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

Trinadh Mathe\textsuperscript{1} and K. Narsimha Raju\textsuperscript{2}

\textsuperscript{1}KL University, Vijaywada, Andhra Pradesh, India; mathe.trinadh@gmail.com
\textsuperscript{2}Department of EEE, KL University, Vijaywada, Andhra Pradesh, India; narsimharaju_eee@kluniversity.in

Abstract

Background/Objectives: Reducing the losses of 3 phase spwm 2 level inverter by replacing the present semiconductor 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\textsuperscript{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\textsuperscript{2}. Later in 2001 2.4 KV 4h-sic Dimosfet having specific on state resistance of 42m\Omega cm\textsuperscript{2} was demonstrated by cree\textsuperscript{3}. In 2004\textsuperscript{4,5} Dr. James Coopers group of Purdue University developed 3KV, 5KV Umofset of 4h-sic having junction termination extension (jte) and trench oxide protection. In 2004\textsuperscript{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\textsuperscript{8,9}.

Considering case of 22kw inverter 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.
Comparitive Loss Evaluation of Si IGBT Versus Sic Mosfet (Silicon Carbide) for 3 Phase Spwm Inverter

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 |

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

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

Figure 1. Si igbt based 3 phase inverter with r load.
Table 3. System specification of si igbt based 3 phase inverter

| Parameter                  | Value          |
|----------------------------|----------------|
| Dc voltage                 | 586            |
| Modulation method          | SPWM           |
| Modulation index           | 1              |
| Switching frequency        | 5KHZ,10KHZ,15KHZ |
| Power factor               | 1              |
| Motor peak current         | 38A            |
| Power rating               | 22KW           |

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

4. Device Parameters

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

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

| Parameter | SI IGBT | SIC MOSFET |
|-----------|---------|------------|
| Vf0       | 3.5V    | 4.1V       |
| rj        | 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

| Parameter | SI IGBT freewheeling diode | Sic mosfet freewheeling diode |
|-----------|-----------------------------|-------------------------------|
| Vd        | 2.3                         | 2.3                           |
| Rg        | 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:

\[ P_c = \frac{1}{T} \int_0^T V_f(wt) i(wt) dw \tag{1} \]

Where \( P_c \) is the total device conduction losses, \( T \) is the switching period, \( V_f(wt) \) 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:

\[ V_f = V_{f0} + r_f i(t) \tag{2} \]

Where \( V_{f0} \) is the device forward voltage at no load and \( r_f \) is the forward resistance of the device. 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 \( r_f = \Delta V_{ce}/\Delta Ic \) 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

\[ P_c = V_{f0} I_{av} + r_f I_{rms} \]

Conduction loss in mosfet is given by the equation.

\[ P_{c(Q1)} = I^{2}_{rms} * R_{DS(on)} \]

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:

\[ I_{av} = \frac{1}{T} \int_0^T i(t) dw \]
\[ I_{rms} = \frac{1}{T} \int_0^T i^2(t) dw \]

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:

\[ E_{sw} = k_1 I_i \]

Where \( k_1 \) is got from the switching energy graph in the device datasheet. The switching loss for the device is calculated as:

\[ P_{sw} = \frac{k_1 f}{2 \pi} \int_0^{\pi/2} I_i \sin(\omega t - \theta) d\omega t = \frac{k_1 f I_{sw}}{\pi} \]

6. Evaluation of Conversion Losses in Two-Level Converters

If the load current is assumed as \( I_{sw} = I_m \sin(\omega t - \theta) \) then the leg phase voltage is defined as \( V_f(wt) = V_m \sin(\omega t - \theta) \) and the duty cycle for the device switches is:

\[ d_{q1} = d_{q1} = \frac{1}{2}(1 - M \sin \omega t) \]
\[ d_{q4} = d_{q4} = 1 - d_{q1} = \frac{1}{2}(1 - M \sin \omega t) \]

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

\[ I_{1a},r = \frac{1}{2\pi} \int_0^{\pi} d_{q1} I_i d\omega = I_{m} \left( \frac{1}{2\pi} + \frac{M \cos \theta}{8} \right) \]
\[ I_{2a},r = \frac{1}{2\pi} \int_0^{\pi} d_{q2} I_i d\omega = I_{m} \left( \frac{1}{2\pi} - \frac{M \cos \theta}{8} \right) \]
\[ I_{1a},rms = \frac{1}{2\pi} \int_0^{\pi} d_{q1} I_{rms} d\omega = I_{m} \left( \frac{1}{8} + \frac{M \cos \theta}{3\pi} \right) \]
\[ I_{2a},rms = \frac{1}{2\pi} \int_0^{\pi} d_{q2} I_{rms} d\omega = I_{m} \left( \frac{1}{8} - \frac{M \cos \theta}{3\pi} \right) \]

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:

\[ P_{sw} = \frac{k_1 f}{2 \pi} \int_0^{\pi/2} I_i \sin(\omega t - \theta) d\omega t = \frac{k_1 f I_{sw}}{\pi} \]

7. Comparisons

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 | Mosfet - 59.91w  |
|                     | Diode - 57.986w | 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 | Mosfet - 59.91w  |
|                     | Diode - 57.986w | 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 | Mosfet - 59.91w  |
|                     | Diode - 57.986w | 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 | Mosfet - 59.91w  |
|                     | Diode - 57.986w | 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...
Comparitive Loss Evaluation of Si IGBT Versus Sic Mosfet (Silicon Carbide) for 3 Phase SPWM Inverter

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.

9. References

1. Palmour JW, Edmond JA, Kong HS, Carter CH, Jr. 6Hsilicon carbide power devices for aerospace applications. Proceedings of 28th Intersociety Energy Conversion Energy Conference; Atlanta: Georgia. 1993.p. 1249–54.
2. Shenoy MP, Baliga BJ. The planar 6H-SiC ACCUFET: A new high-voltage power MOSFET structure. IEEE Electron Device Letters. Dec 1997; 18(12):589–91.
3. Agarwal A, Ryu SH, Das M. Large area 4H-SiC power MOSFETs. Proceedings of the 13th International Symposium on Power Semiconductor Devices and ICs. ISPSD ’01. Jun 2001.p. 183–86.
4. Li Y, Cooper JA, Jr, Capano MA. High-Voltage (3 kV) UMOSFETs in 4H-SiC. IEEE Transactions on Electron Devices. Jun 2002; 49(6):972–75.
5. Khan IA, Cooper JA, Jr, Capano MA, Isaccs-Smith T, Williams JR. High-voltage UMOSFETs in 4H-SiC. International Symposium on Power Semiconductor Devices; Santa Fe, NM. Jun 2002; 3-7:157–60.
6. Ryu SH, Krishnaswami S, O’Loughlin M. 10-kV, 123-m/spl omega/cm/sup 2/4H-SiC power DMOSFETs. IEEE Electron Device Letters. Aug 2004; 25(8):556–58.
7. Baliga BJ. Power semiconductor devices for variable-frequency drives. Proceedings of the IEEE 1994. Aug 1994; 82(8):1112–22.
8. Chang HR, Hanna E, Radun AV. Development and demonstration of silicon carbide (SiC) motor drive inverter modules. Power Electronics Specialist Conference PESC ’03; Acapulco: Mexico. 2003; 1:211–16.
9. Zhang H, Tolbert LM. A SiC-based converter as a utility interface for a battery system. Conference Record of the 2006 IEEE Industry Applications Conference Forty-First IAS Annual Meeting; Tampa: FL. Oct 2006; 1:346–50.
10. Sugaww Y, Ym DT, Pakmuand T. SPSCD, 2001; p. 27.
11. Hui P, et al. Evaluation of losses in VSC-HVDC transmission system. In: Power and energy society general meeting–conversion and delivery of electrical energy in the 21st century. 2008 IEEE. 2008; 27(9):1–6.
12. Blaabjerg F, et al. Power losses in PWM-VSI inverter using NPT or PT IGBT devices. IEEE Transactions on Power Electron. 1995; 10(3):358–67.

13. Tae-Jin K, et al. The analysis of conduction and switching losses in multi-level inverter system. In: Power electronics specialist's conference, PESC. IEEE 32nd Annual, Vancouver, BC. 2001; 3:1363–68.

14. Oh KS. Application note 9016: IGBT basics 1. FAIRCHILD Semiconductor Corporation Rev. A2; Feb 2001.

15. Kolar JW, et al. Influence of the modulation method on the conduction and switching losses of a PWM converter system. IEEE Transactions on Industrial Applications. 1991; 27(6):1063–75.

16. Yushu Z, et al. Voltage source converter in high voltage application: Multilevel versus two-level converters. Presented at the ACDC 2010, the 9th International Conference on AC and DC Power Transmission; London: UK. Oct 2010.p. 1–5.

17. Yazdani A, Iravani R. Voltage-sourced converters in power systems: Modelling control, and applications. Hoboken (New Jersey): John Wiley and Sons Inc.; 2010.