International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 15 (2018) pp. 12283-12288
© Research India Publications. http://www.ripublication.com

Design of SiC MOSFET based High Efficiency Inverter for Solar PV Applications

Monika Agarwal, student
Department of Electrical Engineering
Jamia Millia Islamia University, New Delhi 110025
India.

Dr. Haroon Ashfaq
Department of Electrical Engineering
Jamia Millia Islamia University, New Delhi 110025
India.

Abstract

SiC Power MOSFET is a good replacement for the IGBT based power devices applications due to its superior properties like higher breakdown electric field and large thermal conductivity. In this paper, the analysis and comparison is done to show that multilevel inverter is more potent for solar power application. These inverters are suitable in high voltage and high-power applications due to their ability to synthesize waveforms with better harmonic spectrum. Here the SiC-based multilevel inverters are analysed in detail. The simulated results are shown for both Si and SiC MOSFETs. The power loss analysis is performed on the simulated and the results justify their proposed use.

Keywords: MOSFET; Silicon Carbide(SiC); Insulated Gate bipolar Transistor(IGBT); Loss analysis; Multilevel Inverter

INTRODUCTION

In last decades, with the advance development in the SiC Power MOSFETs are catching attention because of its low on state resistance and high breakdown voltages compared to Si MOSFET and Si IGBT [1]. They also possess high breakdown electric field, large thermal conductivity [2][3] and have a high temperature operation capability.

SiC semiconductor has dielectric breakdown field strength 10 times higher than that of Si, hence high breakdown voltages devices can be achieved with a thin drift layer with high doping concentration. Thus it can be concluded that for the same breakdown voltage, SiC devices have low specific on-resistance than Si devices.

Since, MOSFETs generate no tail current, so SiC MOSFETs have much lower switching loss than IGBTs, which enables higher switching frequency, smaller passives, smaller and less expensive cooling system. Compared to higher voltages Si IGBTs, SIC MOSFETs have smaller chip area (mountable on a compact package) and an ultralow recovery loss of body diodes. Smaller chip size reduces gate charge and capacitance. Existing Si Super junction MOSFETs are only available for breakdown voltages up to around 99V. SiC MOSFETs have breakdown voltages up to 1700V or higher with low on resistance. For these reasons, SIC MOSFETs are increasingly being used in power supplies for industrial equipment and inverters/converters for high efficiency power conditioners.

The first SiC Power MOSFET U was designed by Palmour *et al.* in 1992 [4]. With the tremendous advancement, in 2001, Ryu *et al.* reported about 2.4kV 4H SiC DMOSFET with specific on-resistance of 42 $m\Omega.cm^2$ [5]. The 4H-SiC DMOSFETs with the 10kV blocking capability was reported by Ryu *et al*. in 2004 that was the highest blocking voltage for SiC MOSFET [6]. Further, the characterization and modeling of a 10kV 5A 4H-SIC DMOSFET was reported by Wang *et al.* in 2008[7]. A simple SPICE based behavioral model has also been proposed for a SiC MOSFET. However, low temperature characteristics were not studied. Later, in 2014, Sun *et al.* reported an improved model of medium voltage SiC MOSFET with wide temperature range operation [8].

One of the application for these switches is found in inverters. There is a lot of research going on for the use of inverters in the high-power applications, which leads to the design of multilevel inverters. The early interest in multilevel power conversion technology given by Nabae et al. in 1981 [10] who introduced a neutral point clamped topology. Later, Carpita et al. reported extension of higher number of levels by clamping the intermittent voltage levels with diodes [11]. These multilevel inverters are known as diode clamped inverters where the required voltage blocking capability of the clamping diodes varies with the voltage levels. An alternative multilevel structure using clamping capacitance instead of clamping diode has been proposed by Meynard et al. [12]. These inverters are known as flying capacitor inverters. It is to be noted that the voltage blocking capability of faster devices like IGBT and the switching speed of high voltage devices like thyristors are limited.

In this paper, the switching characteristics of IGBT and SiC MOSFET are shown and then the switching losses for multilevel inverter using SiC MOSFET and IGBT device are calculated based on Pspice Software. The C2M0025120D (1200V/90A) is a typical SiC MOSFET module which has been used here as an application for inverter.

METHODOLOGY

A. Device characterisation

The commercially available 1200V 90A discrete SiC MOSFET molded in TO-247-3 package with C2M0025120D part number [13] is modeled based on doping profiles and cross-sectional structure is shown in Fig. 1 [14] that consists of three electrodes i.e. gate, drain, and source.

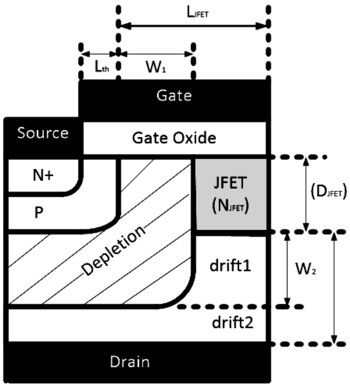


Figure 1. Cross section of the 1200V SiC MOSFET

The equations describing SiC MOSFET are shown in (1) for the linear region, and (2) for the saturation region [14].

$$I_D = \frac{ZC_{OX}}{L_{ch}}\mu_{ch}\left\{(V_{GS}-V_{th})\beta V_{DS}-\frac{1}{2}(\beta V_{DS})^2\right\} \qquad (1)$$
$$(V_{DS} \leq V_{DS}^{sat})$$

$$I_D = I_D^{sat} + \lambda(V_{DS} - V_{DS}^{sat}) \qquad (2)$$
$$(V_{DS} \geq V_{DS}^{sat})$$

Where I_D is drain current, C_{OX} is oxide capacitance per unit area, μ_{ch} adjustment channel mobility, λ channel length modulation coefficient, V_{DS}^{sat} saturation drain-source voltage, I_D^{sat} saturation drain current.

The characteristics of SiC MOSFET obtained from Pspice software are shown in Fig. 2. The case temperature is assumed to be 120^0 C. These characteristic shows different plots for different Gate Source voltages i.e. 10V, 12V,14V, 16V, 18V and 20V.

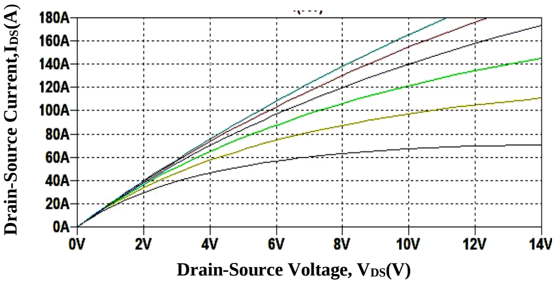


Figure 2. Pspice simulated output characteristics of 1200V 90A SiC MOSFET at 120^0C.

SiC MOSFET has no threshold voltage as that of IGBT. They have a low conduction loss over a wide current range. The on-state drain resistance in quite low in SiC MOSFET as compared to Si IGBT due to its higher dielectric breakdown field strength [9].

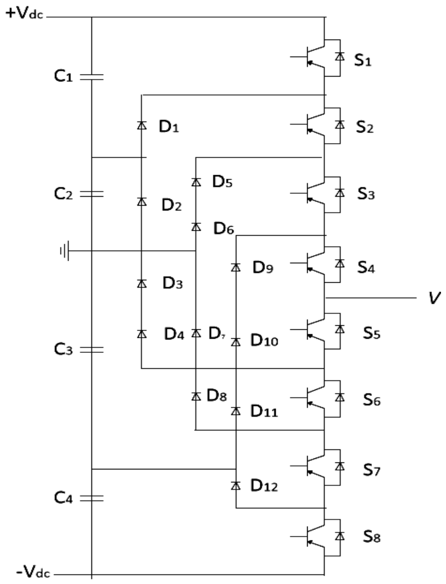


Figure 3. Simplified schematic of a single phase of a 5-level diode clamped inverter

B. System specification

In IGBT based 5-level diode clamped inverter system has eight 1200V single-switch IGBT module (IXBF9N160G) are used with the switching frequency of 5kHz as shown in Fig.3 [15]. As the maximum permissible frequency for the best operation of the inverter is up to 5kHz so the results are obtained for the worst case.

The elementary concept of a multilevel converter is to achieve higher power by using a series of power semiconductor switches with several lower voltage ratings. The power conversion is performed by synthesizing a staircase voltage waveform. These can draw input current with low distortion. Selective harmonic elimination technique along with the multilevel topology results the total harmonic distortion to be low in output waveform without using any filter.

The SPWM modulation technique is used for controlling the inverter output. Modulation Index is assumed as 0.8. Further for conduction loss analysis 0.85 power factor load is assumed [16]. The system specifications are shown in Table I.

Table I. System Parameters

DC voltage V_{DC}	800V
Modulation index M	0.8
Power factor cos ϕ	0.85
Load current I_{peak}	75A
Switching Frequency f_{sw}	5kHz

For SiC based 5-level diode clamped inverter, the IGBTs in Fig. 3 are replaced with the SiC MOSFETs. SiC Schottky diodes are used in place of Si diodes. The system specifications remain identical as shown in Table I.

INVERTER POWER LOSS CALCULATIONS

In order to compare the performance of IGBTs and SiC MOSFETs based multilevel inverter, power loss analysis is performed. The power loss in the power semiconductors of an inverter are consists of conduction and switching losses. While calculating these losses, the switching loss of diode is neglected as it is negligible in comparison with the switching loss of IGBT or SiC MOSFET. Sinusoidal pulse width modulation (SPWM) scheme is employed for controlling inverter output.

A. Conduction Loss

For the SPWM technique, the duty cycle of one phase of the PWM waveform varies as [17];

$$d(t) = \frac{1}{2}\left[1 + M\sin\left(\int_{-\infty}^{t} \omega dt\right)\right] \tag{3}$$

Where M is the modulation index, ω is the angular frequency, and t is time. Under constant frequency, the duty cycle can be simplified as;

$$d(\theta) = \frac{1}{2}[1 + M\sin(\theta)] \tag{4}$$

However, for lagging load the phase current lags the phase voltage by φ. The equations for phase current (i_{ph}) and duty cycle are given by;

$$i_{ph} = I_{peak}\sin\theta \tag{5}$$

$$d(\theta) = \frac{1}{2}[1 + M\sin(\theta + \varphi)] \tag{6}$$

The average current for power device (IGBT or SiC MOSFET) is:

$$I_{avg} = \frac{1}{2\pi}\int_{0}^{\pi} i_{ph} d(\theta) d\theta \tag{7}$$

Substituting equation (5) and (6) in equation (7), we get;

$$I_{avg} = I_{peak}\left[\frac{1}{2\pi} + \frac{M\cos\varphi}{8}\right] \tag{8}$$

Similarly, the duty cycle for diode is;

$$d(\theta) = \frac{1}{2}[1 - M\sin(\theta + \varphi)] \tag{9}$$

Substituting the equation (9) in equation (7), the average current for diode is calculated as;

$$I_{diode} = I_{peak}\left[\frac{1}{2\pi} - \frac{M\cos\varphi}{8}\right] \tag{10}$$

The rms value of power device current and diode current are given by;

$$\left|I_{ph}\right|_{rms} = I_{peak}\sqrt{\left[\frac{1}{8} + \frac{M\cos\varphi}{3\pi}\right]} \tag{11}$$

$$\left|I_{diode}\right|_{rms} = I_{peak}\sqrt{\left[\frac{1}{8} - \frac{M\cos\varphi}{3\pi}\right]} \tag{12}$$

The equations defined for the calculation of conduction loss in IGBT or SiC MOSFET (P_Q) and Diode (P_D) are:

$$P_Q = V_q I_{ph} + \left|I_{ph}\right|_{rms}^{2} R_Q \tag{11}$$

$$P_D = V_d I_{diode} + \left|I_{diode}\right|_{rms}^{2} R_D \tag{12}$$

B. Switching Loss

For the SPWM technique switching losses are the function of switching frequency, the current in each device and the device dynamic characteristics. The average switching losses are given by;

$$P_{SW} = \frac{1}{m}\sum_{n=1}^{m} f_c E_{tot}(i) \tag{13}$$

Where $m = \frac{f_c}{f_s}$

Considering a linearized model of the switching losses versus current the switching energy is expressed as:

$$E_{tot}(i) = \frac{E_{max}}{I_{ph}} i_{\varphi} = E_{max}\sin\theta \tag{14}$$

The maximum switching energy(E_{max})in above equation is the total switching losses at the peak current of the sine wave. Liner interpolation may be used to find this energy from measured values. A continuous form solution may be found for systems where carrier frequency is much higher than the sine frequency. Because the current is each power device is 0 for half of the sine period, the power integral is evaluated from 0 to π.

$$P_{SW} = \frac{1}{2\pi}\sum_{0}^{\pi} P d\theta \tag{15}$$

$$P_{SW} = \frac{1}{2\pi}\sum_{0}^{\pi} f_c E_{tot}(i) \tag{16}$$

Integrating and substituting the eq. (14) in eq. (16) we get;

$$P_{SW} = \frac{f_c E_{max}}{\pi} \tag{17}$$

The above proposed equation is used to determine the overall switching loss of the device.

SIMULATION RESULTS

SiC MOSFET Module (C2M00251200) is selected based on the rating of the inverter. The details of the device structure, fabrication and basic characteristics are considered from Cree Inc. datasheet [13].

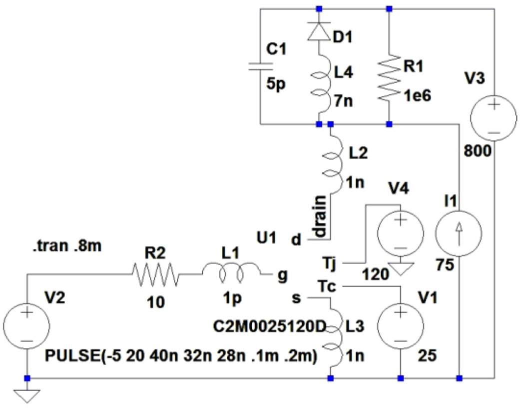
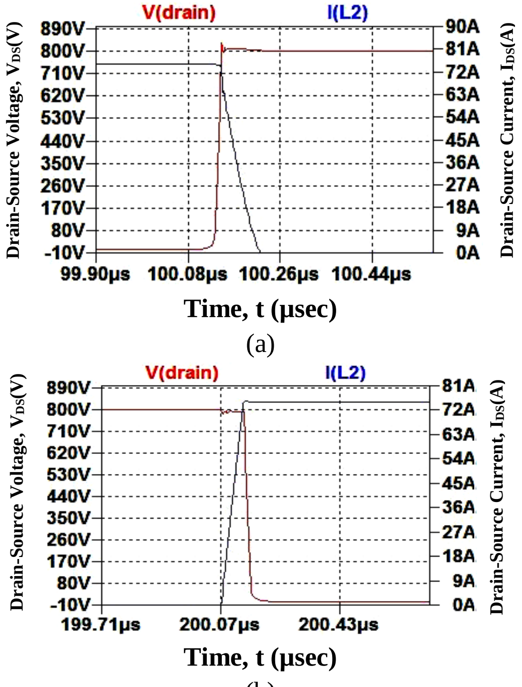


Figure 4. Schematic circuit diagram of a clamped Inductive load test circuit for a 1200V SiC MOSFET.

The clamped inductive load test circuit is drawn for the testing of 1200V 90A SiC MOSFET in Pspice software. Fig. 4 shows the schematic circuit diagram of the inductive load circuit. It includes 1200V 90A SiC MOSFET, 10Ω external gate resistor, 1pH air-core inductor, 800V DC power supply and 1200V, 20A SiC Schottky diode used as a freewheeling diode.



(a)

(b)

Figure 5. Pspice simulated switching waveform of 1200V SiC MOSFET (a) Turn-off characteristics (b) Turn-on characteristics

The case temperatures of the SiC MOSFET in the clamped inductive load circuit are varied and switching loss characteristics are obtained. The switching characteristics waveform for 1200C are shown in Fig. 5(a) & 5(b).

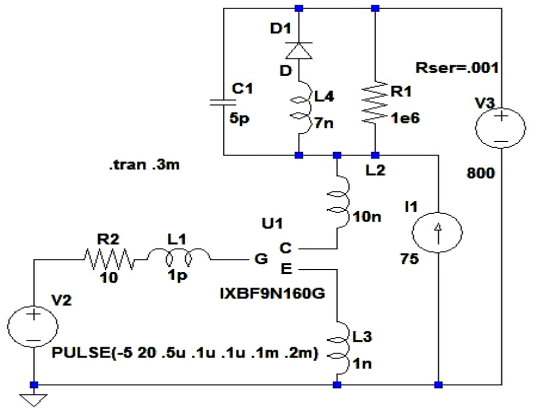
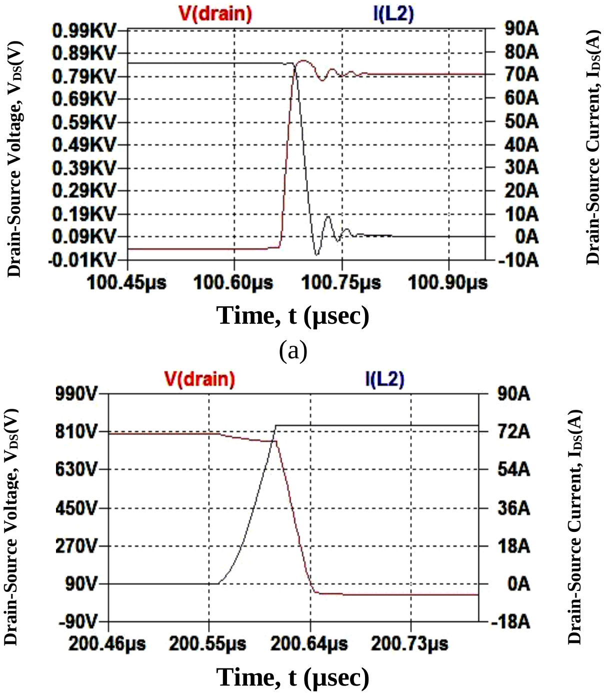


Figure 6. Schematic circuit diagram of a clamped Inductive load test circuit for a 1200V IGBT



(a)

(b)

Figure 7. Pspice simulated switching waveform of 1200V IGBT (a) Turn-off characteristics (b) Turn-on characteristics

Similarly, the Pspice schematic circuit of IGBT based clamped inductive load circuit is shown in Fig. 6 and the switching characteristics i.e., turn-off and turn-on waveforms are shown in Fig. 7(a) & 7(b) respectively.
The switching losses at various temperatures such as 70^0, 90^0 and 120^0C are calculated for IGBT and SiC MOSFET, based on eq. (17) are shown in Table II.

Table II. Switching Loss Comparision (mJ)

Temperature (^{0}C)	IGBT	SiC MOSFET
70	16.975	4.981
90	21.825	5.1
120	29.1	5.25

Based on the results shown in Table II, the overall switching loss is calculated for 5-level IGBT based multilevel inverter. The 5-level inverter is has eight switches, and twelve clamped diodes.

Similarly, the overall switching losses for the SiC MOSFET based 5-level diode clamped inverter are are found to be 1.164 kW.

The conduction losses for the IGBT and SiC MOSFET based 5-level diode clamped inverter are calculated using eq. (11) and eq. (12) and are calculated as 398.816 and 70.972 watts respectively.

The switching losses are also calculated for different levels of the IGBT and SiC MOSFET based diode clamped multilevel inverter. The calculated results are shown in Table III.

Table III. Switching Loss Comparision of Multilevel Inverters (Watts)

	IGBT system	**SiC system**
3-level	582	105
4-level	873	157.5
5-level	1164	210
7-level	1746	315
11-level	2910	525

CONCLUSION

From the above observations, it is seen that the switching losses of the IGBT switch is 4 times more than the switching losses of the SiC switch. Similarly, when the calculations are extended for the inverter, the results show that the overall switching losses in the 5-level diode clamped IGBT based inverter has 5 times more losses than the 5-level diode clamped SiC based inverter. This shows that there will be less heating in the SiC based inverter so there is the need of a lower rating heat sink, which further leads to the improvement in performance and reduction in the cost for SiC based inverter. Further, the reliability of the system will also increase. The low switching losses of the Silicon Carbide (SiC) MOSFET enables the reduction of end-system cost, even at low frequency operation. In brief, it can be concluded that using SiC power device in inverters, particularly in multilevel inverters will increase its reliability and efficiency while reducing size, weight and cost with reduced cooling requirements. It will also make possible to implement new complex topologies that were not previously possible.

REFERENCES

[1] Agarwal, Anant, Mrinal Das, Brett Hull, Sumi Krishnaswami, John Palmour, James Richmond, Sei-Hyung Ryu, and Jon Zhang. "Progress in silicon carbide power devices." In *Device Research Conference, 2006 64th*, pp. 155-158. IEEE, 2006.

[2] Casady, J. B., and R. Wayne Johnson. "Status of silicon carbide (SiC) as a wide-bandgap semiconductor for high-temperature applications: A review." *Solid-State Electronics* 39, no. 10 (1996): 1409-1422.

[3] Saks, N. S. "Silicon Carbide-Recent Major Advances, edited by WJ Choyke, H. Matsunami, and G. Pensl." (2003).

[4] Palmour, John W., C. H. Carter, J. A. Edmund, and H-S. Kong. "6H-silicon carbide power devices for aerospace applications." In *Intersociety Energy Conversion Engineering Conference*, vol. 1, pp. 1-249. AMERICAN NUCLEAR SOCIETY, 1993.

[5] Ryu, Sei-Hyung, Anant Agarwal, James Richmond, John Palmour, Nelson Saks, and John Williams. "10 A, 2.4 kV power DiMOSFETs in 4H-SiC." *IEEE Electron Device Letters* 23, no. 6 (2002): 321-323.

[6] Ryu, Sei-Hyung, Sumi Krishnaswami, Michael O'Loughlin, James Richmond, Anant Agarwal, John Palmour, and Allen R. Hefner. "10-kV, 123-m/spl Omega//spl middot/cm/sup 2/4H-SiC power DMOSFETs." *IEEE Electron Device Letters* 25, no. 8 (2004): 556-558.

[7] Wang, Jun, Tiefu Zhao, Jun Li, Alex Q. Huang, Robert Callanan, Fatima Husna, and Anant Agarwal. "Characterization, modeling, and application of 10-kV SiC MOSFET." *IEEE Transactions on Electron Devices* 55, no. 8 (2008): 1798-1806.

[8] Sun, Kai, Hongfei Wu, Juejing Lu, Yan Xing, and Lipei Huang. "Improved modeling of medium voltage SiC MOSFET within wide temperature range." *IEEE Transactions on Power Electronics* 29, no. 5 (2014): 2229-2237.

[9] Semiconductor, R. O. H. M. "Sic power devices and modules application note." *Issue of June* (2013).

[10] Nabae, Akira, Isao Takahashi, and Hirofumi Akagi. "A new neutral-point-clamped PWM inverter." *IEEE Transactions on industry applications* 5 (1981): 518-523.

[11] Carpita, M., and M. Fracchia. "S. Teconi,“A Novel Multilevel Structure for Voltage Source Inverter,”." *Proc. EPE 1991* (1991): 90-94.

[12] Meynard, T. A., and Henry Foch. "Multi-level conversion: high voltage choppers and voltage-source inverters." In *Power Electronics Specialists Conference, 1992. PESC'92 Record., 23rd Annual IEEE*, pp. 397-403. IEEE, 1992.

[13] Cree ,”Sic datasheet.” 2014.

[14] Marzoughi, Alinaghi, Rolando Burgos, and Dushan Boroyevich. "Characterization and comparison of latest generation 900-V and 1.2-kV SiC MOSFETs." In *Energy Conversion Congress and Exposition (ECCE), 2016 IEEE*, pp. 1-8. IEEE, 2016.

[15] Inver fig chaper 2

[16] Zhao, Tiefu, Jun Wang, Alex Q. Huang, and Anant Agarwal. "Comparisons of SiC MOSFET and Si IGBT based motor drive systems." In *Industry Applications Conference, 2007. 42nd IAS Annual Meeting. Conference Record of the 2007 IEEE*, pp. 331-335. IEEE, 2007.

[17] Berringer, Ken, Jeff Marvin, and Philippe Perruchoud. "Semiconductor power losses in AC inverters." In *Industry Applications Conference, 1995. Thirtieth IAS Annual Meeting, IAS'95., Conference Record of the 1995 IEEE*, vol. 1, pp. 882-888. IEEE, 1995.