Development of SiC BJT based PWM Inverter for renewable energy resources

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Abstract - Silicon Carbide (SiC) BJT switch is attractive for inverters because it does not have the thermal runaway and slow switching problems associated with Si BJTs. This paper investigates the potentials of SiC BJT based PWM inverter for renewable energy resources. The static and switching characteristics of SiC BJT are simulated using MATLAB. Comparisons are carried out with a state-of-the-art Si IGBT with the emphasis on total losses. The simulation results are verified with experimental data. It is found that SiC BJT has much smaller conduction and switching losses than the Si IGBT. A prototype of BITSiC1206 BJT inverter switched at 100 kHz has been developed by employing a novel inverted sine carrier PWM technique. This method is compared with the conventional PWM in terms of THD and switching losses. The proposed modulation technique is implemented using a FPGA processor so that better resolution is achieved in the control of inverter output voltage magnitude and it is verified experimentally.

Index Terms*:* BJT, inverted sine PWM, SiC, Switching loss and THD

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1 INTRODUCTION

SiC is a wide band gap semiconductor that possesses extremely high thermal, chemical, and mechanical stability. It has the advantage of high thermal conductivity, high breakdown electric field, and saturated carrier velocity compared to other semiconductor materials, which makes it an ideal material for power devices. Among the SiC devices, SiC BJT is a promising high power switching device. The power transistors for 600 V and above based on Si have either a relatively high specific on resistance or significant switching power losses, which both result in high power dissipation. In addition, the maximum allowed operating temperature of Si power devices is typically 125 °C, which cannot satisfy the demand of an increasingly dense power electronics system design such as the traction inverter used in electric vehicle [1].Compared to other bipolar devices, like IGBT and GTO, BJT does not have the junction voltage needed to overcome in order to conduct current. Also, the process complexity is reduced greatly as compared to SiC MOSFETs, rendering the SiC BJT a promising high power switching device [2]. The structure and special characteristics of the new device SiC BJT has been explained**.** Static and switching characteristics of SiC BJT are simulated using MATLAB. Comparison has been carried out between the 1200V SiC BJT and a 1200 V Si Insulated Gate Bipolar Transistor (IGBT) in terms of losses. The simulation results are verified with experimentally. A single-phase DC-AC inverter using 4H-SiC BJTs driving an inductive load has been demonstrated. Various modulation strategies have been reported in the literature [3,4]. But this paper focuses on a high frequency inverted sine carrier based PWM technique which results in an enhanced fundamental voltage and reduced Total Harmonic Distortion (THD).The proposed method is compared with the conventional PWM technique. Both the SiC inverter circuit topology and its control scheme are described in detail and their performance is verified based on simulation and experimental results.

2. STRUCTURE OF SIC BJT

SiC BJT is suited for high temperature and high power applications due to their low conduction losses and fast switching capability. A schematic cross-section of 4H-SiC based NPN BJT is shown in Fig.1. A three layer epitaxy (NPN type structure) has been grown in a single continuous growth step. The emitter layer is composed of two steps with different doping concentration. The emitter and base mesa structures have been defined by ICP (Inductively Coupled Plasma) etching using SiO_2 as a mask. Aluminum ions have been implanted to form the low resistance base contact. Another aluminum implantation has been introduced to define the Junction Termination

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Extension (JTE) to suppress the surface electric field. The implants have been activated at 1650°C. A thermal oxide under N_2O environment has been grown for passivation [5]. The emitter and base contact metals are Ni and Ni/Ti/Al respectively while bottom collector contact is based on Ni/Au. The top pad metallization is aluminum.

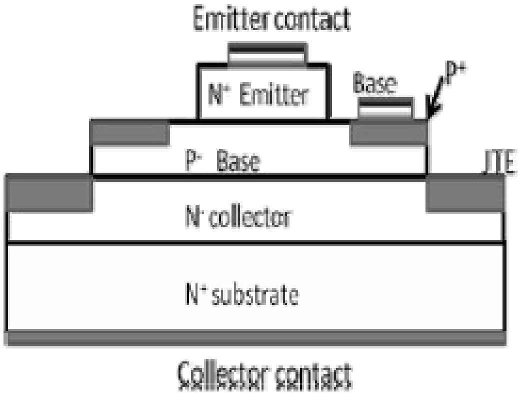

Fig. 1 Schematic cross-section and terminals of SiC BJT

3 MODELING OF SIC BJT

SiC BJT (BITSiC 1206) is modeled in MATLAB using Eber's –Moll equations [6,7,8]. The most important Ebers-Moll parameters which differentiates Si and SiC BJT devices are: parasitic capacitances (C_{BC} and C_{BE}), the forward current gain β_F, the early voltage and the saturation current (I_s) and the modeled parameters of SiC BJT are used to obtain the static and dynamic characteristics and the values are listed in Table 1. Modeling of current gain and parasitic capacitances are important which determines the switching behavior of SiC BJT.

TABLE I PARAMETERS OF SIC BJT

Parameter	**Simulated Values**	**Data sheet values**
Base Emitter capacitance (C_{BE}) with V_{BE} = 0V and Fs = 100kHz	1233pF	1500pF
Base-Collector capacitance (C_{BC}) with V_{BE} = 0V and f_s = 100kHz	425pF	400pF
Early voltage (V_A)	6.25V	5.85V
Saturation current (I_S)	$2.68\text{x}10^{-48}$A	$1.29\text{x}10^{-49}$A
Forward current gain (For V_{CE} = 5V and I_C = 2A)	20	20

Using the device parameters shown in Table 1, the SPICE code for obtaining the characteristics of SiC BJT in LTSPICE is given as

```
.model BitSiC1206 NPN ( IS = 1.5e-48 BF = 20 NF = 1 ISE =
2.2e-26 NE = 2 BR = 0.55 RB = 0.26 RC =0.06 XTI = 3 XTB = -
1.1 EG = 3.2 TRC1 = 4e-3 + CJE = 1233pF VJE = 2.9 MJE = 0.5
CJC = 425pF VJC = 2.9 MJC = 0.5)
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The model includes a temperature dependent collector resistance, which is an important feature that is not available in all SPICE versions. The parameters IS, BF, NF, ISE and NE are important for modeling the current gain and its dependence on the collector current accurately; XTI, XTB and EG model the temperature dependence of the current gain. RC and TRC1 model the on-resistance of the BJT and thus the value of V_{CE} (SAT). The parameters CJE, VJE and MJE model the base-emitter capacitance. CJC, VJC and MJC model the base-collector capacitance which is important for the switching speed [9,10].The output characteristics of SiC BJT are obtained for different junction temperatures using LTSPICE as shown in Figs.2 and 3. Switching characteristics are obtained by taking into account the parasitic inductances for the TO-258 package provided by the manufacturer (L_C = 10nH, L_E = 20nH and L_B = 25nH).

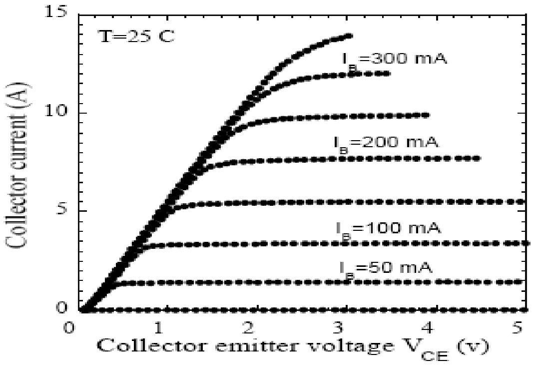


Fig.2 VI characteristics of SiC BJT at 25°C

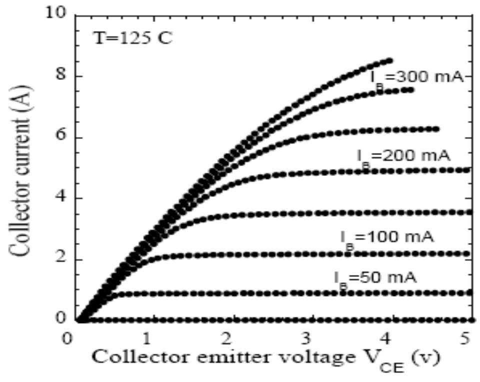


Fig.3 VI characteristics of SiC BJT at 125°C

A state-of-the-art 1200V Si IGBT has been selected for comparing with SiC BJT and the output characteristics of both the devices are shown in Fig.4.

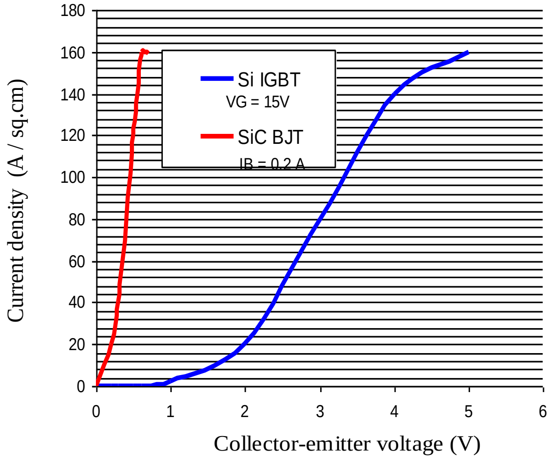


Fig.4 Output characteristics comparison between Si IGBT &SiC BJT

The IGBT has a forward voltage drop of 3.3V at collector current density J_C = 100A/cm^2 while the forward voltage of the SiC BJT is only 0.59V much smaller than the Si IGBT. This means the conduction losses in the SiC BJT will be much smaller than that of Si IGBT. The attractive feature of SiC BJT is that it is basically free of second breakdown and has a square reverse biased safe operating area. The design of driver circuit for SiC BJT is crucial since it requires an on-state base current of at least 400mA [10,11]. The high dynamic base current is achieved by employing a fast IC driver IXDN509. Although the driver loss of SiC BJT is much higher than Si IGBT, all other losses including the turn-on, turn-off, and conduction loss of SiC BJT are much smaller than Si IGBT, making the total loss of SiC BJT much lower than Si IGBT as shown in Fig.5.

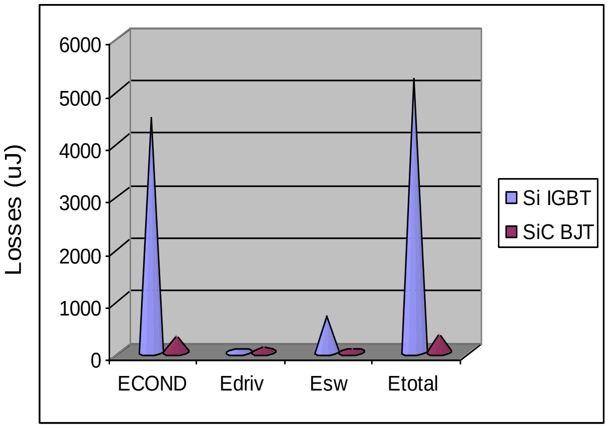


Fig.5 Loss comparison of Si IGBT and SiC BJT

4. INVERTED SINE PWM STRATEGY FOR SIC BJT INVERTER

Sinusoidal PWM is an effective method to reduce lower order harmonics, but it has limitations with respect to maximum attainable output voltage and power transfer. This paper presents an Inverted Sine PWM (ISPWM) technique which uses a high frequency inverted sine wave as a carrier [12]. This helps to maximize the output voltage for a given modulation index. The power circuit for SiC BJT PWM inverter is shown in Fig.6. The reference, carrier and gating pattern for ISPWM is shown in Fig.7. The advantages of ISPWM are :

- Has a better spectral quality and a higher fundamental component compared to the conventional SPWM technique without any pulse dropping.
- It enhances the fundamental output voltage particularly at lower modulation indices.
- The appreciable reduction in Total harmonic Distortion (THD) in the lower range of modulation index attracts drive applications where low speed operation is required.
- Harmonics of carrier frequencies or its multiples are not produced.

The single-phase SiC BJT based PWM inverter is shown in Fig.5.

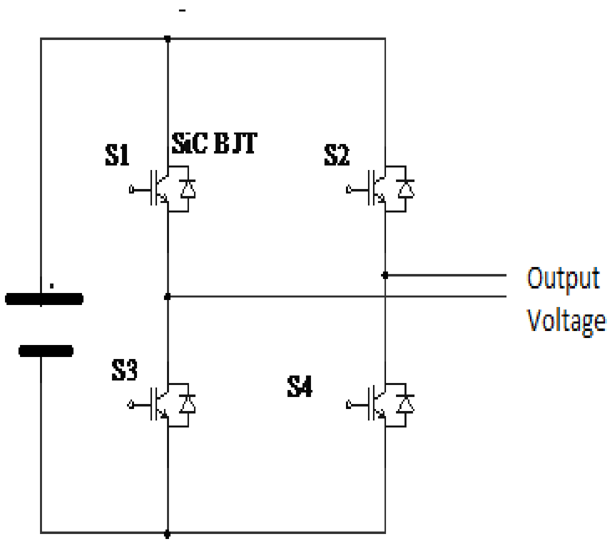


Fig.5.Single-phase SiC BJT PWM Inverter

The reference and carrier waveforms are shown in Fig.6, in which the pulses are generated whenever the amplitude of the reference sine wave is greater than that of the inverted sine carrier wave.

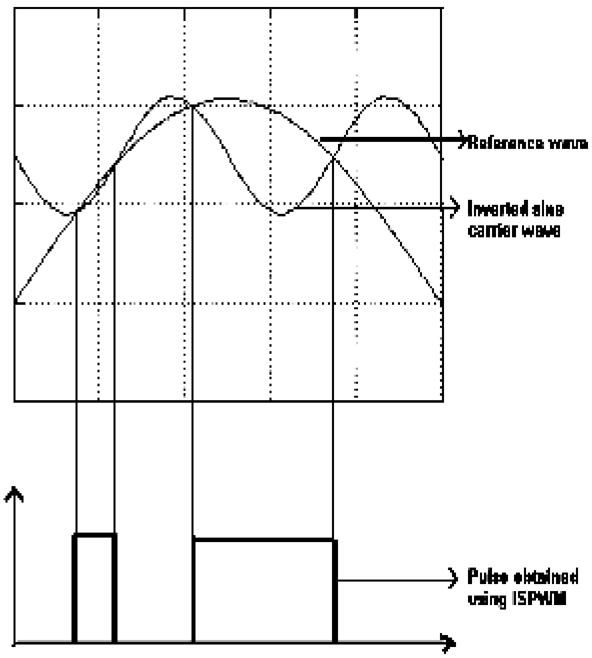


Fig.6 Generation of Gating pulses for ISPWM

The simulation circuit for SiC BJT PWM inverter with ISPWM technique is shown in Fig.7.

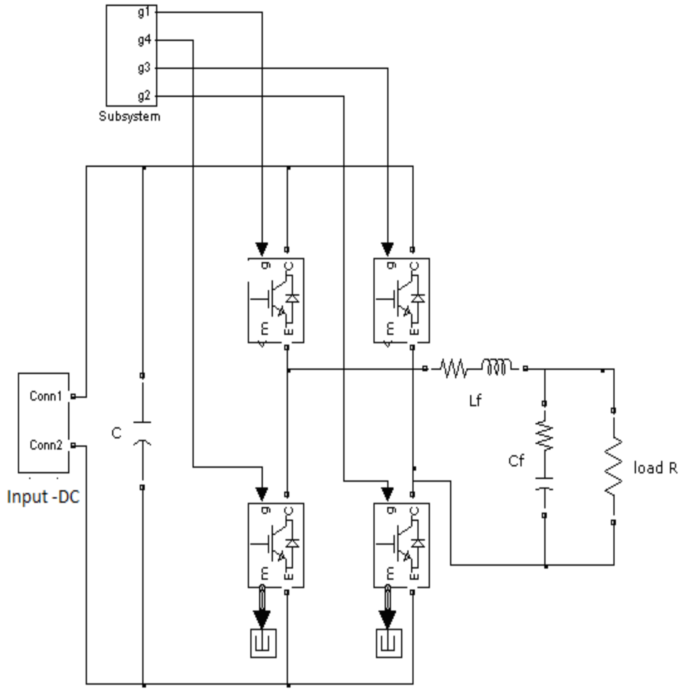


Fig.7. Simulation circuit for SiC BJT PWM Inverter

The gating pattern for switches in PWM inverter is shown in Fig.8.

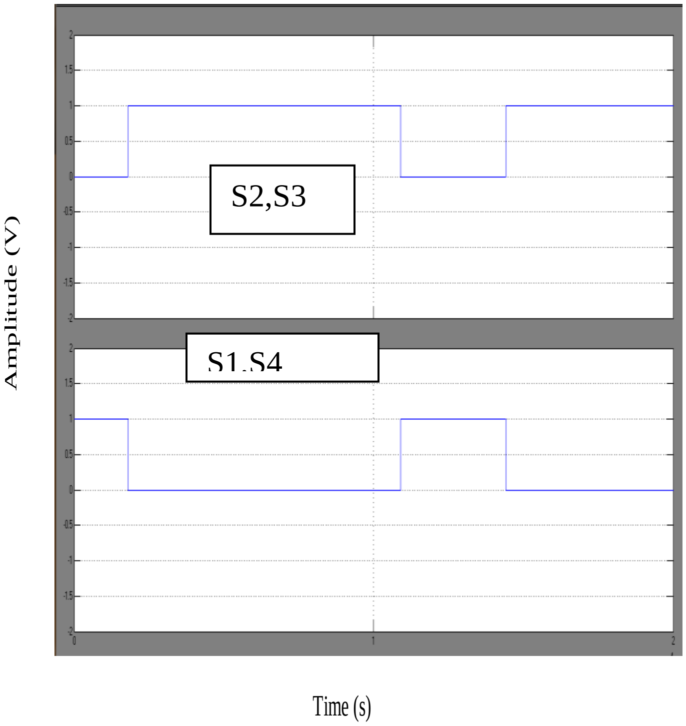


Fig.8. Gating pattern for Switches in SiC BJT Inverter

The simulated load voltage of SiC BJT inverter using ISPWM is shown in Fig.9.

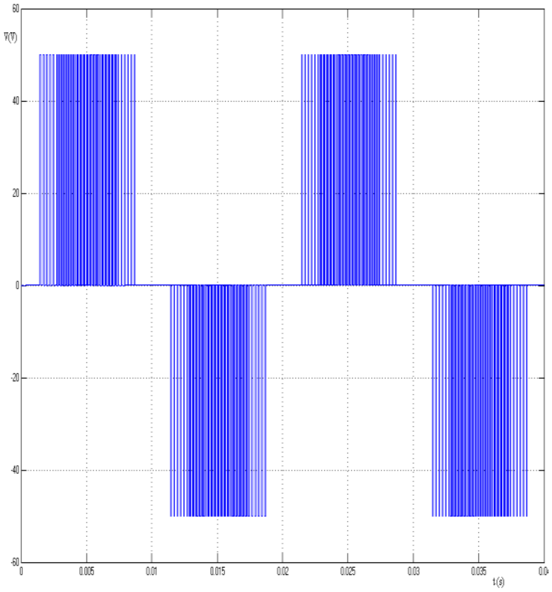


Fig.9 Simulated load voltage of SiC BJT Inverter using ISPWM technique

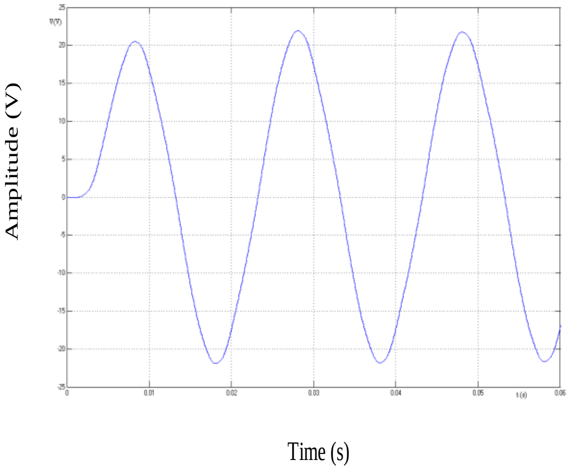


Fig.10 Filtered output voltage of SiC BJT PWM Inverter

The filtered load voltage waveform of SiC BJT inverter is shown in Fig.10 which resembles a sinewave.

5. EXPERIMENTAL RESULTS

This section describes the design and construction of a single-phase SiC BJT inverter to verify the proposed inverted sine modulation scheme .Gating signals are generated using Xilinx Spartan -3A DSP processor.Fig.11 shows the photograph of the overall prototype arrangement. Hardware prototype for this experiment can be divided into the following sections: a Xilinx Spartan board, lab prototype SiC BJT inverter setup as well as LC low pass filter & load configuration.

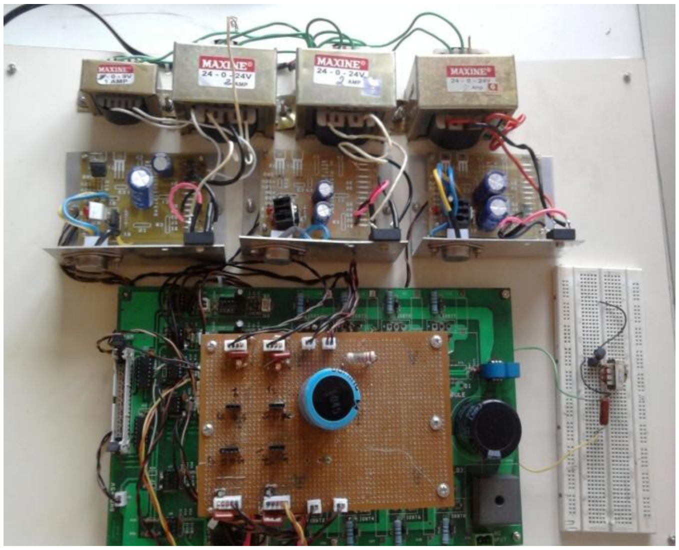


Fig.11. Prototype of Single-phase SiC BJT PWM inverter

5.1. Pulse Generation

Xilinx Spartan 3-A DSP trainer is employed to generate the pulses required to trigger the SiC BJTs. The PWM pins AE3 to AF8 is used to generate the gating pulses to the respective devices. HCPL - 4506 optocoupler modules are used for isolation between PIC PWM logic output signal and the multilevel inverter high voltage circuit parts. The HCPL-4506 optocoupler as shown in Fig.12 contains a GaAsP LED and a high gain photo detector to realize the isolation and to minimize propagation delay. These optocouplers improves the invert efficiency through reduced switching dead time.

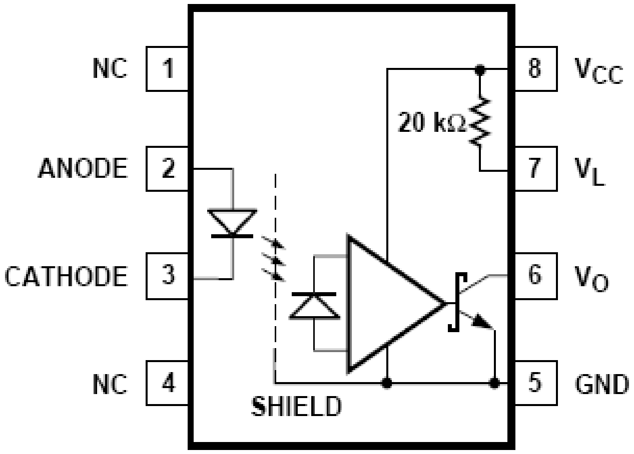
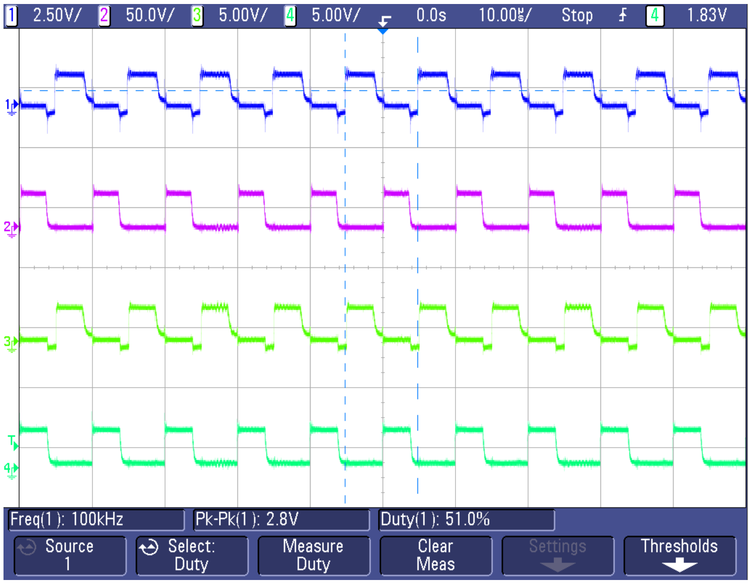


Fig.12 Pin details of optocoupler IC -4506

IXDD509 is used as a driver for SiC BJT. It consists of two 4-Amp CMOS high speed MOSFET gate drivers for driving the BJTs. Each of the output can source and sink 4 Amps of peak current while producing voltage rise and fall times of less than 15ns. The input of each driver is TTL or CMOS compatible and is virtually immune to latch up. This IC has the unique capability of driving the high power SiC BJTs by limiting the Ldi/dt transients. BitSiC 1206, 1200V, 6A BJT is used as a power device for bridge H_2. These transistors have unique properties like: very low losses, handles high voltages and operates at very high temperatures. The fast recovery diode FR107 is used as feedback diodes. The gating pulse for SiC BJT which is switched at 100 kHz is shown in Fig.13.



Freq(1): 100kHz
Pk-Pk(1): 2.8V
Duty(1): 51.0%

Fig.13. Gating pattern for SiC BJT PWM inverter

The experimental load voltage and load current waveform for single-phase SiC BJT PWM inverter for RL load is shown in Fig.14.

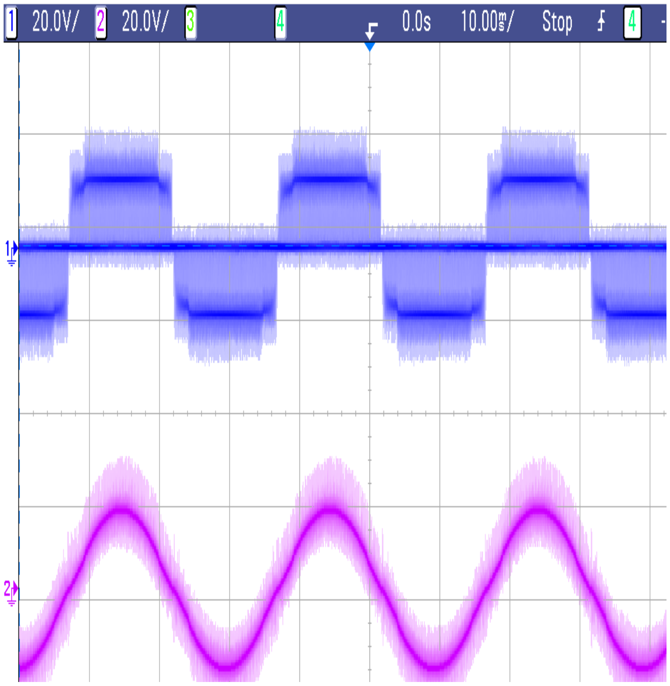


Fig.14. Experimental load voltage and load current waveform for SiC BJT PWM Inverter

The results clearly indicates that SiC BJT PWM inverter is best suited for renewable energy sources as it has lowers witching losses compared to Si BJT inverter. Moreover, it can be switched at higher frequencies and heat sink requirement is also reduced. With ISPWM technique, the inverter gives an improved performance reducing THD.

6. CONCLUSION

This paper has investigated the performance of SiC BJT based PWM inverter for renewable energy resources. The static and switching characteristics of SiC BJT have been simulated using MATLAB. Comparisons have been carried out with a state-of-the-art Si IGBT with the emphasis on switching losses. A novel ISPWM technique has been proposed for the SiC inverter which results in reduced THD. A prototype of single-phase SiC BJT PWM inverter has been developed to verify the proposed modulation technique where the switches are switched at 100kHz.The simulation results are verified with experimental data.

ACKNOWLEDGEMENT

The author wish to thank AICTE , New Delhi, India,for sponsoring the funded project on SiC based BJT PWM inverter which was successfully completed in the year 2011. Also, the author expresses her gratitude to the management of SSN College of Engineering for providing the computational and laboratory facilities for carrying out this work .

REFERENCES

[1] J. Richmond, S.-H. Ryu, M. Das, S. Krishnaswami, S. Hodge, Jr.,A. Agarwal, and J. Palmour, “An overview of Cree silicon carbide power devices,” in *Proc. Power Electron. Transp.*, 2004, pp. 37–42.

[2] A. K. Agarwal, S.-H. Ryu, J. Richmond, C. Capell, J. Palmour,S. Balachandran, T. P. Chow, B. Geil, S. Bayne, C. Scozzie, and K. A. Jones, “Recent progress in SiC bipolar junction transistors,” in *Proc.Int. Symp. Power Semicond. Devices ICs*, 2004, pp. 361–364.

[3] W.V. Muench and P. Hoeck, “Silicon carbide bipolar transistor”,Solid-State Electronics, 1978, Vol. 21, p.479-480.

[4] S. H. Ryu, A. K. Agarwal, R. Singh, and J. W. Palmour, "1800 V NPN Bipolar Junction Transistors in 4H-SiC", IEEE Electron Device Letters, Vol. 22, pp.119 -120, March 2001.

[5] B. Ozpineci, L. M. Tolbert, S. K. Islam, and M. Hasanuzzaman, “Effects of silicon carbide (SiC) power devices on PWM inverter losses,” in *Proc.IEEE Ind. Electron. Conf.*, Nov. 2001, pp. 1061–1066.

[6] Rahman, M.M., and Furukawa, S.: ‘Silicon carbide turns on its power’, ***IEEE Circuits Devices Mag*., 1992,8,** p. **22.**

[7] Charlotte, J., Burk, C. C., Zhang, A., Callanan, R., Geil B. and Scozzie, C. "1200V 4H –SiC bipolar junction transistors with a record beta of 70," in Proc. 49th Electronic Materials Conference, EMC '07, Indiana, USA, pp. 90-96,2007.

[8] Gao, Y., Huang, A.Q., Xu, X., Zhong, D., Agarwal, A.K., Krishnaswami, S. and Ryu, S.H. "4H-SiC BJT Characterization at high current high voltage", in Proc. Power Electronics Specialists Conference, pp. 1-5, 2006.

[9] Y. Tang, J. B. Fedison, and T. P. Chow, "High temperature characterization of implanted-emitter 4H-SiC BJT," in *Proc. IEEE/Cornell Conf. High Perform. Devices*, 2000, pp. 178–181.

[10] K. Sheng, L. C. Yu, J. Zhang, and J. H. Zhao, "High temperature characterization of SiC BJTs for power switching applications," *Solid State Electron.*, vol. 50, no. 6, pp. 1073–1079, Jun. 2006.

[11] M. Roschke and F. Schwierz, "Electron mobility models for 4H, 6H, and 3C SiC," *IEEE Trans. Electron Devices*, vol. 48, no. 7, pp. 1442–1447, Jul. 2001.

[12] R.Seyezhai and B.L.Mathur , 'Performance Evaluation Of Inverted Sine PWM Technique For An Asymmetric Cascaded Multilevel Inverter', Journal of Theoretical and Applied Information Technology, pp. 92-98,2009.