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Comparitive Loss Evaluation of Si IGBT Versus Sic Mosfet (Silicon Carbide) for 3 Phase Spwm Inverter

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Abstract

Background/Objectives: Reducing the losses of 3 phase spwm 2 level inverter by replacing the present semi conductor switches which are si igbt (silicon) with the latest sic mosfet (silicon carbide) switches. **Methods/Statistical Analysis:** si igbt (silicon) and sic mosfet (silicon carbide) are modelled in pspice using the data sheet parameters and the modelled switches are used to simulate the three phase spwm inverter and the losses of the system are compared. **Findings:** The three phase spwm inverter simulated at switching frequency ranges of 5khz, 8khz, 10khz, 15khz and it had been observed that the losses of the 3 phase spwm sic mosfet inverter are 29% less for 5khz switching frequency, 34% less for switching frequency of 8khz, 37% less for switching frequency of 10khz, 42% less for the switching frequency of 15khz over the 3 phase spwm inverter based on si igbt. **Application/Improvements:** The sic mosfet can replace the si igbt in 3 phase spwm inverter system for better efficiency and the pspice simulations showed similar results showing that sic mosfet is efficient than si igbt based three phase spwm inverter.

Keywords: Insulated Gate bi Polar Transistor (IGBT), Losses, Metal Oxide Semi Conductor Field Effect Transistor (MOSFET), Silicon (Si), Silicon Carbide (SIC), Sine Pulse Width Modulation (SPWM)

1. Introduction

In 1992[1] UMOSFET was first among sic mosfet technology that was developed by cree. Later in 1997 Accufet (Accumulation-channel fet) was developed in NC State University by Dr. Baliga's group using 6h-sic dmos geometry and it was the first high voltage (350V) planar vertical sic (Accufet) developed with buried implanted region for shielding the gate oxide[2]. Later in 2001 2.4 KV 4h-sic Dimosfet having specific on state resistance of 42mΩcm2 was demonstrated by cree[3]. In 2004[4,5] Dr. James Coopers group of Purdue University developed 3KV, 5KV Umosfet of 4h-sic having junction termination extension (jte) and trench oxide protection. In 2004[6] 10kv, 4h-sic was developed by cree.

Large effort is put into sic research and development in recent years as the critical electric field of 4h-sic is 8.2 times larger than that of si. So there are more advantages in using sic devices as their electric break down field, electron saturated drift velocity, thermal conductivity, irradiation tolerance making sic available for high voltage, high temperature and frequency and also combining low power loss[8,9].

Considering case of 22kw inverters used to drive motors they conventionally employ si igbts that operate at max temperatures of 125ºc. That has to be mounted on larger heat sink. As they produce more losses on increasing the switching frequency and has to be cooled using forced air cooling or water cooling as their performance is limiting sic has gained more attention.

2. Semiconductor Property Related Application Advantages

Sic devices are expected to enable superior performance compared to si devices. In view of sic's excellent electrical and physical properties.

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Table 1. Semi conductor property based advantages of silicon carbide (sic) material over silicon (si) material

Semiconductor Properties (SiC/Si)	Device Expected Perfprmance (Sic / Si)	Equipment Lmpact	Achieved Performance (>1KV)
Melting Point 2X	High Temperature Operation 2x	Simple heat sinc	2x (300 degree C) 10 *3x (350 degree C)
Band Gap 3X	High breakdown Voltage 10x	Device number reduction	2.5 x(19.5kv) [12] *1x (12.5kv)
Breakdown Lield 10X	High Current density Low Loss 1/100x	Small size High efficiency	1/420x (23m ohm cmsqu) [13] *1/230x (690m ohm cmsqu) [14]
Thenmal Conductivity 3X	High Speed 10x	Small size High Speed	10x (28-100 ns) [15] *3 x (47ns) [14]
Saturation Carrier Velocity 2X			

2.1 Heat Sink

Higher melting point and higher band gap of the sic based device would allow higher temperature operation enabling the use of smaller heat sink compared to si based device.

2.2 Device Count

Higher break down field would result in having higher break down voltage reducing the device count.

2.3 Efficiency

Higher band gap and higher break down field and higher thermal conductivity are the reasons for sic having lower losses and higher efficiency.

2.4 Speed

Higher thermal conductivity and higher saturation carrier velocity would result in smaller seize and high speed operation.

3. System Specification

Two 3 phase spwm inverters are designed basing on si igbt and sic mosfets. Figure1 shows the circuit for the si igbt base 2 level 3 phase spwm inverter. Figure 2 shows the circuit for sic mosfet based 2 level 3 phase spwm inverter.

For si igbt 3 phase inverter six 1200V, 40A single si igbts are considered. The inverter operated at 3 ranges of switching frequencies 5khz, 10khz and 15khz. The inverter is controlled using spwm technique. For easy evaluation the power factor is taken as unity and the modulation index is also taken unity the system specification is in Table 1.

Table 2. System specification of si igbt based 3 phase inverter.

Dc voltage	586
Modulation method	SPWM
Modulation index	1
Switching frequency	5KHZ,1OKHZ,15KHZ
Power factor	1
Motor peak current	38A
Power rating	22KW

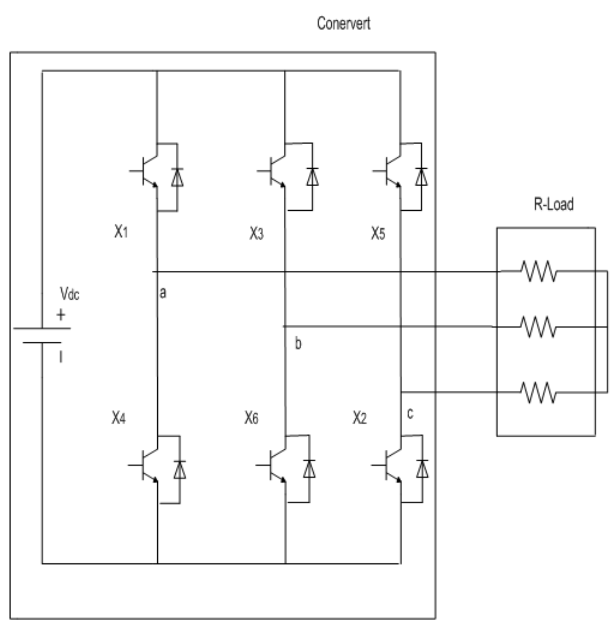

Figure 1. Si igbt based 3 phase inverter with r load.

Table 3. System specification of si igbt based 3 phase inverter

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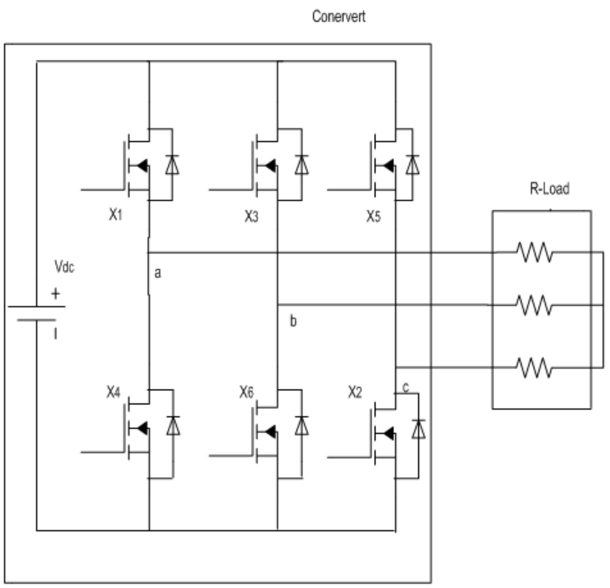

Figure 2. Sic mosfet based 3 phase inverter with r load.

4. Device Paramaters

The Figures were taken from the data sheets of respective si igbt and sic mosfet.

Figure 3 shows the forward characteristics of the si igbt used for the evaluation

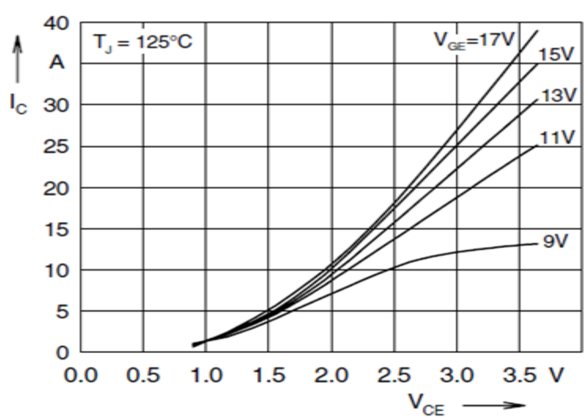

Figure 3. Si igbt device characteristics data sheet.

Figure 4 shows the forward characteristics of the sic mosfet used for the evaluation.

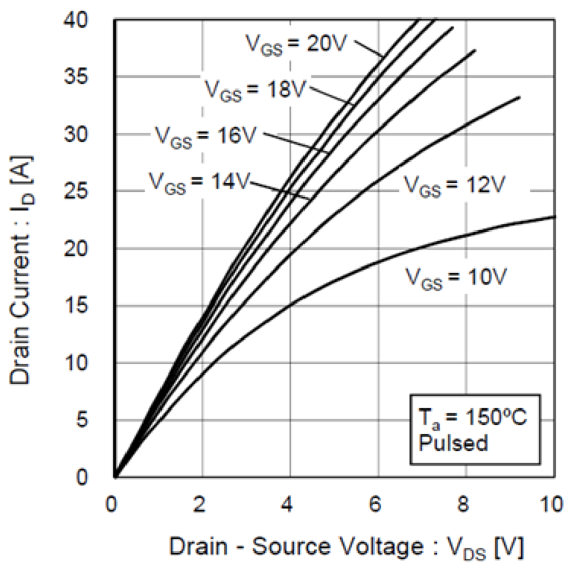

Figure 4. Sic mosfet device characteristics data sheet.

5. Loss Calculation

The conversion losses in the inverter can be divided in two categories.

- Conduction loss
- Switching loss

Table 4. Parameter comparison of si igbt vs sic mosfet considering the same freewheeling diode for both si igbt and sic mosfet

	SI IGBT	SIC MOSFET
Rating		
V_{fo}	3.5V	4.1V
r_f	0.127Ω	0.166Ω
Eon	3.1mJ	218µJ
Eoff	2.4mJ	64 µJ

Table 5. Parameter comparison freewheeling diode of si igbt vs sic mosfet

	Si IGBT freewheeling diode	Sic mosfet freewheeling diode
V_d	2.3	2.3
R_d	0.0836Ω	0.0836Ω

5.1 Conduction Losses

The conduction losses are due to device on-state voltage drop. They calculated by averaging the conduction losses in each switching cycle as shown in below equation:

$$P_c = \frac{1}{T}\int_0^T V_f(wt)i(wt)dwt \quad (1)$$

Where P_C is the total device conduction losses, switching period is T. V_f (wt) is the forward voltage of the device, i (wt) is the current flow through the device in the conduction period. The value of V_f (wt) is calculated as follow:

$$V_f = V_{fo} + r_f i(t) \quad (2)$$

Where V_{f0} is the device forward voltage at no load and device forward resistance is r_f. The values of V_{f0} and r_f are calculated using the datasheet of device characteristics provided by manufacturing companies as shown in Figure 3, 4. The r_f is the ratio between the collector emitter voltage difference and the collector current difference $r_f = \Delta Vce/\Delta Ic$ while V_{f0} is the value in the curve corresponding to the actual collector current flow in the device.
Substituting the expression for the forward voltage in Equation (2) into Equation (1) gives

$$P_c = V_f I_{av} + r_f I_{rms}^2$$

Conduction loss in mosfet is given by the equation.

$$P_{c(Q1)} = I^2_{RMSQ1} * R_{DS\,ON}$$

Where I_{av} and I_{rms} are the average and the rms current passing through the device in the conduction period. These are calculated as follows:

$$i_{av} = \frac{1}{T}\int_0^{T_1} i_0(t)dw$$

$$i_{rms}^2 = \frac{1}{T}\int_0^{T_2} i_0^2(t)dw$$

5.2 Switching Losses

The switching losses are the total sum of on-state switching losses and turn-off switching losses. They depend on the device characteristics, switching frequency and device current. The switching energy is expressed as a function of the device current as:

$$E_{sw} = k_1^i$$

Where k1 is got from the switching energy graph in the device datasheet. The switching loss for the device is calculated as:

$$P_{sw} = \frac{f_s}{2\pi}\int_0^{T_s} k_1\, i\, dwt$$

6. Evaluation of Conversion Losses in Two-Level Converters

If the load current is assumed as $I_a(wt) = I_m Sin\ (wt-\theta)$ then the leg phase voltage is defined as $V_a(wt) = V_m Sin\ (wt-\theta)$ and the duty cycle for the device switches is:

$$d_{T1} = d_{T4} = \frac{1}{2}[1 - M\sin\omega t]$$

$$d_{T4} = d_{D1} = 1 - d_{T1} = \frac{1}{2}[1 - M\sin\omega t]$$

The average and rms currents for IGBTs T1 and T2 are calculated using respective formulae and the duty cycle defined as below:

$$I_{T1,av} = \frac{1}{2\pi}\int_\theta^{\pi+\theta} d_{T1} i_a d\omega = I_m\left[\frac{1}{2\pi} + \frac{M\cos\theta}{8}\right]$$

$$I_{T4,av} = \frac{1}{2\pi}\int_\theta^{\pi+\theta} d_{T4} i_a d\omega = I_m\left[\frac{1}{2\pi} - \frac{M\cos\theta}{8}\right]$$

$$I^2_{T1,rms} = \frac{1}{2\pi}\int_\theta^{\pi+\theta} d_{T1} i_a d\omega = I^2{}_m\left[\frac{1}{8} + \frac{M\cos\theta}{3\pi}\right]$$

$$I^2_{T4,rms} = \frac{1}{2\pi}\int_\theta^{\pi+\theta} d_{T4} I^2{}_a d\omega = I^2{}_m\left[\frac{1}{8} - \frac{M\cos\theta}{3\pi}\right]$$

The average and rms currents for the lower free-wheeling diode are similar to that of the upper IGBT device but in opposite direction therefore:

$$I_{D1,av} = -I_{T4,av} = -I_m\left[\frac{1}{2\pi} + \frac{M\cos\theta}{8}\right]$$

$$I_{D4,av} = -I_{T1,av} = -I_m\left[\frac{1}{2\pi} + \frac{M\cos\theta}{8}\right]$$

$$I^2{}_{D1,rms} = -I^2{}_{T4,rms} = -I^2{}_m\left[\frac{1}{8} + \frac{M\cos\theta}{3\pi}\right]$$

$$I^2{}_{D4,rms} = -I^2{}_{T4,rms} = -I^2{}_m\left[\frac{1}{8} + \frac{M\cos\theta}{3\pi}\right]$$

The free-wheeling diode is switched on/off very fast compared to the IGBT so its switching losses are relatively small compared to that in an IGBT, therefore are not considered in the calculation. The switching losses for the IGBT are calculated using below equation as:

$$P_{sw} = \frac{k_1 f_s}{2\pi}\int_0^{\pi+\theta} I_m \sin(\omega t - \theta)d\omega t = \frac{k_1 f_s I_m}{\pi}$$

7. Comparisions

By substituting the values of the device parameters in the loss evaluation formulae the respective values of the losses have been tabulated in the below Tables 4,5,6,7 for the respective switching frequencies of 5khz, 8khz, 10khz, 15khz.

Table 6. Power loss comparison (F_S = 5KHZ)

	Si IGBT system	Sic mosfet system
Conduction loss (per leg)	IGBT - 88.135w Diode -57.986w	Mosfet- 59.91w Diode - 57.986w
Switching loss per device	13.20w	1.814w
Total inverter loss	517.563w	364.79w

Table 7. Power loss comparison (F_S = 8KHZ)

	Si IGBT system	Sic mosfet system
Conduction loss (per leg)	IGBT - 88.135w Diode -57.986w	Mosfet- 59.91w Diode - 57.986w
Switching loss per device	21.12w	2.90w
Total inverter loss	**565.08w**	**371.1w**

Table 8. Power loss comparison (F_S = 10KHZ)

	Si IGBT system	Sic mosfet system
Conduction loss (per leg)	IGBT - 88.135w Diode -57.986w	Mosfet- 59.91w Diode - 57.986w
Switching loss per device	26.4w	3.62w
Total inverter loss	**596.76w**	**375.42w**

Table 9. Power loss comparison (F_S = 15KHZ)

	Si IGBT system	Sic mosfet system
Conduction loss (per leg)	IGBT - 88.135w Diode -57.986w	Mosfet- 59.91w Diode - 57.986w
Switching loss per device	39.6w	5.442w
Total inverter loss	**675.963w**	**386.35w**

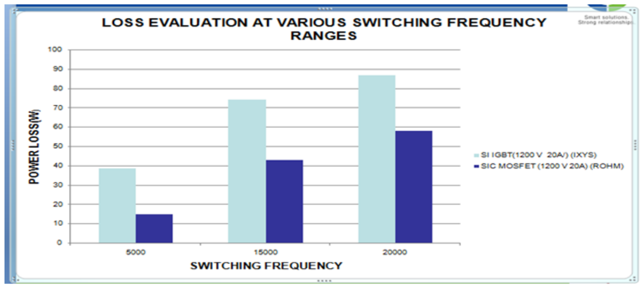

Figure 7. Loss comparison of simulated scenarios of switching frequencies of 5khz, 10khz, 15khz for Si IGBT versus sic mosfet.

The modelled si igbt based 2 level three phase spwm inverter with modelled switches was simulated and compared with sic mosfet based 2 level three phase spwm

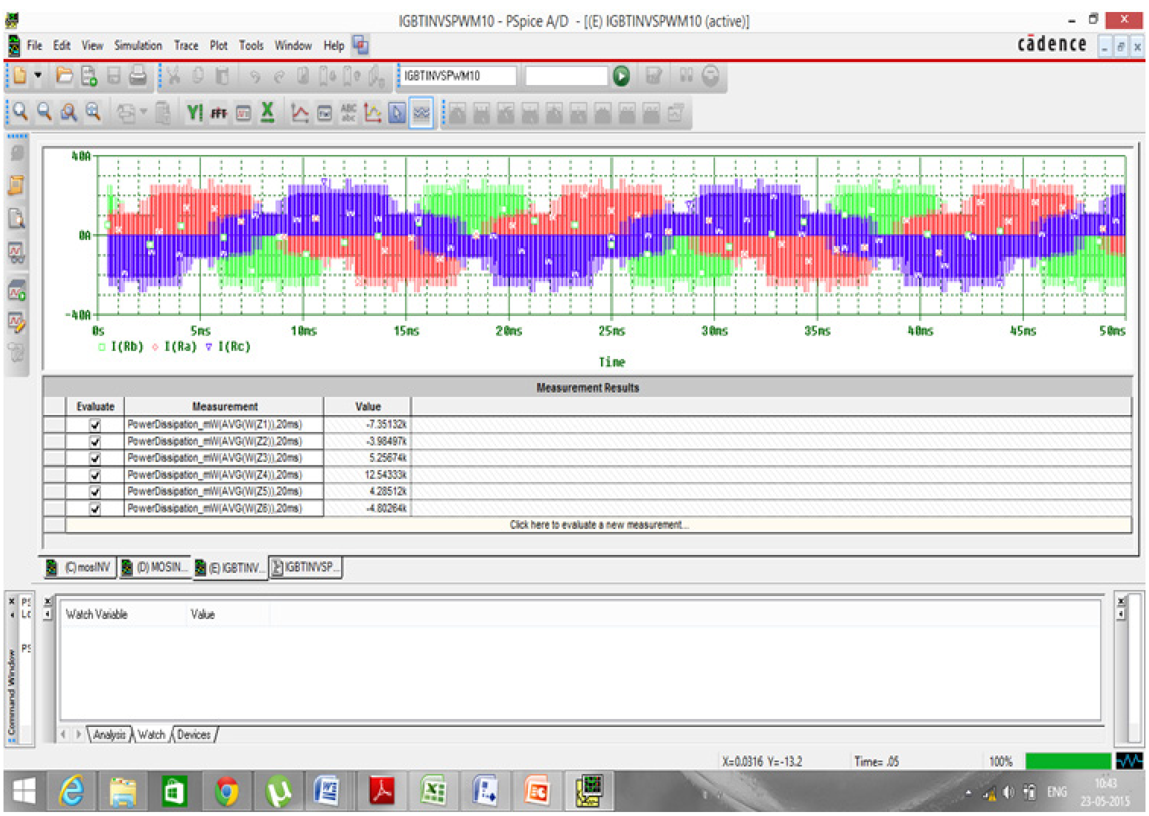

Figure 5. Pspice simulated si IGBT based three phase spwm inverter (FS = 10KHZ).

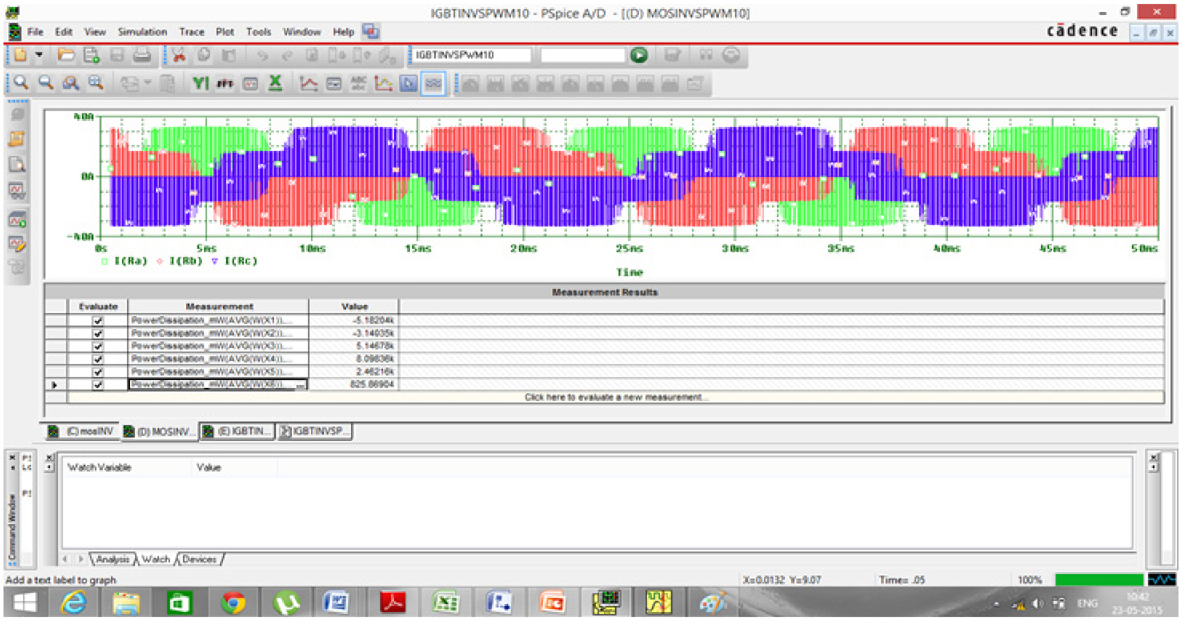

Figure 6. Pspice simulated sic mosfet based three phase spwm inverter (FS = 10KHZ).

inverter using orcad pspice as simulation tool.

Figures 5 and 6 show the 2 scenarios one with si igbt and sic mosfet at switching frequency of 10khz.

Power loss is compared in orcad pspice at various switching frequencies and average power loss is measured across each switch for 20ms and compared.

8. Conclusion

In sum, a 22kw sic mosfet base 3 phase spwm inverter system is designed and compared with that of si igbt base three phase spwm inverter at switching frequency ranges of 5khz, 8khz, 10,khz, 15khz and it had been observed that the losses of the 3 phase spwm sic mosfet inverter where 29% less for 5khz switching frequency, 34% less for switching frequency of 8khz, 37% less for switching frequency of 10khz, 42% less for the switching frequency of 15khz over the 3 phase spwm inverter based on si igbt which in turn shows that the sic mosfet can be replaced by si igbt in 3 phase spwm inverter system for better efficiency and the pspice simulations showed similar results showing that sic mosfet is efficient than si igbt based three phase spwm inverter.

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