows SiC Converter working as utility interface for Battery system [4].

2.2.4 Working as Buck and boost converter for PV system:-

Buck and boost converter is used as interface utility between PV system and grid. By using of SIC based power electronics devices MOSFET and Diode the efficiency of Converter system improved as switching & Turn ON losses of SiC devices are much lesser than conventional Si based power electronic devices [8] [11].

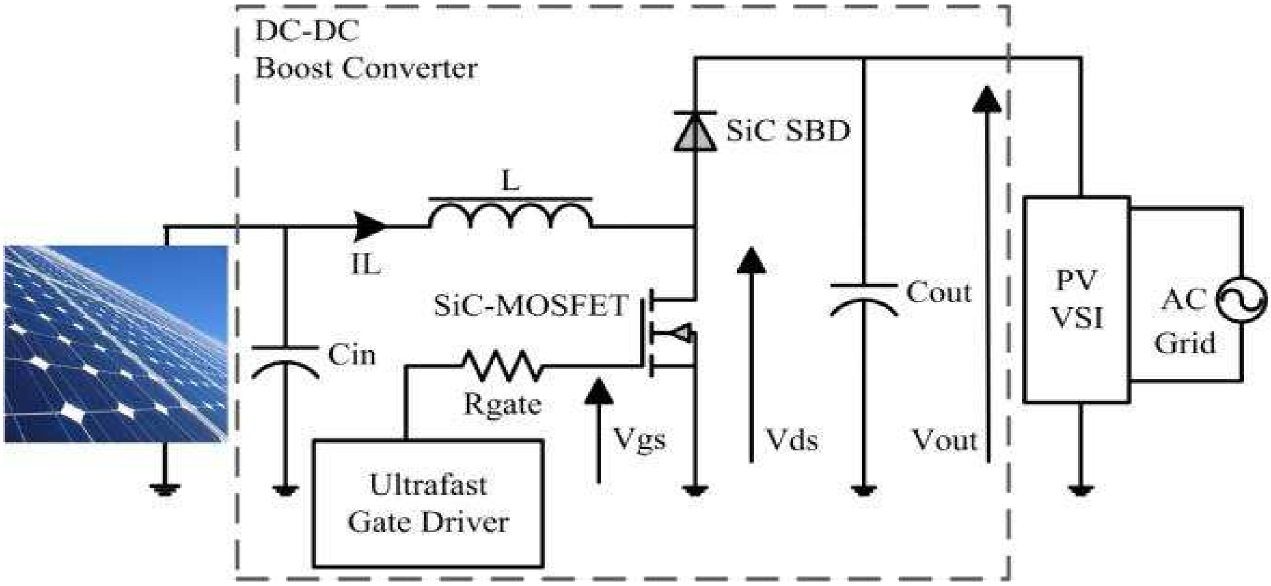


Fig-6 **Buck and boost converter for PV system**

Figure shows SiC Converter used with PV system [8].

2.2.5 Cost Benefits on High Frequency Converter system based on SiC MOSFET approach [22]

Silicon Carbide (SiC) devices have many advantages over silicon based power. There are significant cost benefits by using SiC devices.

Presently, SiC devices are on top on choice for those designers who look for increased power density, safer thermal operation, better efficiency, reduced system form factor as well as a significant reduction of the size and cost of passive components [22].

Presently the demand for improvement in efficiency is becoming more interesting topic of research in Power electronics. In the 1200V device range, SiC is becoming an excellent alternative to the currently used silicon based power devices [22].

The use of high performance silicon carbide power device showed a significant improvement of the efficiency vs the IGBT enabling higher frequency operation (up to 125kHz).

To evaluate the overall system cost and compare system efficiency with a SiC MOSFET approach against the use of conventional IGBT, 2 dedicated boost converters have been built to 2 different switching frequency (25kHz for the IGBT and 100kHz for the SiC MOSFET) while the cost analysis is based on the cost of heat-sink and passive components and logistics etc..

After doing the simulation, results have been drawn in below figure.

The figure below shows the efficiency vs. switching frequency (at given load of 5kW) for both SiC MOSFET (SC T30N120) and a 1200 V/25A Trench Field-stop IGBT [22].

Following can be noted here that With SIC based devices, system efficiency is much better than Si based IGBT.

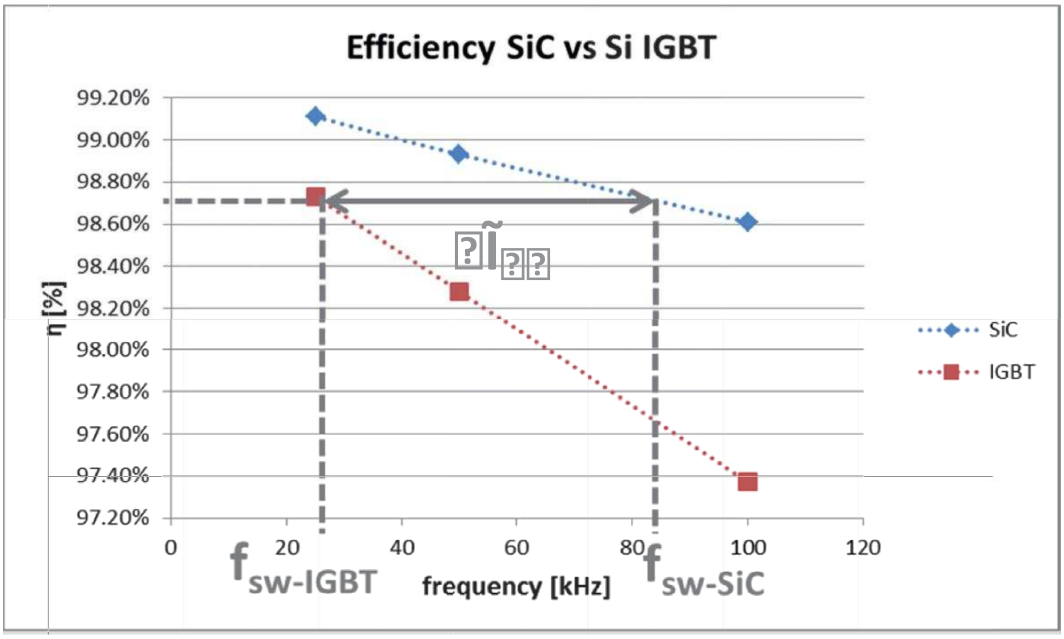


Fig-7 Efficiency vs switching frequency in ST 5kW Boost converter design

In above figures it is concluded that system efficiency improves by using SiC based devices so total system operating cost will be reduced. In addition to efficiency improvement, by using SiC based we can get cost saving in following respective:-

a. Cost saving in passive component (Inductor & Capacitor)

By increasing the switching frequency in a Boost converter, the requirement of size of inductor and capacitor shall be reduced as harmonics distortion being generated by SiC based power devices shall be reduced as compared to silicon based devices. So by using lower size of these components, cost of these components shall be lesser. So we can save some considerable money in this account.

b. Cost saving in the cooling system

In SiC based devices, maximum allowed junction temperature is more than Si based power devices also SiC based devices exhibits high thermal conductivity. If we consider similar losses of both SiC based devices and Si devices then cooling requirement with SiC based devices shall be lesser as compared to Si devices.

In addition to this SiC based devices having lower switching losses so heat generation by devices shall be lesser. So from above it is concluded that by using SiC based devices, less cooling arrangement is required so we can save some considerable money in this account.

c. Cost saving in logistics

The logistical costs of transporting and storing products also having a significant cost to a company. These costs strongly depend on the overall size and weight of the products.

Both volumetric density (W/l) and gravimetric density (W/kg) have an impact on the following logistic variable costs:

a) Warehouse cost for storage
b) Labour cost
c) Fuel cost for transportation
d) Shipment for transportation

As we now that SiC based devices has lesser size and weight as compared to Si based devices so, we can save some considerable money in this account.

Conclusion:-

SiC MOSFET allows increasing the switching frequency, efficiency and power density of power electronics applications. Despite of the higher cost of SiC MOSFET itself, these advantages can be converted in a lower overall system cost.

2.2.6 Working as Intelligent power routing switch for next generation DC Distribution Network [19]

A power routing switch using SiC–MOSFET has been developed for the DC distribution network. The routing switch functions as following:-

1. As an intelligent relay,
2. As a circuit breaker
3. As an inrush avoiding circuit.

The routing switch has a circuit configuration which is based on the non–isolated hard–switching DC–DC converter, and the surge voltage across the SiC–MOSFET is minimized by managing circuit parasitic parameters to prevent malfunction of peripheral equipment [19].

For routing switch control, high frequency digital control has been applied, and the fault current has been interrupted within several microseconds after the accident. A 5 kW and DC 380 V prototype has been fabricated and the performance as the circuit breaker and the inrush avoiding circuit has been evaluated experimentally. The fault current of 37 A has been interrupted within 5 μs after the detection of the fault current of 22 A, suppressing the overshoot voltage of the SiC–MOSFET lower than 500 V. The inrush current has been also avoided by the PWM soft–start operation for the capacitive load without any external protection equipment [19].

The amount of network traffic in the data centers and the telecommunications buildings has recently been rapidly increasing due to the widespread use of information and communication technology

(ICT) equipment [19]. Energy saving in these buildings and data centers will contribute to solving some of our global environmental problems. Therefore, having a highly efficient power feeding system has become indispensable [19].

A 48–V DC distribution system is now widely used for switching facilities, servers, and routers in telecommunications buildings. The increase in the aforementioned equipment requires larger supply current and causes more power loss in the DC power supply and distribution lines. In order to resolve these problems, the NTT Group has been developing 380–V DC distribution system that goes beyond the conventional 48–V DC distribution system [19]. The static and transient characteristics of the system have been evaluated, and the availability based on the demonstration test has already been reported [19].

Now, the next generation DC distribution network has been proposed based on the concept of the environmentally friendly data center in Green Vision 2020 to reduce the global impact [19]. The proposed DC distribution system consists of several 380–V DC distribution systems and the DC 380 V lines are connected each other by using intelligent power routing switches. Figure 1 shows the schematic diagram of the proposed system. The features of the system are summarized as follows [19].

a. The distribution loss in the DC network is minimized by controlling the power routing switches using high–speed and ultra–low loss semiconductor power devices taking conditions of the power sources and loads into consideration [19].

b. The total capacity of the installed storage systems as lead acid and Li–ion batteries is minimized and bundled to realize the ease of maintenance [19].

c. The conversion loss generating from the power converters is minimized by reducing the number of conversion steps and by developing high–power–density and high–gain DC–DC converters using multi–converter topology [19].

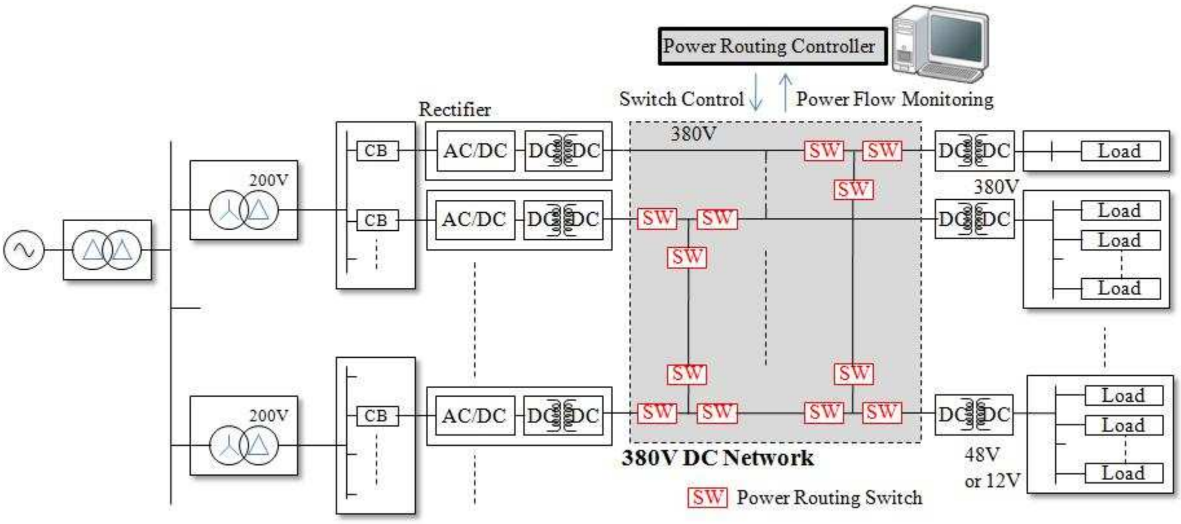


Fig-8 Intelligent power routing switch for next generation DC Distribution Network

Figure 8 shows the circuit configuration of the power routing switch. The typical non–isolated buck DC–DC converter topology is applied here. This switch consists of design parameters as a main switch Q_1, a free–wheeling diode D_1, a current limiting inductor L_{f1}, an input capacitor C_i and an output capacitor C_o. Inductors of L_{pri} and L_{sec} mean the primary and the secondary line inductances which depend on the cable structure. The load which have input filter capacitor C_{Load} are connected, taking the circuit configuration of servers into consideration. The main switch Q_1 is normally turned on to minimize the power loss in the steady state, and the soft–start PWM control is applied to suppress the rush current into the load capacitance C_{Load} during the start–up process. The over current is interrupted with small surge voltage by minimizing parasitic parameters under the grounding fault [19].

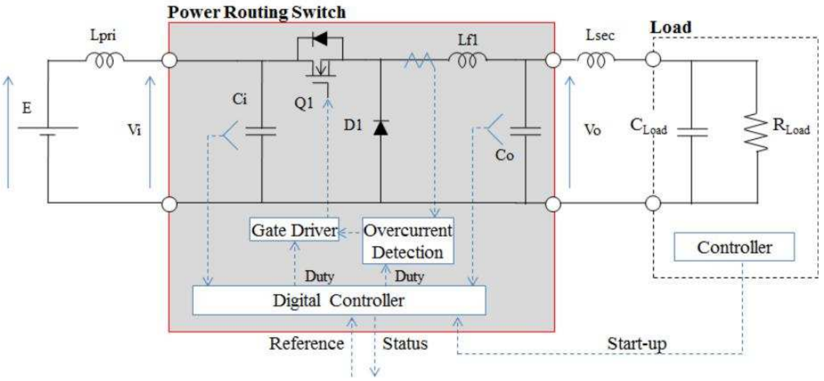


Fig-9 Circuit Configuration of Power Routing Switch Using SiC–MOSFET [19]

Above Figure 9 shows power routing switch’s control flow chart to interrupt the over current in the grounding fault, to suppress the inrush current at the start–up and to suppress the fluctuation current under the rapid load variation. The currents I_1 and I_2 are the threshold values to control the main switch Q_1. When the current through the inductor L_{f1} is larger than I_2, the main switch Q_1 is immediately turned off to interrupt the fault current. In case the current is detected between I_1 and I_2, high frequency PWM control is applied to limit the current. The output voltage recovers to the rated voltage under the rapid load variation, and the inductor current keeps increasing under the grounding fault. The threshold values I_1 and I_2 are determined arbitrarily taking the specification of the semiconductor switches into account, and these values can be changed from the outside PC as the power routing controller shown in Fig. 8[19].

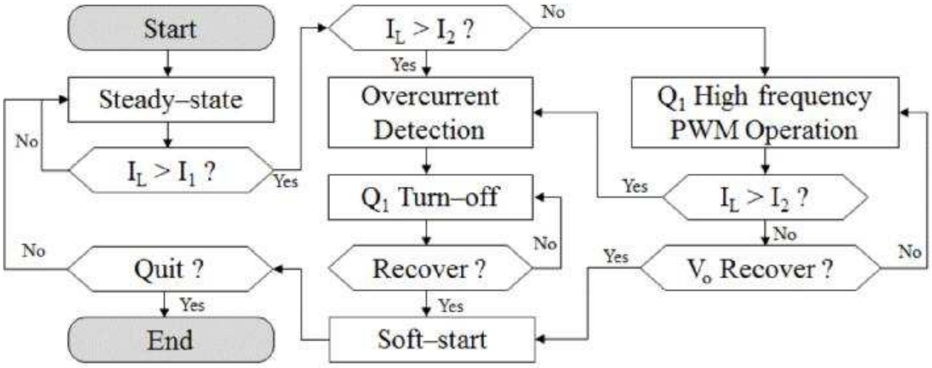


Fig. 10- Control Flowchart of Power Routing Switch for Fault Current Interruption [19]

2.2.7 Other Applications of SIC devices: -

In literature survey following other applications of SiC based power electronics devices was studied:-

a. Working as High frequency isolated bidirectional converter [13].
b. Working as indirect Matrix converter with minimum parasitic inductance [25].
c. Reduction of weight and improvement of efficiency for Hybrid electric vehicles [28].

CHAPTER 3

Static Inverter Circuit Diagram and Control Theory

3.1 General

SIV of Metro train stands for Static inverter. It generates 3- Ø, 415 V, 1- Ø, 230 V & 110 VDC output. It contains one converter power unit, one inverter power unit & one rectifier unit. Detail description of SIV control & Power circuit is given below:-

3.2 Circuit Diagram and its Explanation:-

Figure shows block diagram of static inverter.

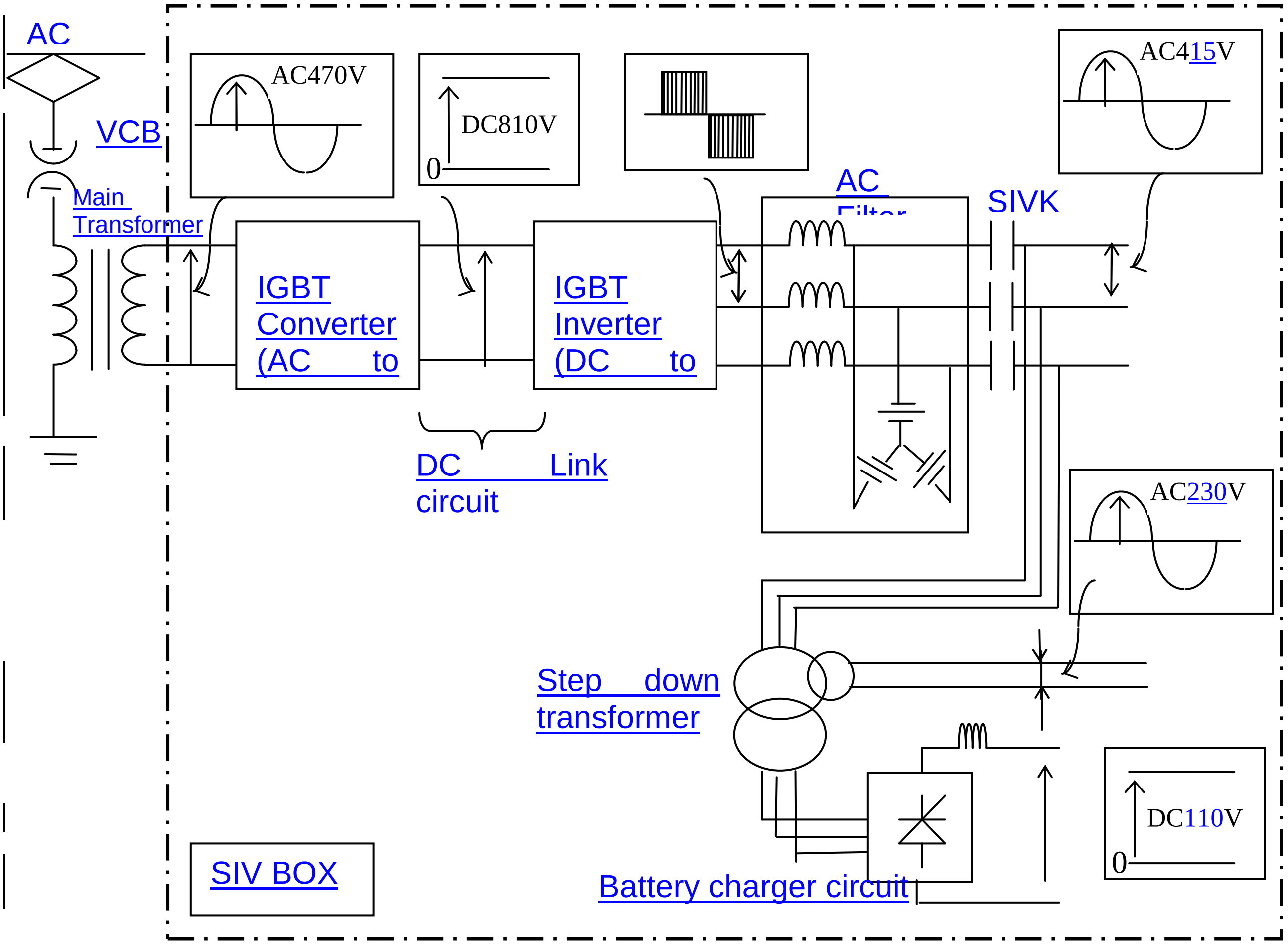


Fig. 11- block diagram of static inverter

The different components/Sub system of static inverter is given below:-

1. Input Circuit
2. Converter circuit
3. DC Link circuit
4. Constant Voltage Constant Frequency Inverter Circuit

5. Output AC filter circuit
6. SIVK Contactor
7. Grounding detection circuit
8. Battery Charger Box
9. Gate control unit Circuit

Functional details of each component/sub-system are given below:-

1. Input Circuit

A 470 V AC, single-phase power is supplied from the catenary through the tertiary windings of the main transformer. Input contactors (IVK1 and IVK2) of static inverter are installed on the tertiary windings at the main transformer. IVK2 (Charging Contactor) is turned on for initial charging of the filter capacitor (FCU). Charging resistor (RC) which in series with IVK2 prevents the flow of inrush current on filter capacitor (FCU) charging condition. After IVK2 turns on, FCU is charged up to approximately 580V.

Input filter reactor (ACL1) function is smoothening of SIV input current by decreasing high Harmonic Current. IVK1 is turned on after initial charging, and remain turned ON and turned off when SIV stopped.

VDT1 is transformer for detecting SIV input voltage, and HCT is current transformer for detecting SIV input current. PTVD is Potential transformer used for detecting the phase of catenary voltage for Converter control.

Converter Circuit

The PWM Converter rectifies the 470 V AC, single-phase to 810 V DC. Four sets of SiC power device are used in the Converter portion. The switching frequency for the Converter is 5300 Hz. The DC link voltage is 810 V and the DC link condition is stabilized under constant input voltage variations and output load variation. The control method of the converter is of Pulse Width Modulation (PWM) control using four large capacity SiC power devices.

Gate control is carried out through the gate drive unit.

DC Link Circuit

In order to obtain the stabilized operation of the Inverter, the DC link voltage (810V) is kept constant against the variation of the Centenary’s input voltage and output load conditions. The control is done by the PWM Converter. A large capacity Filter Capacitor (FC) is provided to absorb ripple produced by the

Converter output. VS1 is voltage sensor for detecting DC circuit voltage.

Earthing switch (GS) is used for discharging filter capacitor voltage, for safety of maintenance personal.

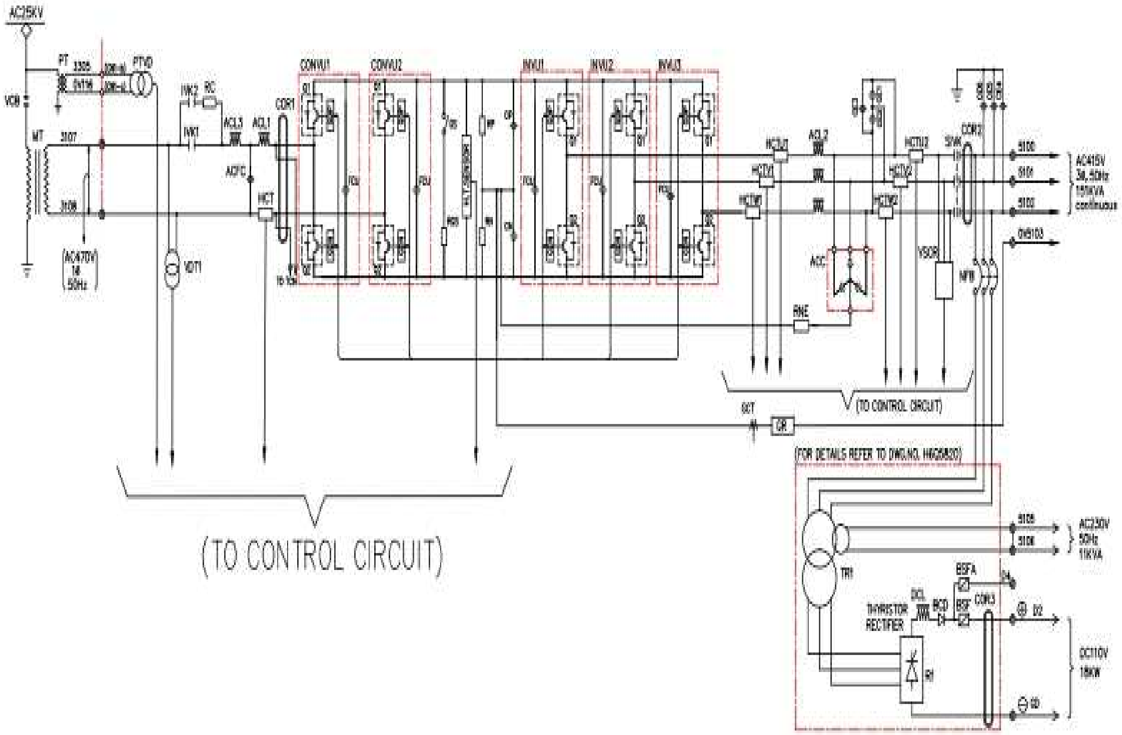


Fig. No.11.1 Control & Power Circuit of SIV

26

Fig 11.1 Control & Power circuit of SIV

Constant Voltage Constant Frequency Inverter Circuit

The Constant Voltage and Constant Frequency (CVCF) Inverter has the function to convert 810 V DC link voltage to 415 V AC three-phase to provide three-phase AC power for the on-board Equipment. The Inverter consists of three sets of SiC power devices. The control method of the Inverter is of 2-level PWM method using SiC power devices.

The switching frequency for the Inverter is 5500 Hz.

Output AC Filter Circuit

The output AC filter circuit consists of filter capacitors (ACC) and filter reactor (ACL2). The output AC filter makes 3-phase sign wave output by eliminating the switching ripples and harmonics. Thus the waveform distortion is lesser.

HCTU1, HCTV1, HCTW1 are Current Transformers for detecting Inverter output current to use current control (control loop). HCTU2, HCTV2, HCTW2 are Current Transformers for detecting SIV output current.

SIV K Contactor

The SIV K1 Contactor isolates the output of SIV Box from the Auxiliary Loads.

Grounding Detection Circuit

The earthing point of the SIV is the middle potential of the AC filter capacitor (ACC). The potential of this point is the earth potential. Ground fault is detected by the current sensor (GCT). All output circuits and the Electrical Equipment should be isolated from the earth potential.

Any earthing failure, not only of the output circuits / Equipment, but also of the input circuit of the SIV is detected with this grounding circuit to cut off the VCB (Vacuum Circuit Breaker).The ground detection circuit is available even if the SIV operation is isolated.

230 V 1-Ø phase Output Circuit

SIV output 3- Ø 415 V is being tapped and then feeded to a isolation transformer. This isolation transformer has one input winding and 2 output winding. First output winding generate 230 V 1-Ø phase output which is further used in train by 1-Ø loads.

110 VDC Output Circuit

2nd output winding of isolation transformer generates 94 V 3- Ø output. This output further goes to a rectifier circuit. This rectifier circuit, further generates 110 VDC output, which is further used in train by 1-Ø loads.

Gate Control Unit Circuit

The system control consists of High frequency independent PWM control, Three-phase independent control and Instantaneous voltage waveform control.

The Control Circuit has the fault data logging function, which stores all fault waveforms and identifications. This data is available for output.

The Control Unit carries out the following functions

1. Converter control function
2. Inverter control function
3. Input and output protection against the abnormal operations.
4. Self-diagnostic functions
5. Serial transmission for TCMS (Train control & monitoring system) for different status.

3.3 Loads being Feeded by Static Inverter

Followings are the loads being feeded by static inverter:-

- **3 Phase Loads:-**
-

1. Air-conditioners
2. Blower Motors
3. Transformer Oil Pump Motors
4. Air compressors

- **1 Phase Loads:-**

4. Saloon Light
5. Maintenance Socket
6. Charging Sockets

- **110 VDC Loads:-**

3 Battery Charging

4 DC saloon light

3.3.1 Performance Specification of SIV

Type of output	AC output	AC output	DC output
Rated voltage	AC415V ± 5%	AC230V ± 5%	DC110V ± 5%
Rated frequency	50Hz ± 1%	50Hz ± 1%	-
Rated capacity	151kVA	11kVA	18kW
Output voltage distortion	Below 5%	Below 5%	-
Overload Capacity	150%, 10sec.	100% continuous	100% continuous

3.4 Control theory of SIV Converter & Inverter

Control functions of PWM Converter

The PWM converter is controlled on a stable condition by the following control operations against the following disturbances.

1. Primary Voltage Fluctuation
2. Load Power Fluctuation
3. DC Link Voltage Fluctuation
4. Input Power Factor Fluctuation

Control Functions of PWM Inverter:-

The PWM inverter provides the control functions to control its output voltage to provide stable and distortion less voltage 415 V AC.

Control Operation of PWM Inverter

Followings are the disturbance against which PWM inverter provide control functions to control it:-

1. Load Power Fluctuation
2. Output Voltage Fluctuation.

3.5 SIV Energy Consumption Calculation Method:-

Energy consumption of SIV is calculated by the following scheme.

The energy consumption of each SIV is calculated by the tertiary voltage of (instantaneous value) of main transformer using voltage sensor (VTD1) and input current (instantaneous value) using CT's installed on the respective tertiary winding.

SIV Input Side Energy Consumption:-

The energy consumption of input side of SIV is calculated by RMS value of primary voltage of main transformer and input current of SIV. SIV accumulates the calculated input energy. Calculation data is accumulated separately at the regenerative mode and non regenerative mode.

SIV Output Side Energy Consumption:-

The energy consumption of output side of SIV is calculated by RMS value of output voltage of SIV and output current of SIV. SIV accumulates the calculated output energy. Calculation data is accumulated separately at the regenerative mode and non regenerative mode.

3.6 Rating and specification of different component

Sl. No.	Description	Symbol	Nominal Value
1	Input Source Voltage	Vs	470 V, 1-phase, RMS
2	Input Source Voltage	Is	500 Amp (Peak) at 100% laod
3	DC Link Voltage	Vdc	810 VDC
4	Output Voltage	Vo	415V, 3- Phase, RMS
5	Output Current	Io	300 Amp, RMS at 100% laod
8	Power Output	Po	180 KW at 100% Load
9	Input Filter inductor	Ls	3 mH
10	DC Link Filter Capacitor	Fc	15000 µ F
11	Output Filter Capacitor	Filter C	100 µ F
12	Output Filter Inductor	Filter L	0.8 mH

CHAPTER 4

MATLAB Simulation, Model & Performance Evaluation

4.1 General: - To compare the efficiency improvement by using the SiC based MOSFET with Si IGBT used in metro train static inverter, MATLAB simulation has been done for different loading condition i.e. 50%, 75% & 100% of static inverter.

4.2 MATLAB Simulation with SI IGBT:-

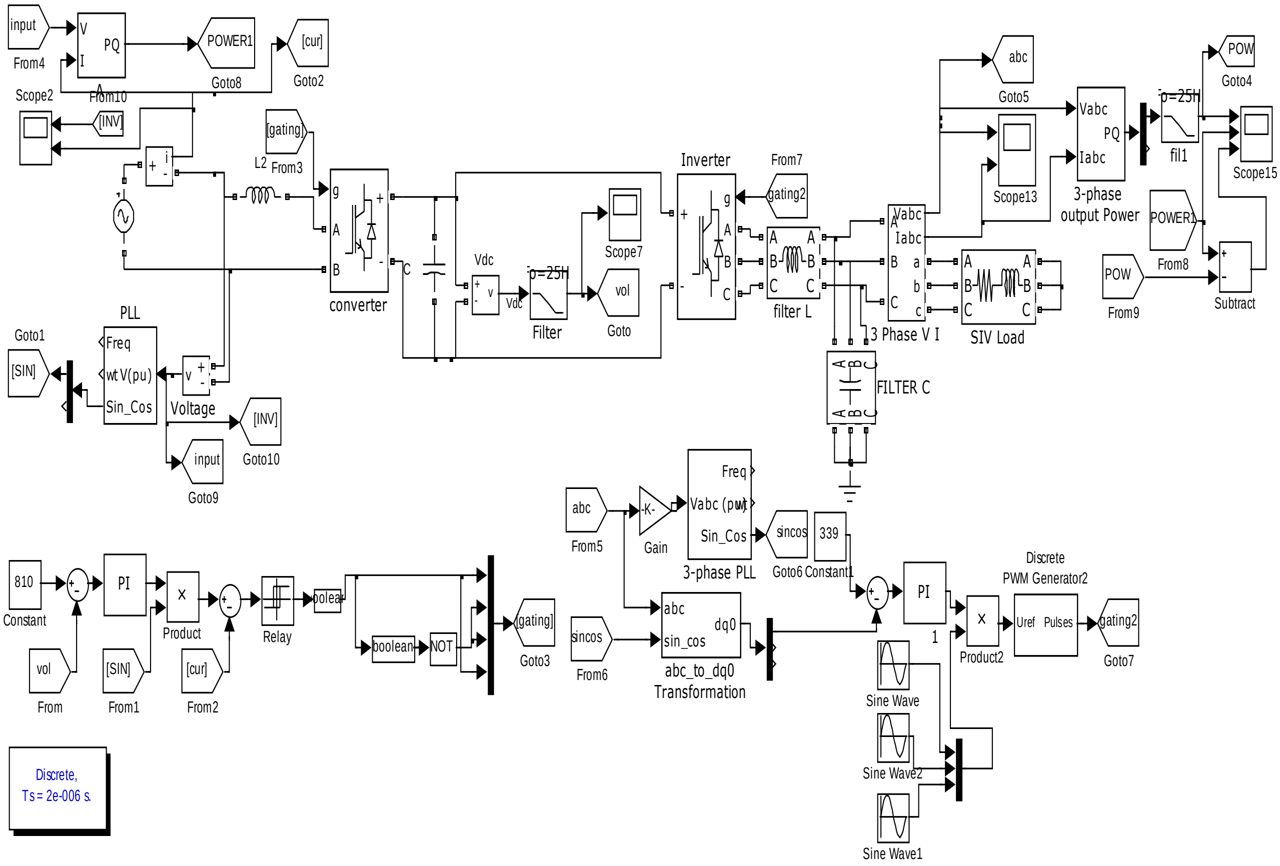


Fig. 12- MATLAB simulation with SI IGBT

4.2.1 Model Description:- Above figure shows MATLAB simulation circuit for SIV. This model represent for SIV with SI IGBT. It has following parts in power circuit,

1. Input Circuit
2. Converter circuit
3. DC Link Circuit
4. Inverter Circuit
5. Output Filter Circuit
6. Load Circuit
7. Input & Output power comparision

It has following control Circuit

1. Converter gate firing circuit to maintain DC link
2. Inverter Gate firing circuit.

Details of each parts is given below:-

1. Input Circuit: - 1- Ø, 664 V (Peak) is connected in input circuit. Input voltage is being measured by Scope2. Input current is also being measured by Scope2.

2. Converter Circuit:- IGBT based power converter is used here. Converter is converting 1- Ø to DC, which is further connected to DC Link circuit. Converter is connected to Input source through an input inductor (L_s). Converter gate firing circuit command is coming from a control circuit. Details of control circuit are given separately.

3. DC Link circuit: - Converter is generating DC link voltage which is 810 VDC. DC link voltage is being measured by Scope 7.

4. Inverter Circuit: - IGBT based power inverter is used here. Inverter is converting DC to 3-Ø 415 V, which is further connected with Output filter circuit. Inverter is connected to DC Link through an input inductor (L_s). Inverter gate firing circuit command is coming from a control circuit. Details of control circuit are given separately.

5. Output Filter Circuit:- 3-Ø L-C Filter is connected with inverter Output. This filter prevent harmonics to flow in load circuit and provide smooth, distortion less voltage to output load. Output Voltage and current is being measured by Scope 13.

6. Load Circuit: - 3-Ø, R-L Load is connected with output Voltage. This Load will be varied as per the different loading condition i.e. 100%, 75% & 50%.

7. Input & Output power comparison: - Input and output power is being measured by Scope 15. Difference between input and output power is also being measured by Scope 15.

Description of firing control circuits is given below:-

1. Converter Gate firing circuit to maintain DC link:- Here DC link voltage which is being measured by Scope 7 is being compared with Constant 810 and if DC link voltage is different from 810 V the error signal will be generated which will go to PI Controller. Output of PI will be multiplied by sin of input voltage. Output of multiplying block is being compared by input current and difference of it will go to relay unit for hysteresis. Output of relay unit will generate 4 nos gate firing command for each IGBT unit. In these 4 firing command 2 will be in same phase and other 2 will be opposite in phase as these will be passed through a not gate. These 4 commends will go to a multiplexor unit which will generate a single firing command which will go further to converter unit for firing of converter.

2. Inverter Gate firing circuit:- Here inverter output voltage which is being measured by Scope 13 is being compared with Constant 339 and if inverter output voltage is different from 339V (Phase to ground) then error signal will be generated which will go to PI Controller. Output of PI will be multiplied by sin of output voltage. Output of multiplying block is going to PWM generator. PWM generator generates gating pulse which will go further to inverter unit for firing of inverter.

Note: - This software simulation has been done for 50%, 75% & 100% loading condition of SIV by varying different R-L loading.

4.3 MATLAB Simulation with SIC MOSFET

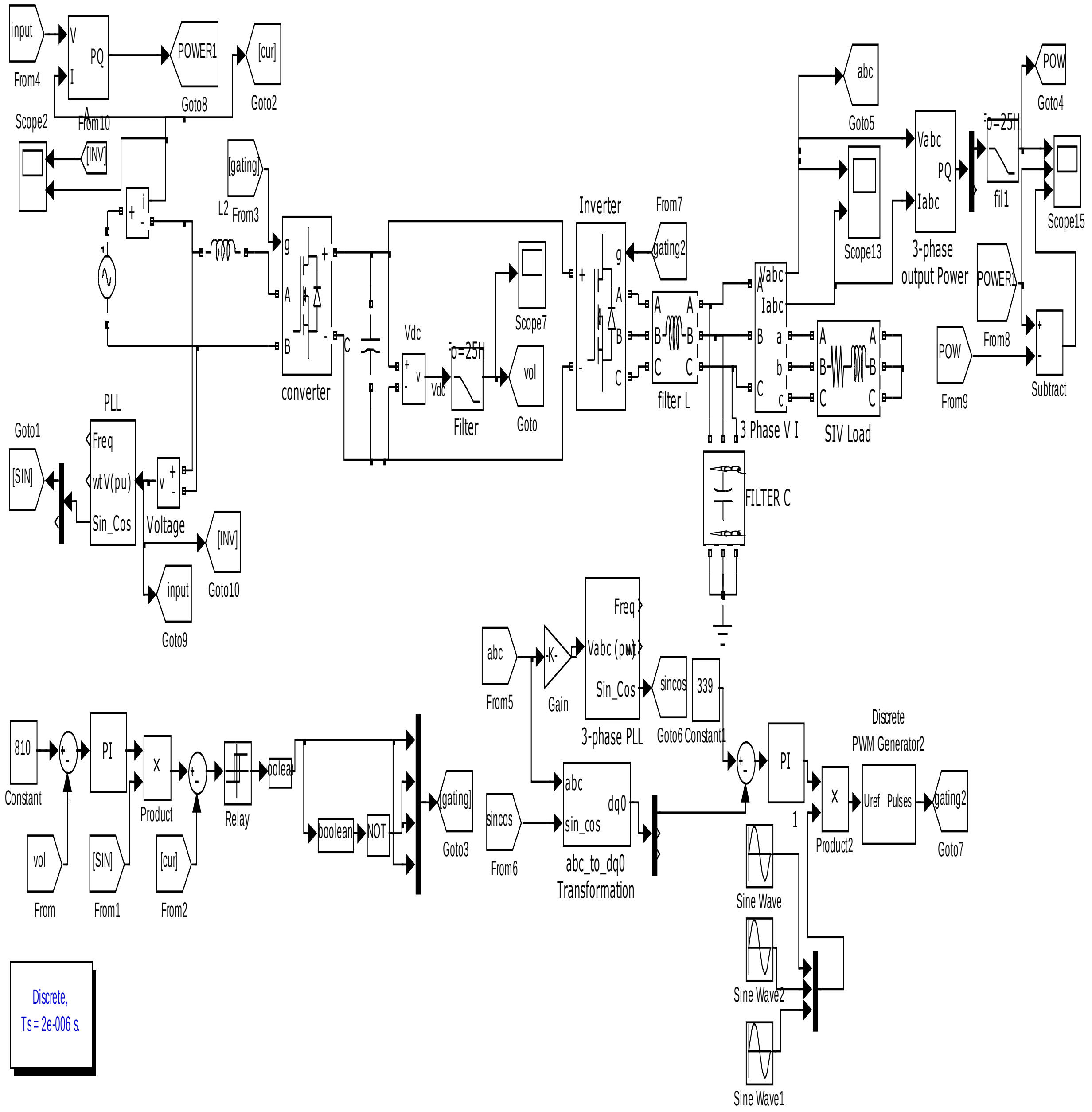


Fig. 13- MATLAB simulation with SIC MOSFET

4.3.1 Model Description

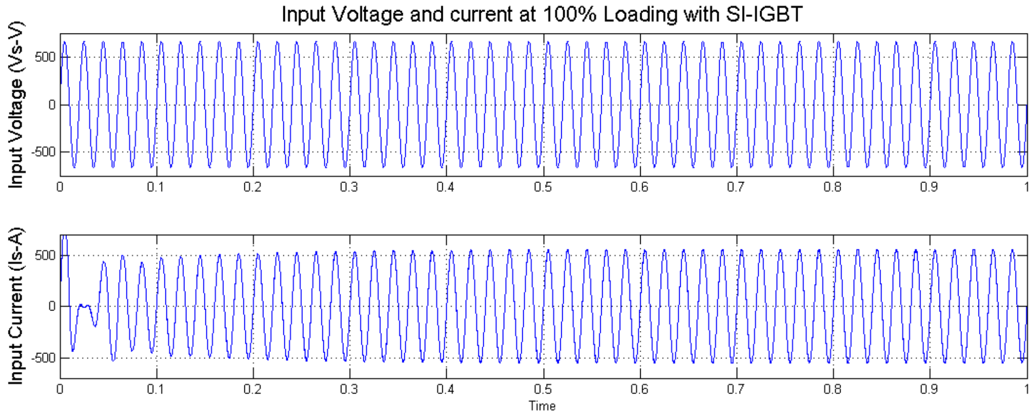
Above figure shows MATLAB simulation circuit for SIV. This model represent for SIV with SIC MOSFET. All components of this circuit are similar to figure -12 expect that all power devices are SIC based.

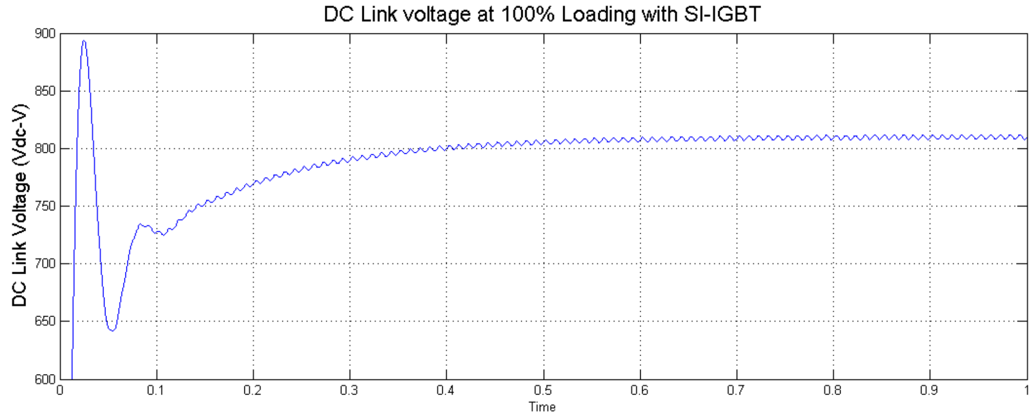
Description of this model is similar to as given in para 4.2.1.

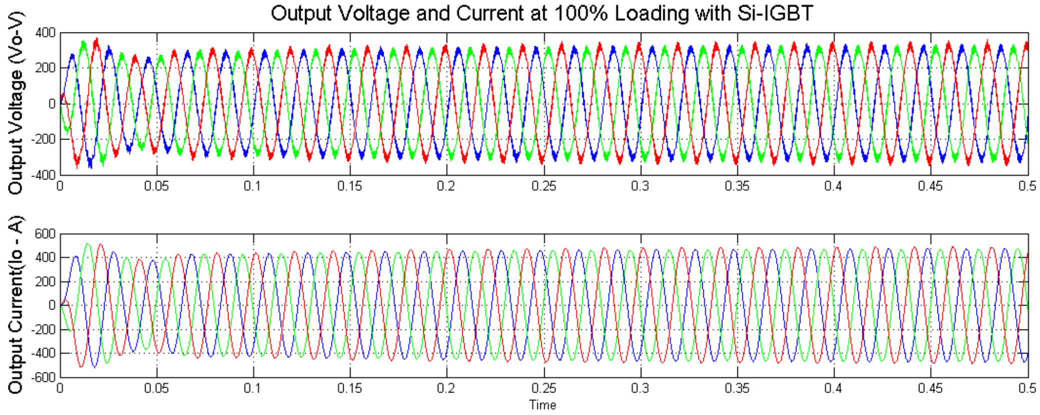
4.4 Waveforms

Simulation has been done for 50%, 75% & 100 % loading condition with both Si-IGBT and SiC MOSFET. So waveforms of different lloading condition are attached below:

4.5 Wave forms of SI-IGBT with 100% loading condition







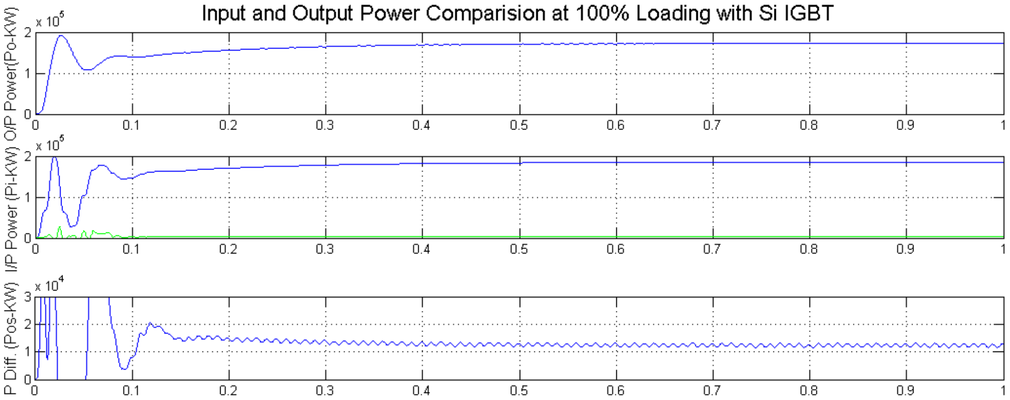
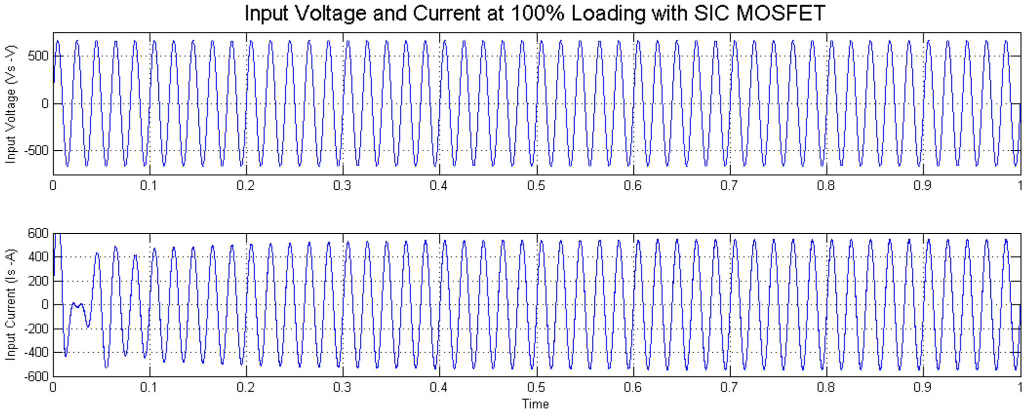


Fig. 14- Wave forms of SI-IGBT with 100% loading condition

4.5.1 Description of waveforms:-

Fig-14 shows wave forms of SI-IGBT with 100% loading condition. In this Figure , Input Voltage(Vs), Input Current (Is), DC Link Voltage (V_{dc}), Output Voltage (Vo), Output current (Io), Input Power (Pi), Output Power (Po) & Power difference (Pos) is being measured with respect to time. Here we can see that in graph-1 input voltage (Vs) is constantly maintained at 664 V (Peak). In graph-2, Input current (Is) is shown. It is almost constant as load is constant at 100% loading condition. Graph-3 is showing DC Link voltage (Vdc). DC link voltage is maintained at 810 V and it is constant. Graph-4 is showing output voltage (Vo). It is maintained constantly. Graph-5 is showing SIV output current (Io). Output current is also constant with respect to time. Graph-6 is showing output power consumption. Graph-7 is showing Input power supplied to SIV. Graph-8 is showing power difference between input power and output power. From graph-6, 7 & 8, it is clearly shown that Input power supplied to SIV is more that output power consumption by loads. Difference of both is equivalent to losses in SIV.

4.6 Wave forms of SIC-MOSFET with 100% loading condition



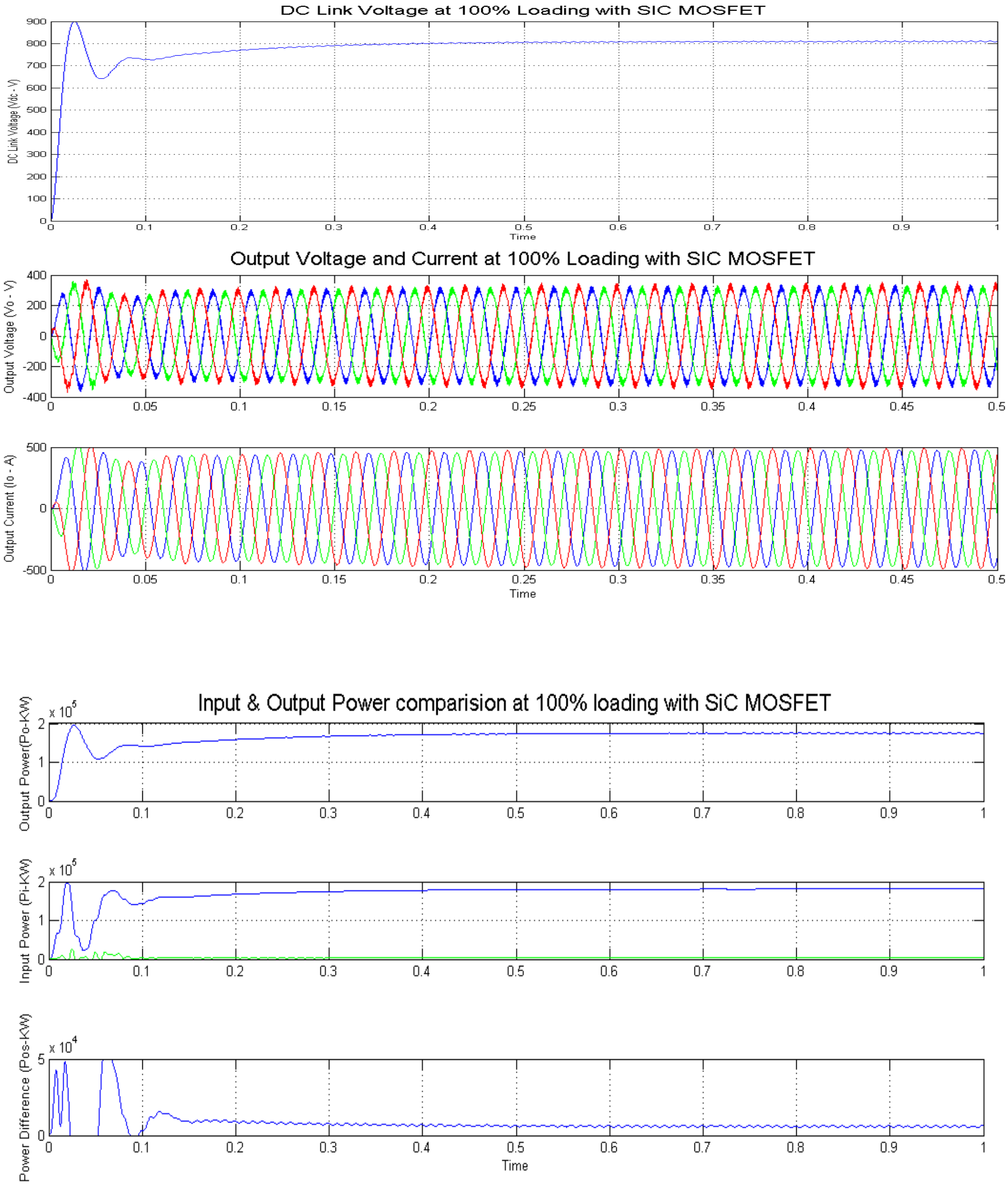
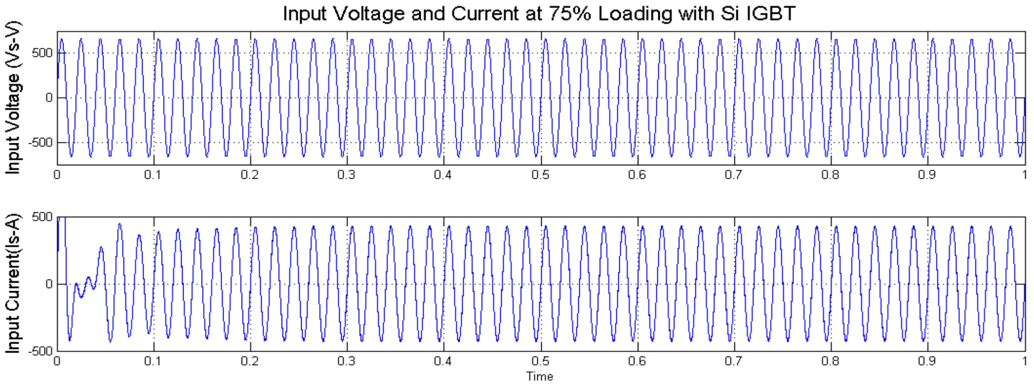


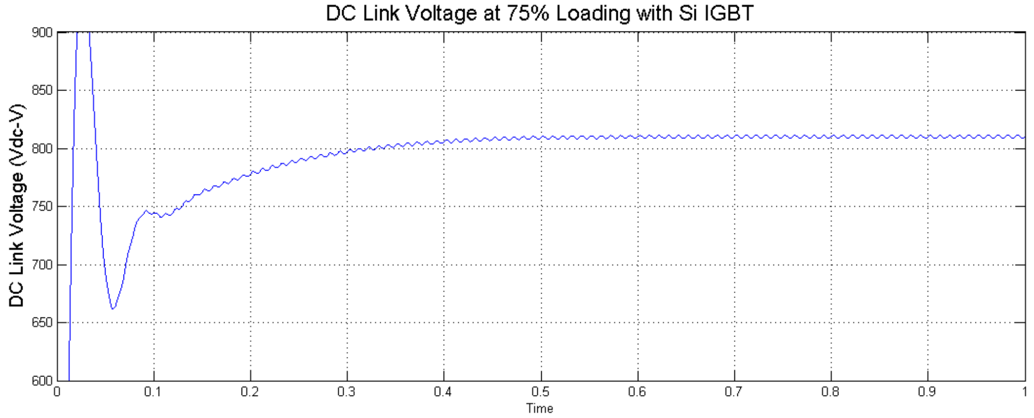
Fig. 15- Wave forms of SIC-MOSFET with 100% loading condition

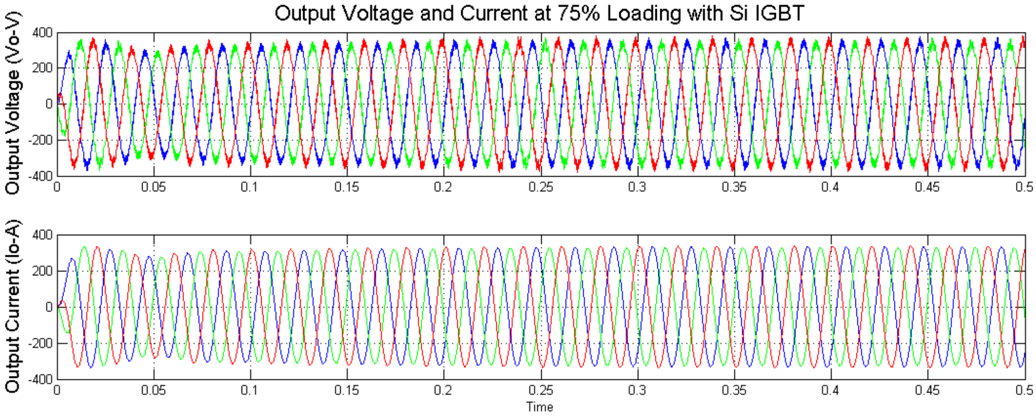
4.6.1 Description of Wave forms

Fig-15 shows wave forms of SIC-MOSFET with 100% loading condition. In this Figure , Input Voltage(Vs), Input Current (Is), DC Link Voltage (V_{dc}), Output Voltage (Vo), Output current (Io), Input Power (Pi), Output Power (Po) & Power difference (Pos) is being measured with respect to time. Here we can see that in graph-1 input voltage (Vs) is constantly maintained at 664 V (Peak). In graph-2, Input current (Is) is shown. It is almost constant as load is constant at 100% loading condition. Graph-3 is showing DC Link voltage (Vdc). DC link voltage is maintained at 810 V and it is constant. Graph-4 is showing output voltage (Vo). It is maintained constantly. Graph-5 is showing SIV output current (Io). Output current is also constant with respect to time. Graph-6 is showing output power consumption. Graph-7 is showing Input power supplied to SIV. Graph-8 is showing power difference between input power and output power. From graph-6, 7 & 8, it is clearly shown that Input power supplied to SIV is more that output power consumption by loads. Difference of both is equivalent to losses in SIV.

4.7 Wave forms of SI-IGBT with 75% loading condition







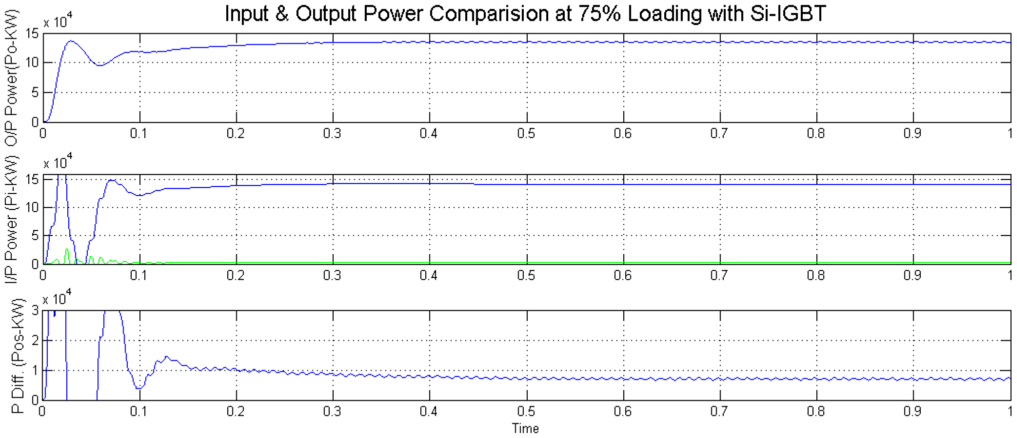
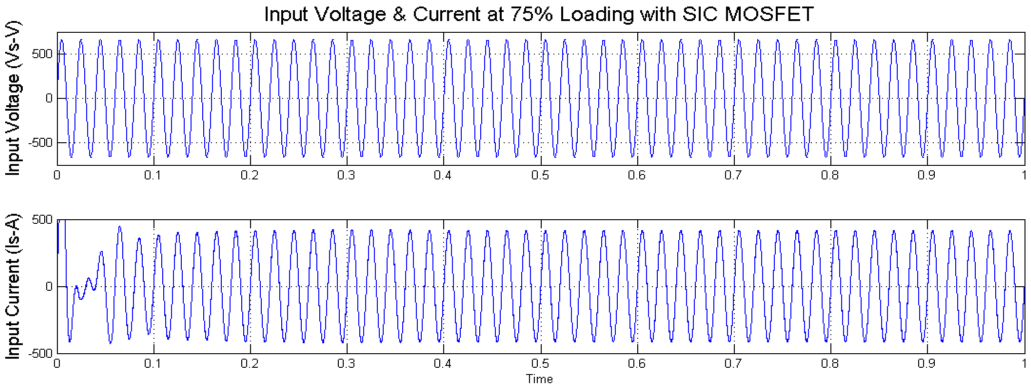


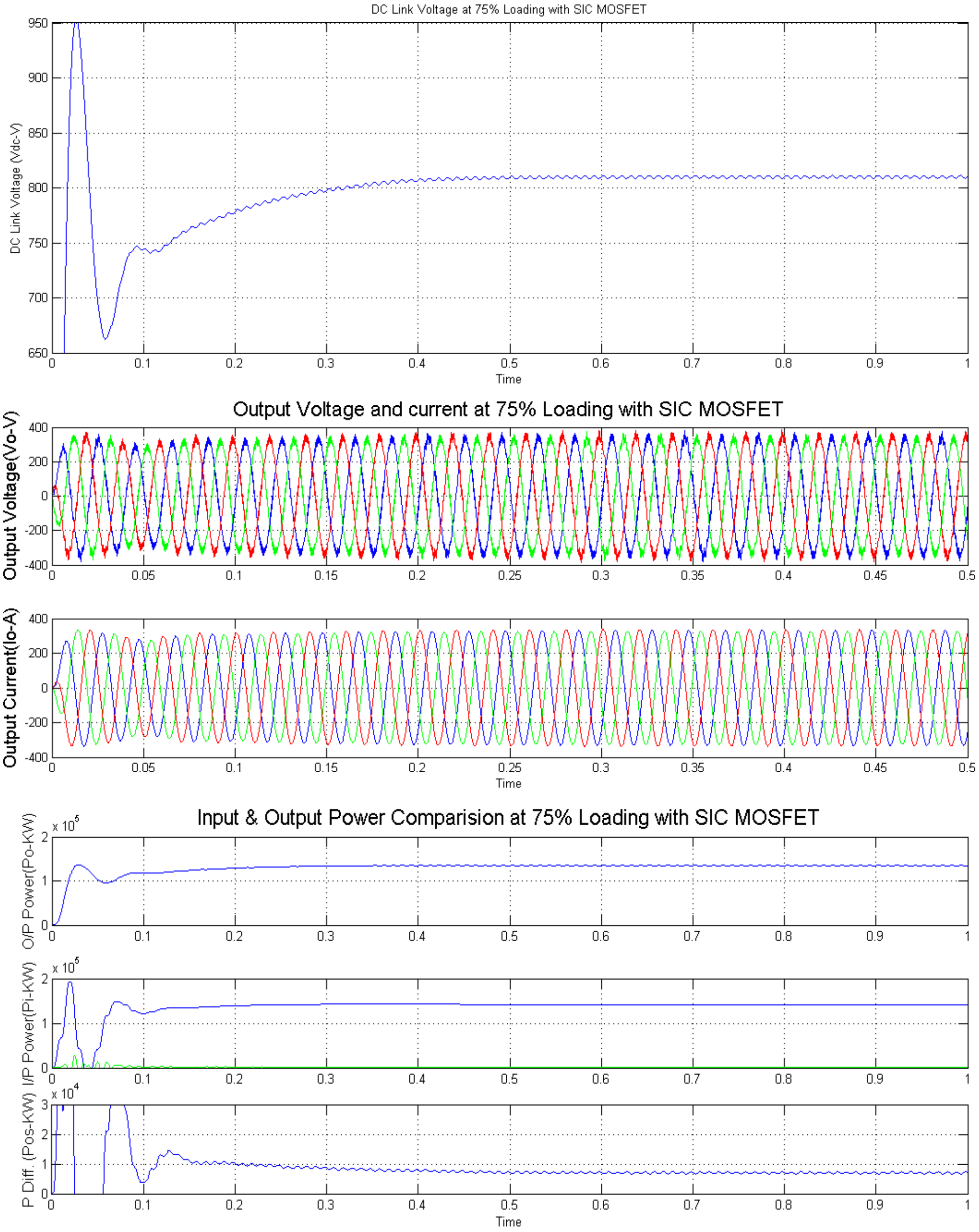
Fig. 16- Wave forms of SI-IGBT with 75% loading condition

4.7.1 Description of waveforms

Fig-16 shows wave forms of SI-IGBT with 75% loading condition. In this Figure , Input Voltage(Vs), Input Current (Is), DC Link Voltage (V_{dc}), Output Voltage (Vo), Output current (Io), Input Power (Pi), Output Power (Po) & Power difference (Pos) is being measured with respect to time. Here we can see that in graph-1 input voltage (Vs) is constantly maintained at 664 V (Peak). In graph-2, Input current (Is) is shown. It is almost constant as load is constant at 100% loading condition. Graph-3 is showing DC Link voltage (Vdc). DC link voltage is maintained at 810 V and it is constant. Graph-4 is showing output voltage (Vo). It is maintained constantly. Graph-5 is showing SIV output current (Io). Output current is also constant with respect to time. Graph-6 is showing output power consumption. Graph-7 is showing Input power supplied to SIV. Graph-8 is showing power difference between input power and output power. From graph-6, 7 & 8, it is clearly shown that Input power supplied to SIV is more that output power consumption by loads. Difference of both is equivalent to losses in SIV.

4.8 Wave forms of SIC-MOSFET with 75% loading condition





DC Link Voltage at 75% Loading with SIC MOSFET

Output Voltage and current at 75% Loading with SIC MOSFET

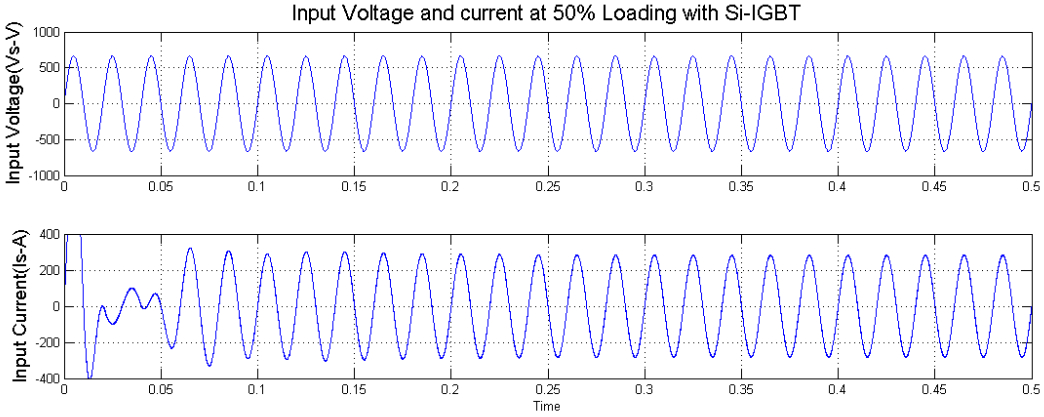
Input & Output Power Comparision at 75% Loading with SIC MOSFET

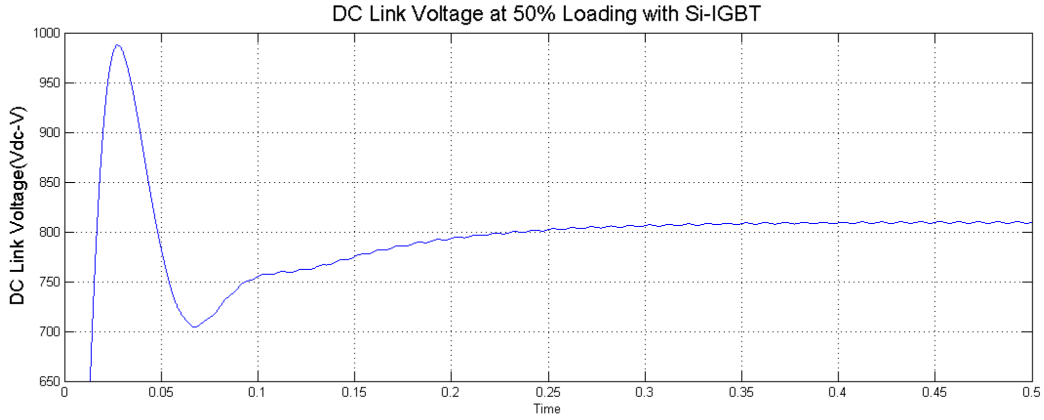
Fig. 17- Wave forms of SIC-MOSFET with 75% loading condition

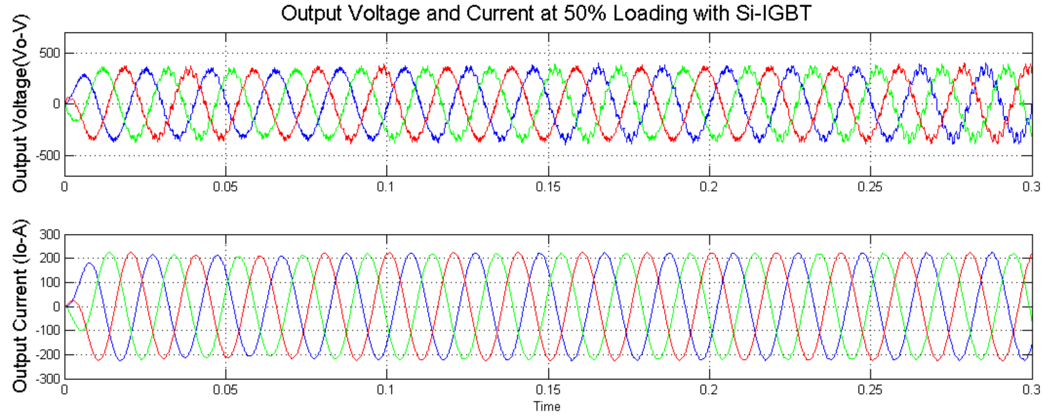
4.8.1 Description of waveforms

Fig-17 shows wave forms of SIC-MOSFET with 75% loading condition. In this Figure , Input Voltage(Vs), Input Current (Is), DC Link Voltage (V_{dc}), Output Voltage (Vo), Output current (Io), Input Power (Pi), Output Power (Po) & Power difference (Pos) is being measured with respect to time. Here we can see that in graph-1 input voltage (Vs) is constantly maintained at 664 V (Peak). In graph-2, Input current (Is) is shown. It is almost constant as load is constant at 100% loading condition. Graph-3 is showing DC Link voltage (Vdc). DC link voltage is maintained at 810 V and it is constant. Graph-4 is showing output voltage (Vo). It is maintained constantly. Graph-5 is showing SIV output current (Io). Output current is also constant with respect to time. Graph-6 is showing output power consumption. Graph-7 is showing Input power supplied to SIV. Graph-8 is showing power difference between input power and output power. From graph-6, 7 & 8, it is clearly shown that Input power supplied to SIV is more that output power consumption by loads. Difference of both is equivalent to losses in SIV.

4.9 Wave forms of SIC-IGBT with 50% loading condition


Input Voltage and current at 50% Loading with Si-IGBT


DC Link Voltage at 50% Loading with Si-IGBT


Output Voltage and Current at 50% Loading with Si-IGBT

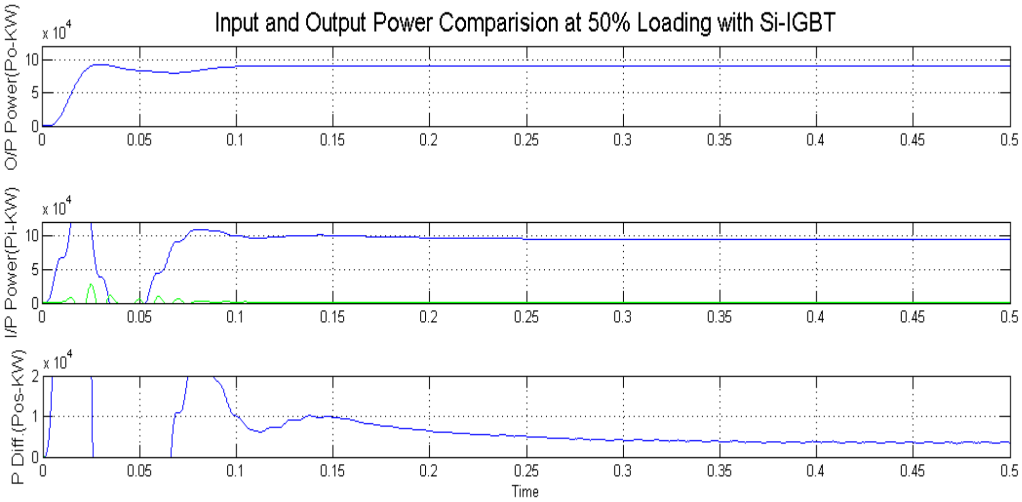
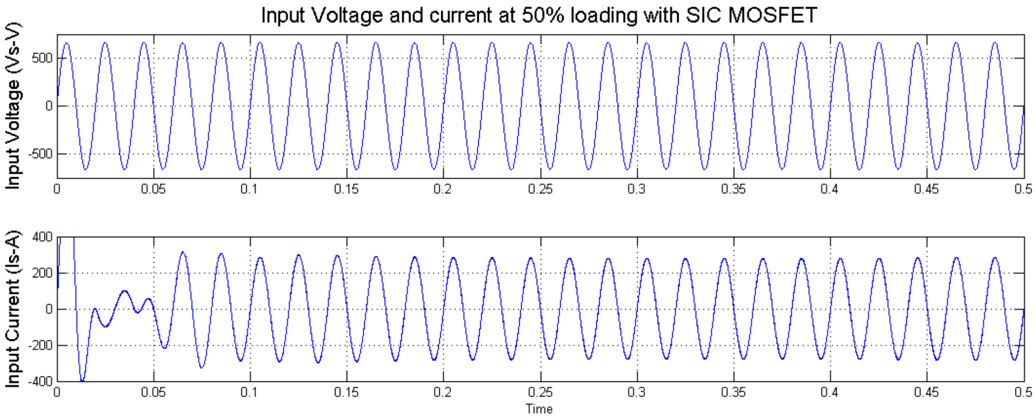


Fig. 18- Wave forms of SI-IGBT with 50% loading condition

4.9.1 Description of waveforms

Fig-18 shows wave forms of SIC-IGBT with 50% loading condition. In this Figure , Input Voltage(Vs), Input Current (Is), DC Link Voltage (V_{dc}), Output Voltage (Vo), Output current (Io), Input Power (Pi), Output Power (Po) & Power difference (Pos) is being measured with respect to time. Here we can see that in graph-1 input voltage (Vs) is constantly maintained at 664 V (Peak). In graph-2, Input current (Is) is shown. It is almost constant as load is constant at 100% loading condition. Graph-3 is showing DC Link voltage (Vdc). DC link voltage is maintained at 810 V and it is constant. Graph-4 is showing output voltage (Vo). It is maintained constantly. Graph-5 is showing SIV output current (Io). Output current is also constant with respect to time. Graph-6 is showing output power consumption. Graph-7 is showing Input power supplied to SIV. Graph-8 is showing power difference between input power and output power. From graph-6, 7 & 8, it is clearly shown that Input power supplied to SIV is more that output power consumption by loads. Difference of both is equivalent to losses in SIV.

4.10 Wave forms of SIC-MOSFET with 50% loading condition



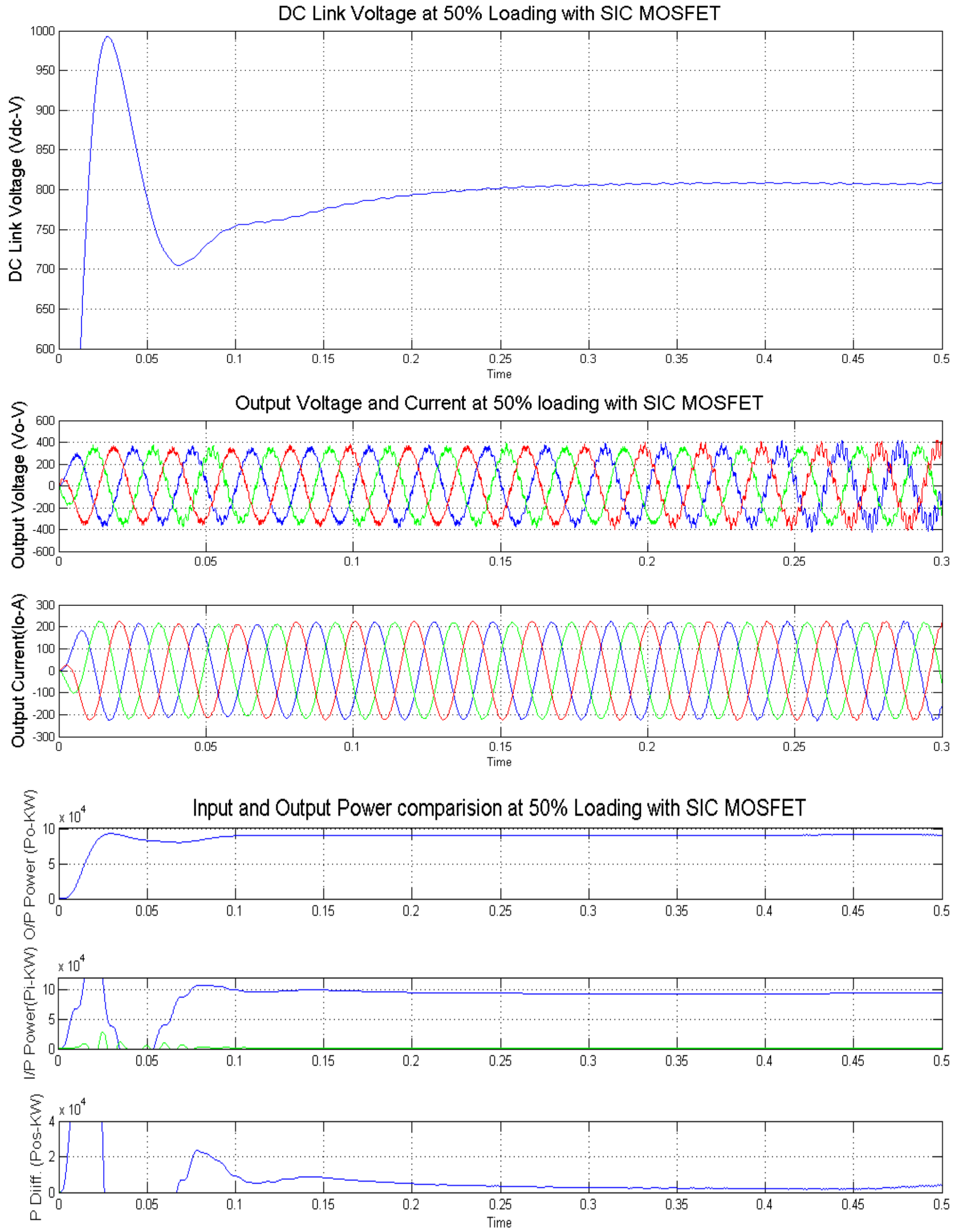


Fig. 19- Wave forms of SIC-MOSFET with 50% loading condition

4.10.1 Description of waveforms

Fig-19 shows wave forms of SIC-MOSFET with 50% loading condition. In this Figure , Input Voltage(Vs), Input Current (Is), DC Link Voltage (V_{dc}), Output Voltage (Vo), Output current (Io), Input Power (Pi), Output Power (Po) & Power difference (Pos) is being measured with respect to time. Here we can see that in graph-1 input voltage (Vs) is constantly maintained at 664 V (Peak). In graph-2, Input current (Is) is shown. It is almost constant as load is constant at 100% loading condition. Graph-3 is showing DC Link voltage (Vdc). DC link voltage is maintained at 810 V and it is constant. Graph-4 is showing output voltage (Vo). It is maintained constantly. Graph-5 is showing SIV output current (Io). Output current is also constant with respect to time. Graph-6 is showing output power consumption. Graph-7 is showing Input power supplied to SIV. Graph-8 is showing power difference between input power and output power. From graph-6, 7 & 8, it is clearly shown that Input power supplied to SIV is more that output power consumption by loads. Difference of both is equivalent to losses in SIV.

4.11 Selection of Impedence for different loading condition:-

For MATLAB simulation of different loading condition of static inverter, impedence connected as SIV laod has been varied. Calculation for load components for different loading condition is given below:-

4.11.1 For 100% Loading:-

SIV 100% Load = 180 KW

Assume Load Power Factor = 0.8

Assume Load connected in Star connection

$V_L = 415$ V

$V_{ph} = 415/\sqrt{3} = 239.60$ V

$P = 3 \times V_{ph} \times I_{ph} \times \cos \text{Ø}$

So, $I_{ph} = P/3 \times V_{ph} \times \cos \text{Ø}$

$I_{ph} = 180000/3 \times 239.6 \times 0.8 = 313.6$ Amp

In star Connection Phase current I_{ph} = Line Current I_L

So Per phase Impedance = 239.60/313.6 = 0.7 Ω

As power factor is 0.8 so by calculation

Load Resistance $R_{\text{per phase}} = 0.56\ \Omega$

Load Inductance $L_{\text{per phase}} = 1.3375$ mH.

4.11.2 For 75% Loading:-

SIV 75% Load = 135 KW

Assume Load Power Factor = 0.8

Assume Load connected in Star connection

$V_L = 415$ V

$V_{ph} = 415/\sqrt{3} = 239.60$ V

$P = 3 \times V_{ph} \times I_{ph} \times \cos \text{Ø}$

So, $I_{ph} = P/3 \times V_{ph} \times \cos \text{Ø}$

$I_{ph} = 135000/3 \times 239.6 \times 0.8 = 234.375$ Amp

In star Connection Phase current I_{ph} = Line Current I_L

So Per phase Impedance = 239.6/234.375 = 1.024 Ω

As power factor is 0.8 so by calculation

Load Resistance $R_{\text{per phase}}$ = 0.8192 Ω

Load Inductance $L_{\text{per phase}}$ = 1.956 mH.

4.11.3 For 50% Loading:-

SIV 50% Load = 90 KW

Assume Load Power Factor = 0.8

Assume Load connected in Star connection

V_L = 415 V

V_{ph} = 415/√3 = 239.60 V

P = 3 x V_{ph} x I_{ph} x Cos Ø

So, $I_{ph\,=}$ P/3 x V_{ph} x Cos Ø

I_{ph} = 90000/3 x 239.6 x 0.8 = 156.25 Amp

In star Connection Phase current I_{ph} = Line Current I_L

So Per phase Impedance = 239.6/156.25 = 1.536 Ω

As power factor is 0.8 so by calculation

Load Resistance $R_{\text{per phase}}$ = 0.1.2288 Ω

Load Inductance $L_{\text{per phase}}$ = 2.935mH.

4.11.4 Summary of calculation

For MATLAB simulation of different loading condition of static inverter, impedence connected as SIV laod has been varied as per below values:-

50% Loading condition: -

Z= 1.536 Ω /Phase

R = 1.2288 Ω /Phase

L = 2.935 mH

75% Loading condition: -

Z= 1.02 Ω /phase

R= 0.8192 Ω /phase

L= 1.956 mH

100% Loading condition: -

Z= .70 Ω /phase

R= 0.56 Ω /phase

L= 1.3375 mH

4.12 Performance Evaluation of using SIC based MOSFET Vs Si IGBT

MATLAB simulation has been done for 50%, 75% & 100% loading condition. Based on result of simulations, calculation of system efficiency is given below:-

If we consider a constant time for power consumption, then the ratio of output power and input power will give efficiency of the system.

Calculation of system efficiency with different loading is given below:-

4.12.1 For 100% Loading:-

With SI- IGBT

Output Power = 173.2 KW
Input Power = 185 KW
SIV efficiency = 173.2 x 100/185 = 93.2%

With SIC- MOSFET

Output Power = 174.5 KW
Input Power = 180.8 KW
SIV efficiency = 174.5 x 100/180.8 = 96.5%

4.12.2 For 75% Loading:-

With SI- IGBT

Output Power = 134.8 KW
Input Power = 142.7 KW
SIV efficiency = 134.8 x 100/142.7 = 94.46%

With SIC- MOSFET

Output Power = 134.8 KW
Input Power = 138.4 KW
SIV efficiency = 134.8 x 100/138.4 = 97.3%

4.12.3 For 50% Loading:-

With SI- IGBT

Output Power = 89.6 KW
Input Power = 94.2 KW
SIV efficiency = 89.6 x 100/94.2 = 95.1%

With SIC- MOSFET

Output Power = 89.8 KW
Input Power = 92.5 KW
SIV efficiency = 89.8 x 100/92.5 = 97.3%

4.12.4 Summary of Results

After MATLAB simulation all results have been comapred as per different loading condition. Summary of results are given below:-

Sl. No.	**Load %**	**Si-IGBT**	**SiC- MOSFET**
		Efficiency	**Efficiency**
1	50%	95.1%	97.3%
2	75%	94.4%	97.3%
3	100%	93.2%	96.5%

From above data it is concluded that SiC MOSFET based converter is having more efficiency than that of Si based IGBT converter.

CHAPTER 5

Main Conclusions and Future Scope of Work

5.1 Main Conclusion:-

As per MATLAB simulation, it is concluded that efficiency of system improved in the range of 3-4% at each 50%, 75% & 100% loading condition.

5.2 Future Scope of Work

Presently SiC based devices has been developed for 1200 volt, so it is being start to use in static inverter of Metro train as static inverter operates at < 1000 Volt. But metro train Traction system which operates at higher voltage (Approx 2 KV), it cannot be used at present. So dedicated effort to be made for development of high voltage SiC devices in future, so that it can be used in high voltage applications. As traction system consumes huge power, so by use of SiC devices we will be able to save large power.

In addition to above, Presently IGBT and MOSFET are being used as Power Electronics devices at many areas. As researchers already accepted the improvement of SiC based devices and involved in development of SiC based devices so in future, those area’s conventional devices may be replaced with SiC devices to achieve better performance and energy saving.

At present SiC devices are having Turn-ON delay, Turn-OFF dalay, Reverse Recovery time in the range of Nano Seconds. In future we may try to develop lesser time value of these parameters, which would leads to better performance of these devices.

CHAPTER 6

REFERENCES:-

1. Tatsuya Matsukawa, Ryuichi Shimadaa, “Efficiency Improvement of AC/DC Converter Using SiC-based Power Electronics Device”, 2003.
2. Qiaoliang CHEN, Xu YANG, “Practical Design Considerations for IPEM-based PFC Converter Employing Cool MOS and SiC Diode”, 2006.
3. S. Mounce, B. McPherson, R. Schupbach, A. B. Lostetter, “Ultra-Lightweight, High Efficiency SiC Based Power Electronic Converters for Extreme Environments”, 2006,
4. Hui Zhang, Leon M. Tolbert, Burak Ozpineci, Madhu S. Chinthavali, “A SiC-Based Converter as a Utility Interface for a Battery System”, 2006.
5. D. Aggeler, J. Biela, J. W. Kolar, “A compact, high voltage 25kW, 50 kHz DC-DC converter based on SiC JFETs”, 2008.
6. Jun Wang, Jun Li, Xiaohu Zhou, Tiefu Zhao, Alex Q. Huang,” 10 kV SiC MOSFET Based Boost Converter”, 2008.
7. Jun Wang, Student Member, IEEE, Xiaohu Zhou, Student Member, IEEE, Jun Li, Tiefu Zhao, Student Member, IEEE, Alex Q. Huang, Fellow, IEEE, Robert Callanan, Fatima Husna, and Anant Agarwal, Member, IEEE,” 10 kV SiC MOSFET Based Boost Converter”, 2009.
8. A. Hensel, C. Wilhelm, D. Kranzer, “Development of a Boost Converter for PV Systems based on SiC BJTs”.
9. Zhang Chao, Tang Xiao-Yan, Zhang Yu-Ming, Wang Wen, Zhang Yi-Men,” a DC-DC boost converter based on SiC MOSFET and SiC SBD”, 2011.
10. O. Mostaghimi, D.R.Brennan, N.G. Wright, A.B. Horsfall,” A New SiC/SOI-based PWM Generator for SiC-based Power Converters in High Temperature Environments”, 2012.
11. Omid Mostaghimi, Nick Wright, Alton Horsfall,” Design and Performance Evaluation of SiC Based DC-DC Converters for PV Applications, 2012.
12. Gangyao Wang, Alex Huang, ZVS Range Extension of 10A 15kV SiC MOSFET Based 20kW Dual Active Half Bridge (DHB) DC-DC Converter”, 2012.
13. Biao Zhao, Qiang Song, Wenhua Liu, Yandong Sun, “ Characterization and Application of Next Generation SiC Power Devices for High-Frequency Isolated Bidirectional DC-DC Converter”, 2012.
14. Biao Zhao, Experimental Comparison of Isolated Bidirectional DC–DC Converters Based on All-Si and All-SiC Power Devices for Next-Generation Power Conversion Application”, 2014.
15. A. Vazquez, A. Rodriguez, M. Fernandez, M.M. Hernando, J. Sebastian, “On the Use of Front-End Cascode Rectifiers Based on Normally-on SiC JFET and Si MOSFET”, 2013.

16. Lars Hiller and Jörg Pezoldt, “AlGaN/GaN Three-Terminal Junction Devices for Rectification and Transistor Applications on 3C-SiC/Si Pseudosubstrates”,2013.
17. Aitor V´azquez, “On the Use of Front-End Cascode Rectifiers Based on Normally On SiC JFET and Si MOSFET”, 2014.
18. Di Han, Jukkrit Noppakunkajorn,” Efficiency Comparison of SiC and Si-Based Bidirectional DC-DC Converters”, 2013.
19. Yusuke Hayashi, Akira Matsumoto,” Fundamental Study of an Intelligent Power Routing Switch Based on SiC DC–DC Converter for Next Generation DC Distribution Network”.
20. Sachin Madhusoodhanan,” Comparative Evaluation of SiC Devices for PWM Buck Rectifier Based Active Front End Converter for MV Grid Interface”, 2013.
21. Samir Hazra, Sachin Madhusoodhanan, Subhashish Bhattacharya,” Design Considerations and Performance Evaluation of 1200 V, 100 A SiC MOSFET Based Converter for High Power Density Application”, 2013.
22. Rasmus Ørndrup Nielsen,”Efficiency and Cost Comparison of Si IGBT and SiC JFET Isolated DC/DC Converters”, 2013.
23. Szymon Piasecki, “Jacek Rąbkowski, Grzegorz Wrona, Tadeusz Płatek,” SiC-Based Support Converter for Passive Front-End AC Drive Applications”, 2013.
24. Hesam Mirzaee, “Design Comparison of High-Power Medium-Voltage Converters Based on a 6.5-kV Si-IGBT/Si-PiN Diode, a 6.5-kV Si-IGBT/SiC-JBS Diode, and a 10-kV SiC-MOSFET/SiC-JBS Diode”, 2014.
25. Jonathan K. Hayes1, Andrés Escobar-Mejía2, Juan Carlos Balda3, Atanu Dutta4, Simon S. Ang5,” Realization of a SiC Module-Based Indirect Matrix Converter with Minimum Parasitic Inductances”, 2014.
26. Héctor Sarnago,” SiC BJT-based Full-ZCS Quasi-Resonant Converter with Improved Efficiency for Induction Heating Applications.
27. Luigi Abbatelli, Michele Macauda, Giuseppe Catalisano,” Fully SiC based High Efficiency Boost Converter”, 2014.
28. Di Han, “Comprehensive Efficiency, Weight, and Volume Comparison of SiC- and Si-Based Bidirectional DC–DC Converters for Hybrid Electric Vehicles”, 2014.
29. Luigi Abbatelli,” Cost Benefits on High Frequency Converter system based on SiC MOSFET approach”, 2014.
30. Emre Gurpinar,” Performance Analysis of SiC MOSFET Based 3-Level ANPC Grid-Connected Inverter with Novel Modulation Scheme”, 2014.
31. Liyao Wu, “Efficiency Evaluation of the Modular Multilevel Converter Based on Si and SiC Switching Devices for Medium/High-Voltage Applications”, 2015.
32. Sachin Madhusoodhanan, “Solid-State Transformer and MV Grid Tie Applications Enabled by 15 kV SiC IGBTs and 10 kV SiC MOSFETs Based Multilevel Converters”, 2015.

33. Liyao Wu, Jiangchao Qin, and Maryam Saeedifard,” Loss Comparison of Si- and SiC-Based Modular Multilevel Converter for Medium/High-Voltag Applications”, 2015.
34. Georgios Kampitsis, Michail Antivachis, Sotirios Kokosis,” An Accurate Matlab/Simulink Based SiC MOSFET Model for Power Converter Applications”, 2015.
35. Samir Hazra, High Switching Performance of 1700-V, 50-A SiC Power MOSFET Over Si IGBT/Bi MOSFET for Advanced Power Conversion Applications”, 2016.
36. Antonio León-Masich, Hugo Valderrama-Blavi, Josep María Bosque-Moncusí, Efficiency comparison between Si and SiC-based implementations in a high gain DC–DC boost converter”, 2015.
37. J. Nicolas-Apruzzese, “Efficiency Comparison between SiC- and Si-based Active Neutral-Point Clamped Converters”, 2015.
38. Alberto Ferro1, Elena Gaio1, Matteo Tomasini2, Paolo Milani2, Emanuele Massarelli2, Makoto Matsukawa3, Luca Novello4,” A 72 kVA very fast four-quadrant converter based on hybrid Si-SiC IGBTs”.
39. Sandra Zeljkovic, Radovan Vuletic, Andreas Miller and Alann Denais,” A Three Phase Bidirectional V2G Interface Converter Based on SiC JFETs”.
40. Sachin Madhusoodhanan, Krishna Mainali, Awneesh Tripathi, Dhaval Patel, Arun Kadavelugu, Subhashish Bhattacharya,” Performance Evaluation of 15 kV SiC IGBT based Medium Voltage Grid Connected Three-Phase Three-Level NPC Converter”, 2015.
41. Szymon Pisecki, Jacek Rąbkowski,” Experimental Investigations on the Grid-connected AC/DC Converter Based on Three-phase SiC MOSFET Module”.
42. Mengqi Wang, Qingyun Huang,” An Isolated Bi-directional High-Frequency-AC Link DC-AC Converter Using Hybrid SiC Switches with Carrier-Based Unipolar Modulation Technique”, 2015.
43. Nisha Kondrath and Mace Al-Chalabi;” Performance Evaluation of SiC Based Bidirectional DC-DC Buck-Boost Converter Operating in CCM using Temperature-Dependent L3 Spice Model”, 2015.
44. DMRC Design Documents 2015