SIMULATION OF THE PERFORMANCE OF HIGH VOLTAGE DIRECT CURRENT (HVDC) SYSTEM WITH SI-GTO AND SIC-GTO THYRISTORS IN TERMS OF EFFICIENCY

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ABSTRACT

The paper studied how best Silicon Carbide gate turn off (SiC-GTO) thyristor can substitute Silicon gate turn off (Si-GTO) thyristor for an effective converter operation in a typical High Voltage Direct Current (HVDC) system. A monopolar HVDC 6-pulse converter configuration was chosen for the study and emphasis was placed on the converter performance results. The HVDC system was simulated using PSCAD/EMTDC software, which is a software/simulation tool for analyzing power systems. It was evident from the study that the range of efficiency for SiC GTO converter's controlled switches were higher than that of Si GTO converter's controlled switches. Sequel to these findings, SiC device is highly recommended since it has high efficiency compared to Si.
Keywords: simulation, HVDC, Silicon Carbide, Silicon GTO

INTRODUCTION

The history of electric power transmission reveals that transmission was originally developed with Direct Current (DC). However, DC power at low voltage could not be transmitted over long distances, thus it led to the development of alternating current (AC) electrical systems. Also the availability of transformers and improvement in AC machines led to the greater usage of AC transmission. The advent of the mercury arc valve for high power and voltage proved to be a vital break through for High Voltage Direct Current (HVDC) transmission. These mercury valves were the key elements in the converter stations, and the filtering was done using oil immersed components. The control was analog and most of the operations were left to the operator. After enough experiments were conducted on mercury valves, the first HVDC line was built in 1954 and was a 100km submarine cable with ground return between the island of Gotland and the Swedish mainland (Vadhera, 2004).

The development of thyristors is another milestone in the development of HVDC technology. The first solid-state semi conductor valves were commissioned in 1970. The mercury arc valves in the primitive projects were replaced by thyristor valves. The semiconductor devices like insulated gate bipolar transistors (IGBTs) and gate turn off (GTOs) thyristors in conjunction with microcomputers and digital signal processors have proved to be very effective compare to older mercury valves. The wider usage of semiconductor technology in present day HVDC systems has initiated great contributions in the research of power electronics (Fedison, 2001). With increase demand for high quality power, application of power electronics in the field of power distribution and transmission systems is attracting wide attention throughout the world. The purpose of this work, therefore, is to study how best SiC GTO can substitute Si GTO thyristor for an effective converter operation in a monopolar High Voltage Direct Current (HVDC) system.

THE PRINCIPLE OF HVDC SYSTEM OPERATION

When using direct current to provide an asynchronous link between two Alternative Current (AC) systems, it is necessary to have two converter stations one at each end, connected by a Direct Current (DC) transmission line. The main equipment in a converter station are transformers and thyristor valves. Chokes and filters are provided at each end to ensure smooth DC and suppress harmonics. At the sending end the thyristor valves act as rectifiers to convert AC into DC which is transmitted over the line. At the receiving end the thyristor valves act as inverters to convert DC into AC which is utilized at the receiving end (Gupta, 2004). In converter station at the sending end the voltage is stepped up to appropriate value by step-up transformer and then converted into DC by the thyristor valves. Thus at the start of transmission line, we have high voltage direct current. This rectified current flows along the transmission line to the receiving end converting station B, where it is converted into 3-phase AC current by the thyristor valves and then stepped down to low voltage for further distribution (Mohan, Undeland and Robins, 1995).

Monopolar DC Link: As the name suggests, monopolar link has only one conductor and return path is provided by permanent earth or sea. The line usually operates with negative polarity with respect to ground so as to reduce corona loss and radio interference. Monopolar line is more economical than a bipolar line because the ground return saves the cost of the one metallic conductor and losses in it (Vadhera, 2004). Monopolar HVDC links were used only for low power rating and mainly for cable transmission. In some cases the monopolar line installed earlier are converted into bipolar systems by adding additional substation pole and transmission pole.

Bipolar DC Link: This is the most widely used DC link for over head long distance HVDC transmission systems and also for back-to-back HVDC system. This link has two conductors, one operating with positive polarity and the other with negative polarity with respect to the earthed tower structure. There are two converters of equal voltage rating and connected in series at each end of the DC line. The neutral points may be grounded at one end or at both ends. If it is grounded at both ends each pole can operate independently. The rated voltage of a bipolar link is expressed as ± 500V. Power rating of one pole is about half of bipole power rating. The earth carries only a small out-of-balance current during the normal operation. When the current in the two conductors are equal, the ground current is zero. During fault on one of the lines, the other line along with ground return can supply half of the rated load. Thus continuity of supply is maintained. After taking corrective measures, the system is switched over to normal bipolar operation (Fedison, 2001).

Homopolar DC Link: A homopolar link has two or more conductors having the same polarity, usually negative, and always operates with ground as the return conductor. In case of a fault on any one of the conductors, the converter equipment can be reconnected so that the healthy conductors can supply power. Such a scheme is very complicated and may be used for the following:

(a) Two homopolar over head lines supplying to a common monopolar cable termination.
(b) One overhead transmission tower carrying insulator strings supporting two homopolar transmission line conductors.

Thus, homopolar DC link has limited applications (Schettler, Huang and Christl, 2000).

SIMULATION OF THE HVDC SYSTEM

The configuration chosen for the study is a monopolar configuration as described earlier, the transmission system is based on Voltage Source Converter (VSC) technology. The converter at both ends is a voltage source converter also known as a forced commutated converter. The system model is designed and the main assumption made in the model is that, one substation is the sending end and the other the receiving end.

System Specifications

- Transformers
  Rectifier (sending) end: 3 phase 2 winding transformer 100MVA, 60Hz, Y-Δ, 13.8KV - 62.5KV.
  Inverter (receiving) end: 3phase 2 winding transformer 100MVA, 60Hz, Δ-Y, 62.5KV - 115KV.
- Filters
  Rectifier end: Capacitor bank – 2 μF
  Inverter end: RC filter bank – 139 μF, 0.5ohm
- Cable
  The cable modeled represents two coaxial cables buried 1m underground and separated by 40cm. It is 100Km long.
- Synchronous generator: 75MVA
- Three voltage source
  115KV (line-line base voltage), 60Hz, 100MVA base (3 phase)

Simulation specifications

System ratings: 120KV dc link up to 75MW power delivered to the receiving end.
Device ratings: SiC - 20KV, 200A/cm^2, Si - 5KV, 200A/cm^2, Number of devices: As discussed earlier, by arranging the devices in series and parallel, the converter can handle high voltages and currents. For a rating of 120KV, 1000A, which is the maximum voltage and current, there are several possible arrangements based on the device rating.

SiC devices: 5 parallel strings of 6 devices in series (for 20KV, 200A device)
5 parallel strings of 24 devices in series (for 5KV, 200A device).
Simulation starts from a snap shot to initialize the steady state operating values.
The switching frequency is 2 KHz, as the frequency modulation index is 33 times the fundamental frequency.

RESULTS AND DISCUSSION

The simulation results for different operating conditions are presented in figure 1 to figure 7. The graphs show the total device losses at different temperatures. As shown in the graphs, the losses are a function of the conduction current and vary proportionally with the square of current. When the device is not conducting, it blocks the voltage across it and there is no loss in the device. However, for the same switching frequency, the losses are more in Si GTO than SiC GTO. The total loss of SiC GTO is less than Si GTO as expected, since the on-state resistance of Si GTO is more than SiC GTO. The losses increase with increase in temperature due to increase in on-state resistance with temperature. However, the increase in loss of Si GTO is more than SiC GTO. These results are used to calculate the efficiency.

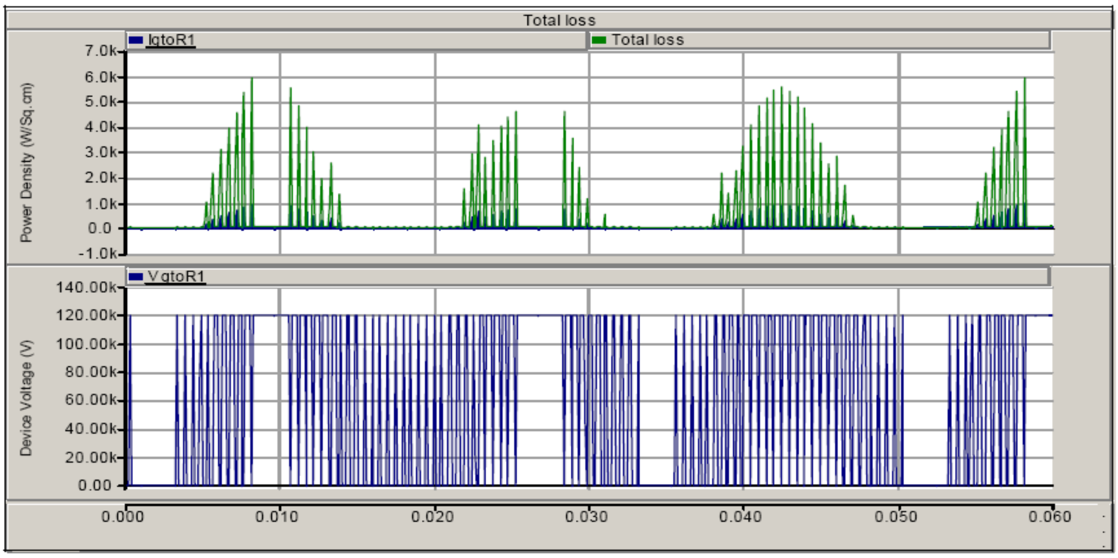

Figure 1: Loss profile for SiC GTO (300K)

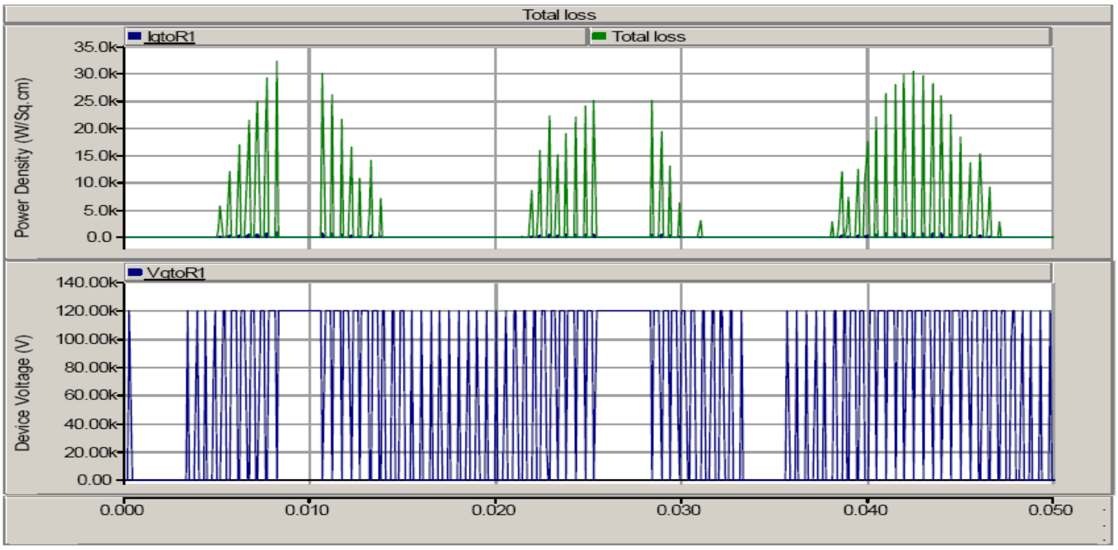

Figure 2: Loss profile for SiC GTO (423 K)

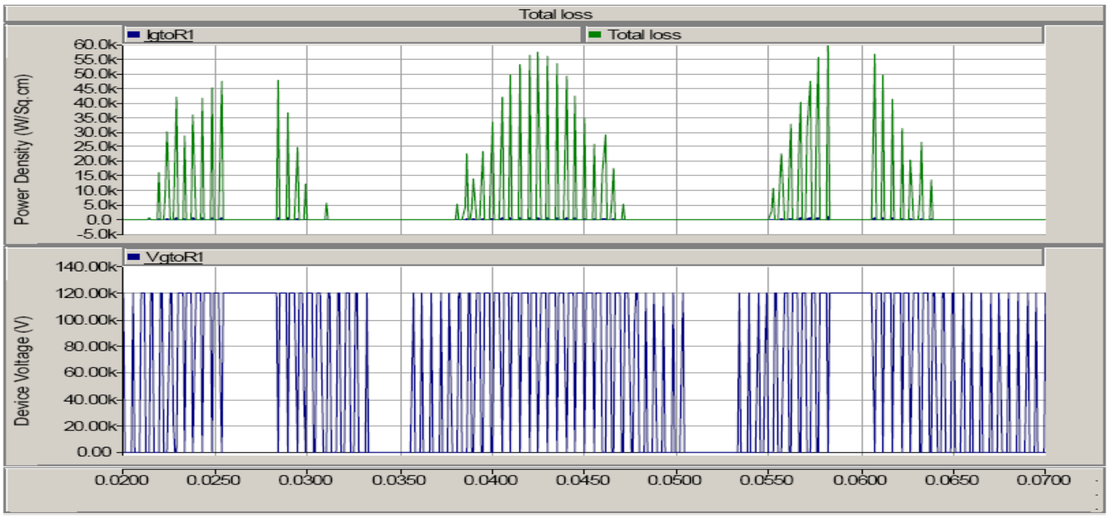

Figure 3: Loss profile for SiC GTO (473 K)

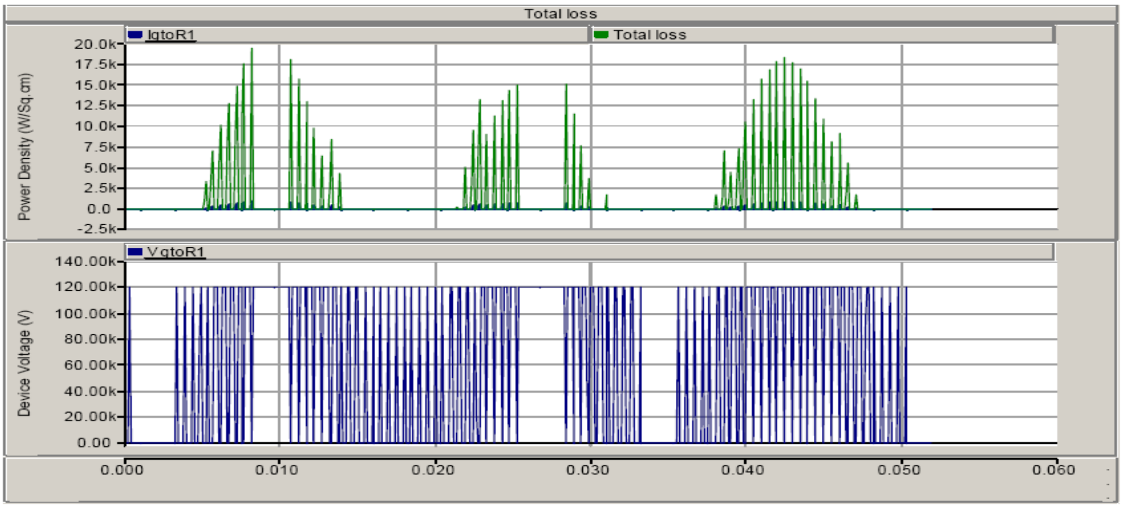

Figure 4: Loss profile for Si GTO (373 K)

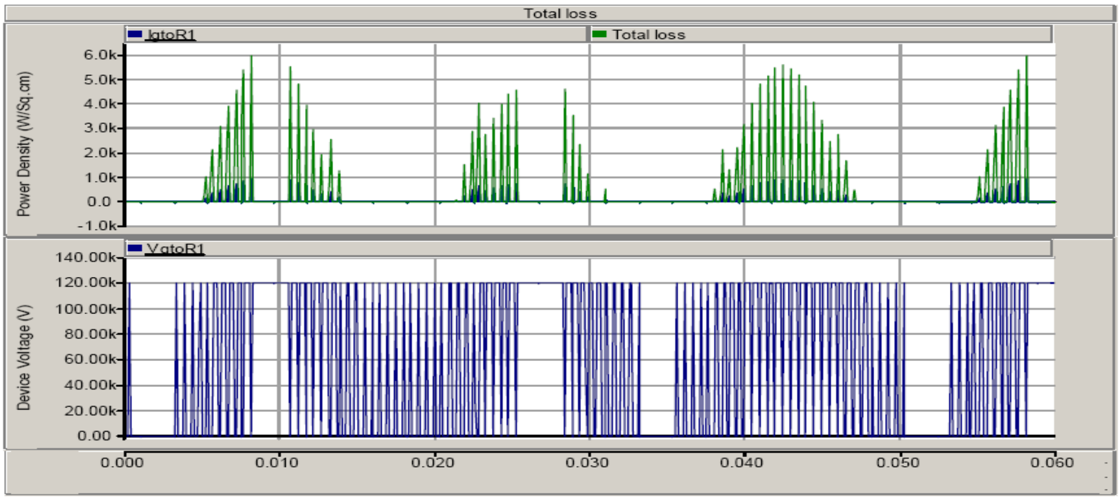

Figure 5: Loss profile for Si GTO (300 K)

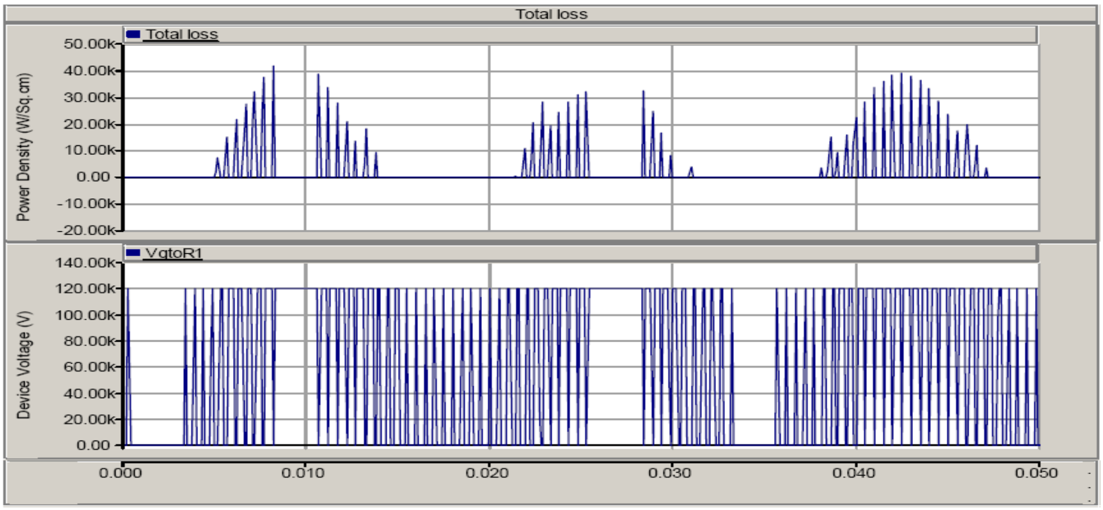

Figure 6: Loss profile for Si GTO (423 K)

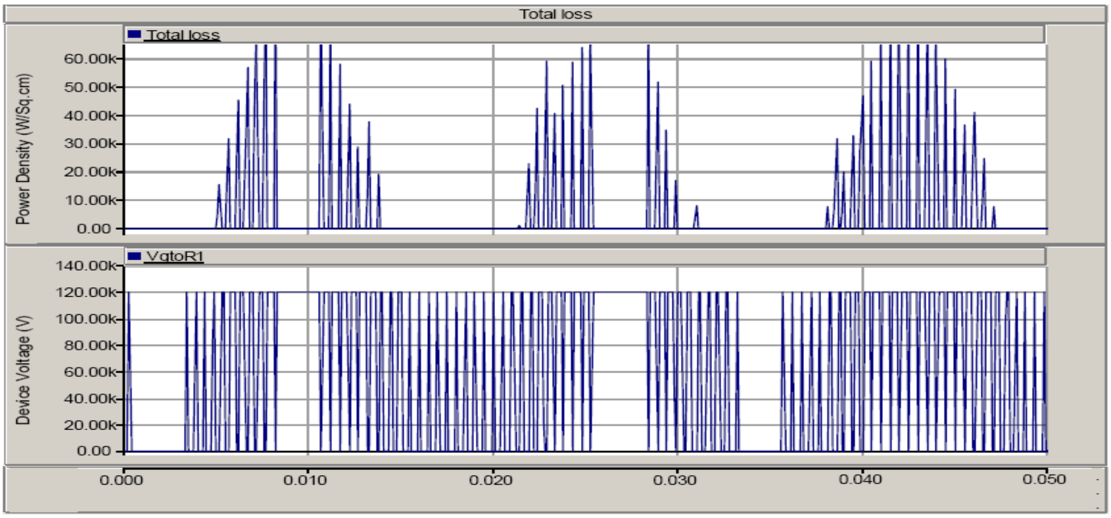

Figure 7: Loss profile for Si GTO (473 K)

EFFICIENCY CALCULATION

The efficiency is calculated based on the power loss profile obtained for different operating conditions. It is the instantaneous loss as a function of the instantaneous current. The average loss over few cycles of the fundamental is calculated to find the cyclic power loss (average power loss) for each cycle of the output voltage. The plots of average power loss for Si GTO and SiC GTO are shown in figure 8 and figure 9. The maximum and minimum power loss for a single device over a few cycles is measured from the plots, and the corresponding converter controlled switches efficiency is calculated. The efficiency calculations are based on the dc power in the dc link, average loss in the devices, and the number of devices in the converter.

Maximum efficiency = (dc power- $P_{loss(\min)}$)/dc power

$P_{loss(\min)} = P_{\min}$. (no. of devices in the converter)

Minimum efficiency = (dc power- $P_{loss(\max)}$)/dc power

$P_{loss(\max)} = P_{\max}$ (no. of devices in the converter)

N0. of devices = (no. of devices for voltage sharing).(no. of devices for current dividing). 6

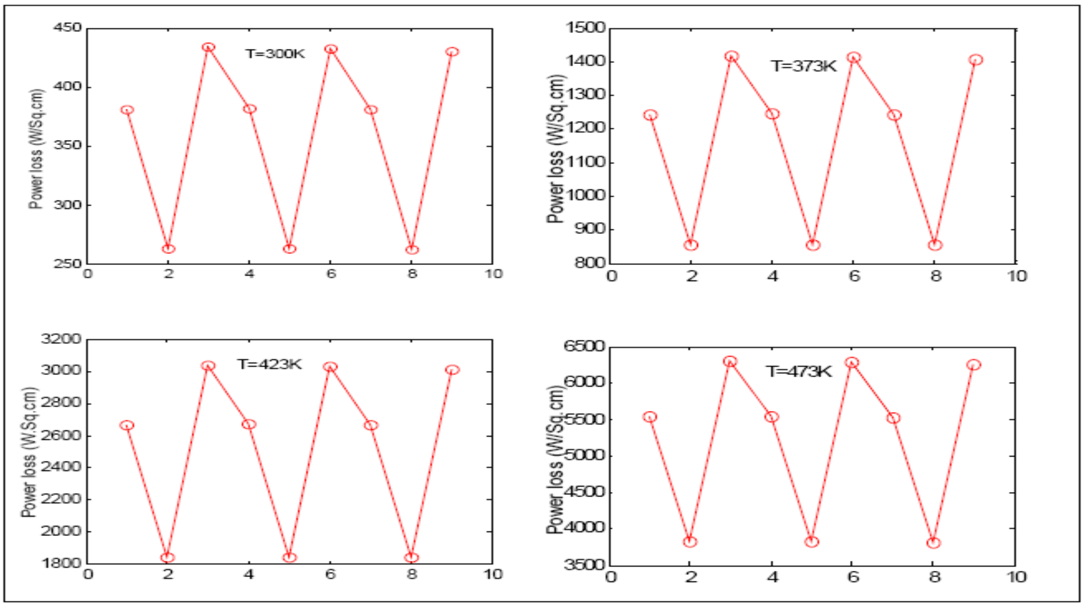

Figure 8: Cyclic power loss plots for Si 5KV, 200 A/cm^2 GTO

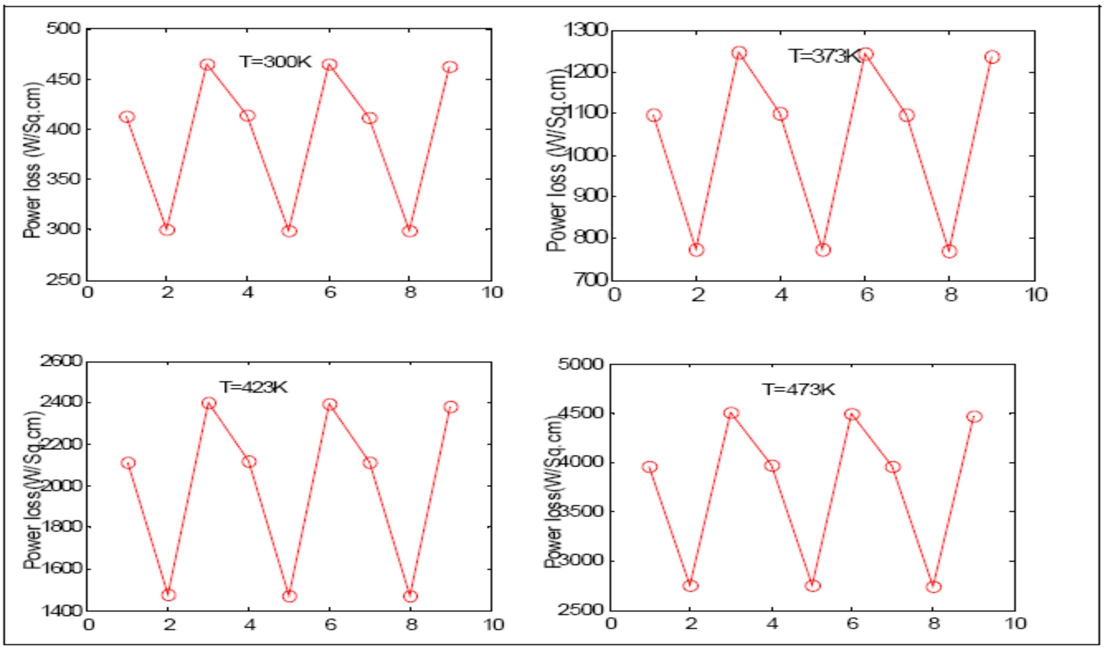

Figure 9: Cyclic power loss plots for SiC 20KV, 200 A/cm^2 GTO

Tables 1 and 2 show the maximum and minimum efficiencies of Si GTO rated at 5KV, 200A/cm^2 and SiC GTO rated at 20KV, 200A/cm^2. Figure 10 shows the efficiency plot for Si GTO and SiC GTO converter's controlled switches efficiency. The range of efficiency for SiC converter is higher than Si converter, due to the lesser number of devices and also the average power loss per device is less for SiC GTO. It can also be seen from the plot, that at 27^{0}C, the efficiency is almost the same for the Si converter and SiC converter. However, at higher temperatures the efficiency of the Si converter's controlled switches drops down, but the efficiency of the SiC converter controlled switches is still high. This illustrates that SiC devices can operate efficiently at high temperature.

Table 1: Efficiency of Si GTO Converter's Controlled Switches

Temp (K)	P_{max}	P_{min}	Max. eff %	Min. eff %
300	433.3	262.7	99.68	99.48
373	1443.1	837.7	98.75	98.26
423	3041.2	1842.4	97.78	96.35
473	6301.9	3818.9	95.41	92.43

Table 2: Efficiency of SiC GTO Converter's ControlledSwitches

Temp (K)	P_{max}	P_{min}	Max. eff %	Min. eff %
300	475.2	300.6	99.9	99.85
373	1245.6	771.8	99.76	99.62
423	2402.1	1472.8	99.55	99.77
473	4506.9	2749.3	99.17	98.64

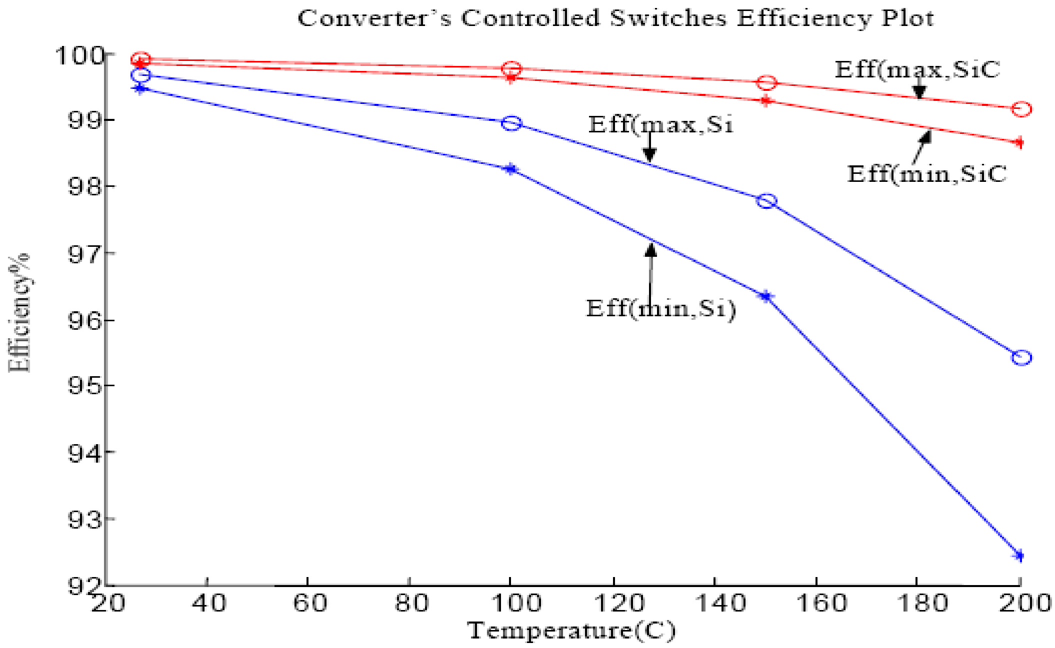

Figure 10: Converter's Controlled Switches efficiency plot

CONCLUSION

Based on the simulation results and efficiency calculation, it is evident that the difference in losses shows that SiC devices have high efficiency compared to Si. Also the number of SiC devices per converter leg required is less, due to the higher voltage rating of the device. This implies that the range of efficiency for SiC GTO converter's controlled switches was higher than Si GTO converter's controlled switches. It is suggested that, since SiC devices can withstand high temperature and since the losses are also less, thermal management requirements such as heat sink size can be greatly reduced. Also the devices operating area limits can be improved due to reduced losses, and hence the maximum frequency can be increased for a given current density and operating voltage.

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