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Design of Silicon-Carbide Based Cascaded Multilevel Inverter

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Abstract: Presently, almost all the power electronic converters use Silicon (Si) based power semiconductor switches whose performance is approaching the theoretical limits of the silicon material. So, the emergence of Silicon Carbide (SiC) based semiconductor switches with their superior features compared with silicon based switches has resulted in substantial improvements in the performance of power electronic systems. Sic power devices are more compact, lighter and more efficient so that they are ideal for high power, high voltage switching applications. In addition, Sic based devices can operate at high temperatures (up to 600 degrees) without much change in their electrical properties. This paper focuses on the design of SiC based DC-AC converter using embedded controller. Also reductions in heat sink size and device losses with the increase in the efficiency will be analyzed using inverted sinusoidal pulse- width modulated (ISPWM) three phase multilevel inverter. The emergence of multilevel converters has been in increase since the last decade. These new types of converters are suitable for high voltage and high power application due to their ability to synthesize waveforms with better harmonic spectrum. The general function of multilevel inverters is to synthesize a desired voltage from several levels of dc voltage desired waveform. Three presentable topologies can be considered for multilevel inverters: Diode- clamped, flying capacitor and cascaded H- bridge cells with separate dc sources. This paper focuses on cascaded power rating, improved harmonics performance and reduced electromagnetic interference. A theoretical study and computer simulation (PSPICE) works of the five- level voltage inverter controlled with ISPWM modulation strategy is presented. In addition, this paper gives a comparative study of Si and Sic based multilevel inverter for FACTS application.

Key words: Silicon carbide MOSFET · Multilevel inverter · Inverted SPWM and THD

INTRODUCTION

Silicon carbide is a wide bandgap semiconductor that possesses many favourable properties making it interesting for high temperature, high frequency and high power application. Also, SiC has led to the creation of near perfect high voltage diodes whose speed and power handling capabilities open new applications in variable- frequency motor drives [1]. This will, lead to higher density power modules that operate at higher junction temperatures. Silicon carbide consists of an equal number of silicon and carbon atoms arranged in a hexagonal lattice. It is the hardest material having high thermal and chemical stability. SiC has over 70 polytypes. The most commonly known polytypes are 3C- SiC, 4h-SiC and 6H-SiC and 4H- SiC is preferred for power devices because of its high carrier mobility and its low dopant ionization energy. This paper highlights the potential advantages of SiC power MOSFETS over Si power MOSFETS in the areas of switching, operating temperature and blocking voltage. Moreover, Sic based multilevel inverter is designed using ISPWM. This principal motivation for multilevel topology is the increase of power, the reduction of voltage stress on the power switching devices and the sinusoidal currents [2]. This paper takes into account the merits of SiC based power device and multilevel topology and aims to develop a cascaded multilevel inverter based FACTS device (Unified Power Flow Controller) which greatly improves the power transmission capacity of the transmission line. Computer simulation of this SiC based inverter is presented and the output result is verified.

Advantages of Sic Compared with si: As mentioned before, SiC power devices with their close-to-ideal characteristics, bring great performance improvements

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to power converter applications. Some of these advantages compared with Si based power devices are as follows [2]:

- SiC unipolar devices are thinner and they have lower on-resistances. With lower on resistance, SiC power devices have lower conduction losses and therefore higher overall efficiency.
- SiC based power devices have higher breakdown voltages because of their higher electric breakdown field.
- SiC can operate at high temperatures up to 600°C whereas Si devices can operate at a maximum junction temperature of only 150°C.
- SiC power devices are highly reliable as their forward and reverse characteristics vary only slightly with temperature and time.
- SiC is extremely radiation hard that is radiation does not degrade the electronic properties of SiC.
- SiC has a higher thermal conductivity and SiC power devices have a lower junction-to-case thermal resistance, thus device temperature increase is slower.
- SiC based devices can operate at higher frequencies not possible with silicon-based devices in power levels of more than a few tens of kilowatts because of low switching losses.
- SiC based bipolar devices have excellent reverse recovery characteristics. With less reverse recovery current, the switching losses and EMI are reduced and there is no need for snubbers.

Merits of Silicon Carbide: The Silicon carbide materials have superior electrical characteristics compared with silicon. Some of these characteristics are tabulated for the most popular wide band gap semiconductors and silicon in Table 1.

From the Table 1, it is obvious that wide band gap semiconductor materials have superior electrical characteristics compared with silicon. The wide band gap energy and low intrinsic carrier concentration of SiC makes it to operate at high temperature than silicon [3]. In addition a higher electric break down field results in power devices with higher breakdown voltages. Another consequence of the higher electric breakdown field and higher doping density is the width reduction in the drift region of the devices. The width of the drift region is calculated for all the semiconductors as shown in Table 1. and the results are plotted which is shown in Fig. 2. for the breakdown voltage range of 100 to 10,000V. Diamond, as expected, requires the minimum width, while 6H-SiC, 4H-SiC GaN follow diamond in the order of increasing widths. Compared to these, Si requires approximately a ten times thicker drift region. From the above graphs, it is predicted that the most promising new material for power electronics currently is silicon carbide [3].

SiC Based Power Mosfet (SiC 711CD10): Silicon carbide, specifically, 4H- SiC has an order of magnitude higher breakdown electric field than silicon, thus leading to the design of SiC power devices with thinner and more highly doped voltage blocking layers. For majority carrier power devices such as power MOSFETS, this combination can yield a SiC device with a 100X advantage in resistance compared to that of Si majority carrier devices. A SiC MOSFET can block voltages more than 3kv unlike a Si MOSFET, which can typically block up to 300v because of the high electric breakdown field strength of Sic [4]. In SiC MOSFETS, the epitaxial layer resistance is much smaller and the channel resistance is higher, thus making the MOSFET channel a more significant contributor to the on-state voltage. This is due to the low channel surface mobility of SiC compared to Si. The structure of SiC MOSFET is shown in the Figure (3). The type of SiC MOSFET that is used for the design of multilevel inverter is SiC711CD10. The SiC711CD10 has an internal break- before make function to ensure that high-side and low side MOSFETS are not turned on the same time. Also, the MOSFET has a built- in delay time that is optimized fro the MOSFET pair. When the PWM signal goes low, the high side driver will turn off, after circuit delay (toff) and the output will start to ramp down. After a further delay, the low- side driver turns on. When the PWM goes high, the low side driver turns off. As the body diode starts to conduct, the high-side MOSFET turns on after a short delay. The delay is minimised to limit body diode conduction. The output then ramps up. The structure of SiC 711CD10 is shown in the Figure (4). Using this SiC based MOSFET, a cascaded MLI is implemented [5].

SiC Based Multilevel Inverter: Multilevel voltage source inverter has been recognized as an important alternative to the normal two level voltage source inverter, especially in high power application. Using multilevel technique, the output voltage amplitude is increased, switching devices stress is reduced and the overall harmonics profile is improved. Three presentable topologies can be considered for multilevel inverter (MLI): diode-clamped,

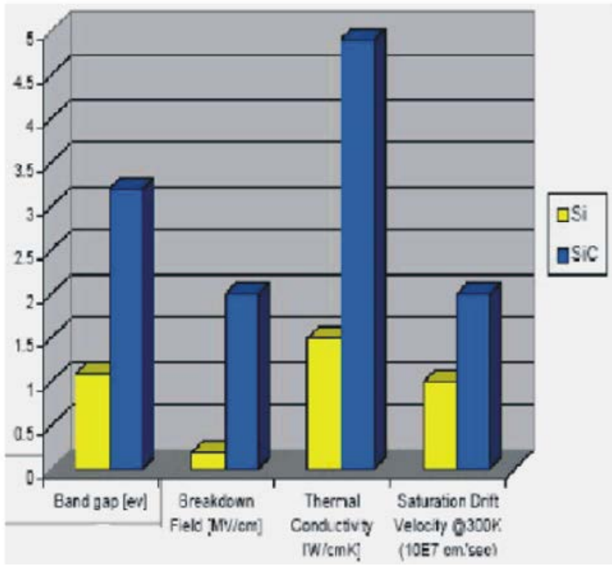

Fig. 1: Physical Properties of Silicon Carbide compared with Silicon

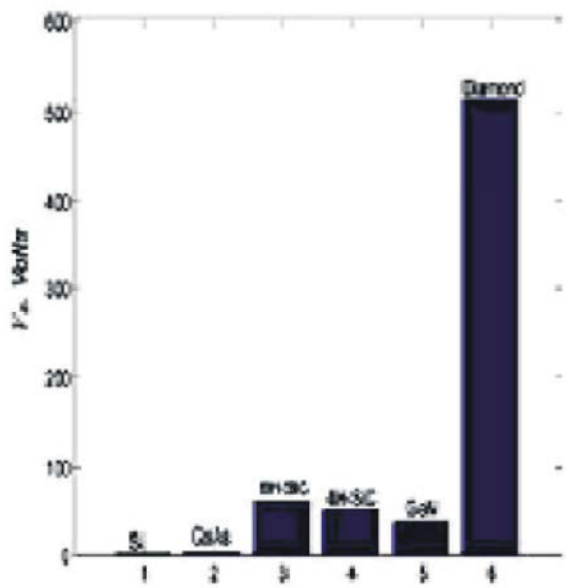

Fig. 2: Maximum Breakdown voltage of a power device at the same doping density normalized to Si

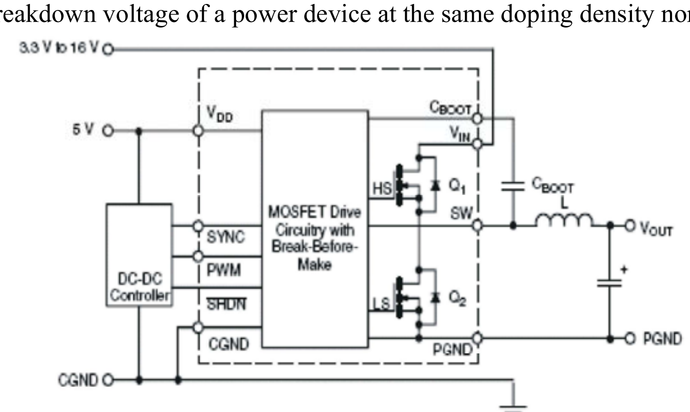

Fig. 3: Structure of SiC711CD10 Power MOSFET

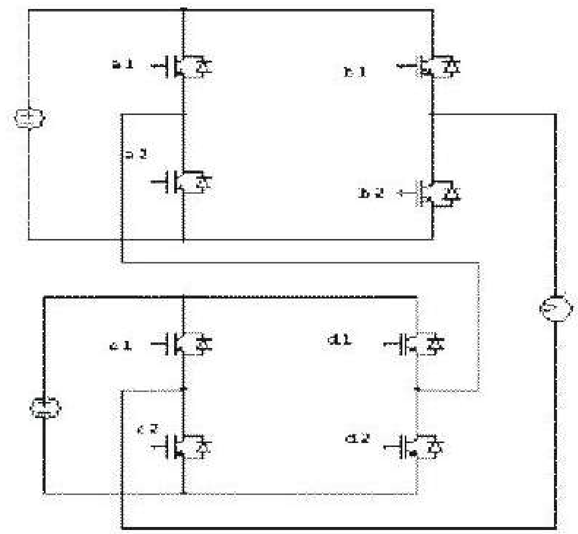

Fig. 4: A Five - Level Cascaded Inverter

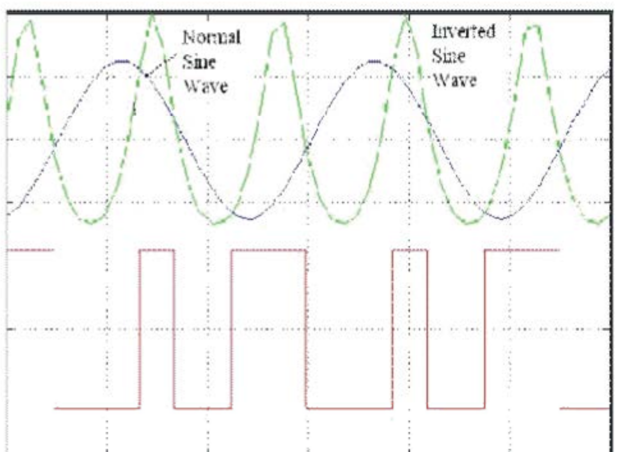

Fig. 5: Generation of ISPWM Pulses

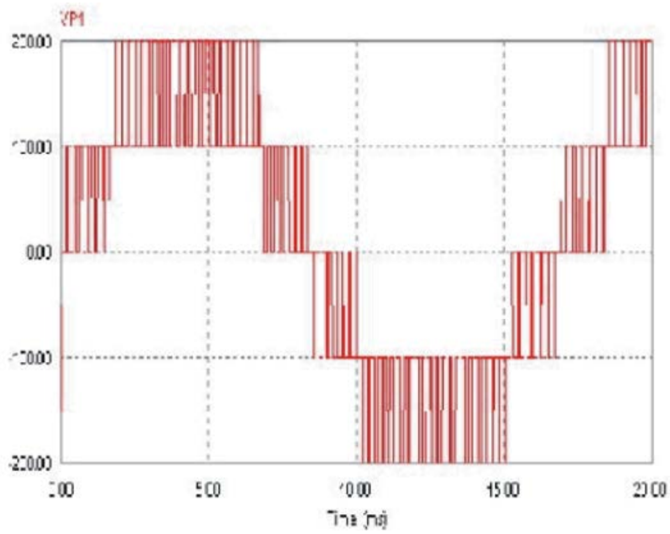

Fig. 6: Output Waveform of a 5-Level MLI

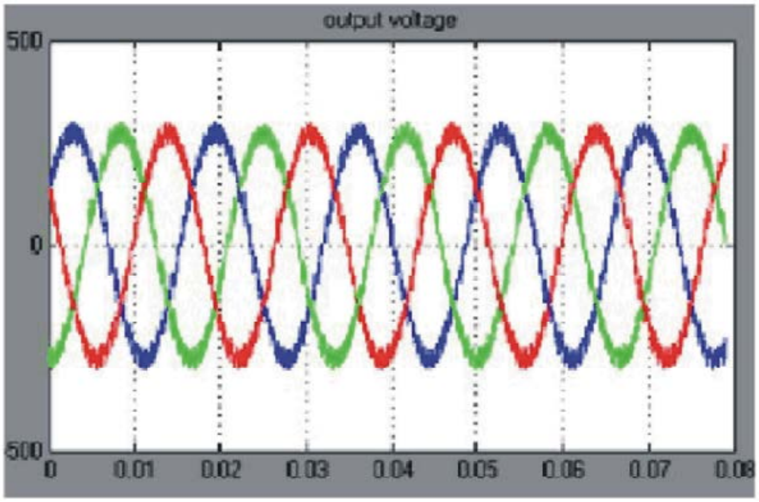

Fig. 7: Output Waveform of aSi- based MLI UPFC

0

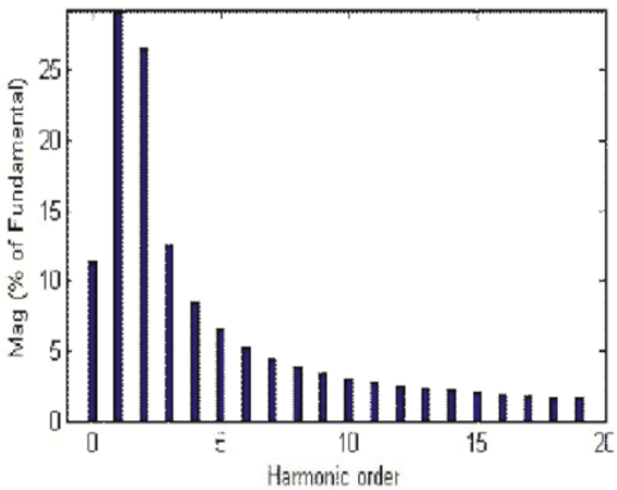

Fig. 8: Harmonic spectrum of Si-based MLI

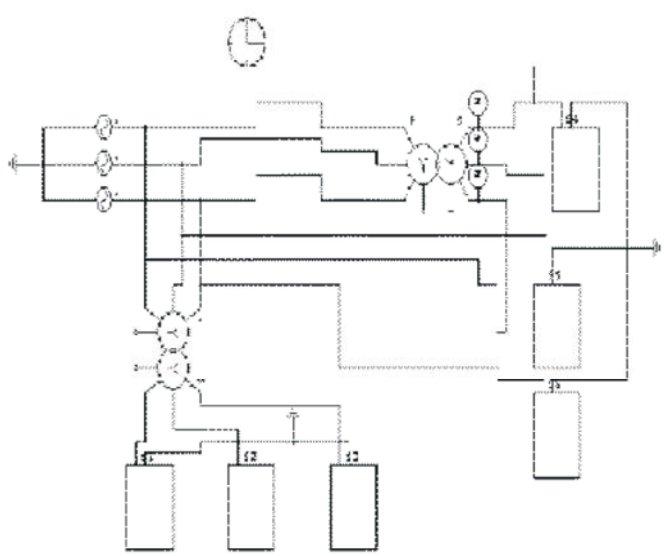

Fig. 9: Simulation Circuit of a SiC -based MLI UPFC

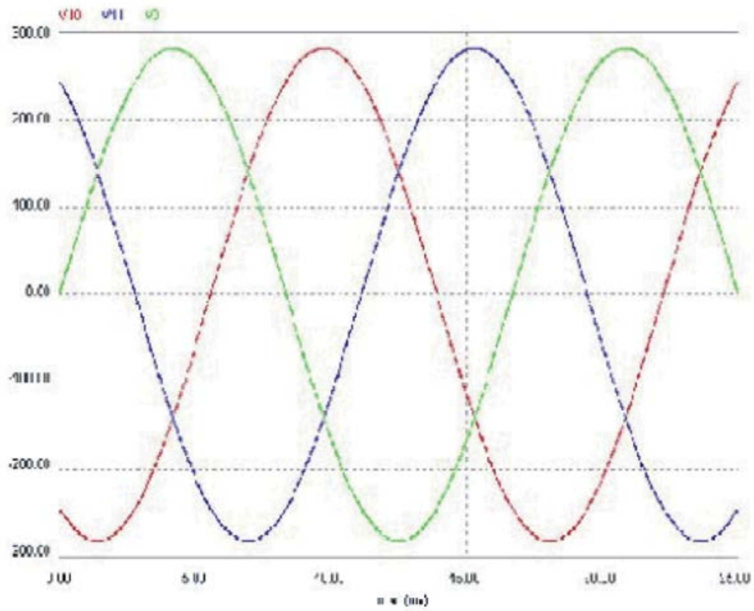

Fig. 10: Output Waveform of aSiC based MLI UPFC

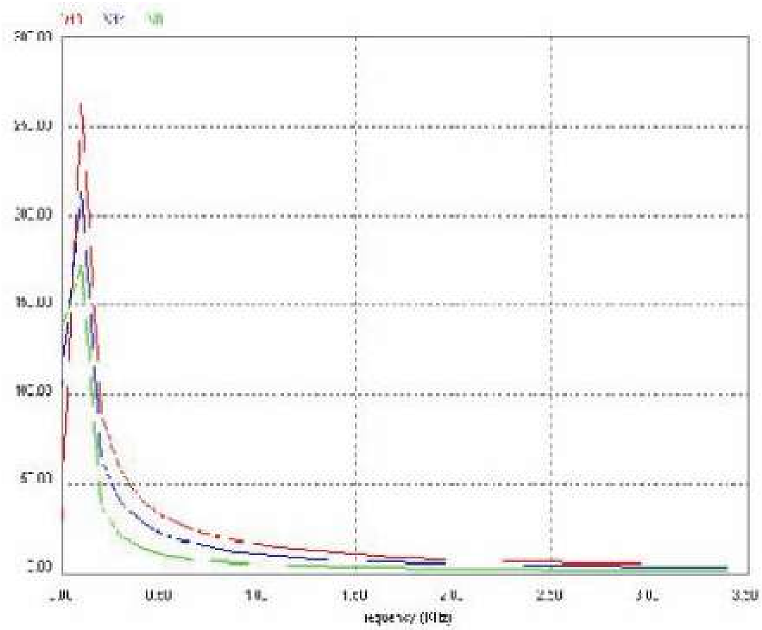

Fig. 11: Harmonic Spectrum of SiC- based MLI UPFC

flying capacitor and cascaded H-bridge cells with separate dc sources. This paper focuses on cascaded multilevel inverter. In this topology, a number of full bridge single phase inverters with dedicated isolated dc voltage sources is connected together in series to form a high voltage inverter for each phase of the system Fig. 4. shows H-bridge inverters which is capable of synthesizing five distinct voltage levels ($\pm 2V_{dc}$, $\pm V_{dc}$, 0) if all the dc voltage sources are equal to V_{dc}.The main advantage of this inverter is that it provides flexibility for expansion of the number of levels easily without introducing undue complexity in the power circuit. Also, extra clamping diodes are not needed. Modularized circuit layout and packaging is possible because each level has the same structure and there are no extra clamping diodes or voltage balancing capacitor.

Table 1: Physical Characteristics of Si and main Wide band gap Semiconductors

Property	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Bandgap, Eg (eV)	1.12	1.43	3.03	3.26	3.45	5.45
Dielectric constant, ε_r[1]	11.9	13.1	9.66	10.1	9	5.5
Electric Breakdown Field, E_c (kV/cm)	300	400	2500	2200	2000	10000
Electron Mobility, μ_n ($cm^2/V\cdot s$)	1500	8500	500 80	1000	1250	2200
Hole Mobility, μ_p ($cm^2/V\cdot s$)	600	400	101	115	850	850
Thermal Conductivity, λ (W/cm·K)	1.5	0.46	4.9	4.9	1.3	22
Saturated Electron Drift Velocity, v_{sat} ($\times 10^7$ cm/s)	1	1	2	2	2.2	2.7

[1] $\varepsilon = \varepsilon_r \cdot \varepsilon_0$ where ε_0=8.85×10^{-12} F/m

This cascade inverter is suitable for many utility applications as it costs less, have higher performance, less EMI and higher efficiency than the traditional inverter.

Pulse width modulation is a most important part of power electronic systems and there has been considerable research effort over the years to determine optimum PWM strategies and operating criteria for various applications. Of all the different modulation techniques, this paper focuses on inverted sinusoidal pulse width modulation. In this modulation strategy, the ispwm pulses are generated by comparing normal and inverted sine wave using embedded controller as shown in the Fig. 5.

Simulation Result and Comparison: A five-level cascaded inverter using silicon carbide based power MOSFET is simulated and the result is shown in the Fig. 6. Also, the simulation is performed to analyse and compare the characteristics of a Si and SiC based multilevel inverter for FACTS application (UPFC). The Fig. 7. shows the output for a Si-based MLI UPFC. Fig. 8. shows the simulation circuit and output waveforms for a SiC -based cascaded MLI UPFC. From the simulation results, the Si inverter has high losses compared with that of the SiC inverter [5]. From the Fig. 9. It is obvious that the Sic based MLI has reduced harmonics, low losses as the specific on-resistance for the Sic MOFET is 0.3x 10E-3 $cm^{-2.}$ With lower device loses, the SiC inverter is expected to have high efficiency. Calculations show that the Si MOSFET needs to prevent thermal damage, while the SiC MOSFET needs only a small one for either junction temperature limit. Therefore, with SiC inverter, the designers will have the freedom to select higher operating frequencies, which will allow a much wider application of PWM as the switching technique.

CONCLUSION

Silicon carbide material quality, size and cost significantly improved over the last several years to make it a viable replacement for silicon in power devices. System studies show that power electronic systems using SiC power devices are on average 10% points more efficient because of the low losses of the SiC power devices. In this paper, the SiC based MLI has been studied and also simulation results has been analyzed for minimizing losses. Hence SiC is the best suitable transition material for feature power devices. When the technology matures, for power devices, the medium to high power range, the future will be SiC.

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