Performance Comparison of Single-Phase Cycloconverter with SiC Transistor and IGBT with Different Control Strategies

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***Abstract*—Silicon Carbide (SiC) MOSFET devices exhibiting several advantages, including high blocking voltage, lower conduction losses, and lower switching losses, when compared to silicon-based devices have become commercially available, enabling their adoption into power supply products. This paper presents a novel approach to designing a cycloconverter using SiC MOSFETs as opposed to the conventional usage of IGBT. A comparative study is attempted between the two with respect to power loss, system efficiency, leakage current, etc. Furthermore, different closed-loop control strategies are used to control the speed of an induction motor using the SiC cycloconverter model designed in this paper. MATLAB/Simulink models and simulations are used to analyze the results for the above.**

***Keywords—*Cycloconverter, IGBT, Silicon Carbide MOSFET, PID controller.**

# INTRODUCTION

Wide-bandgap (WBG) based semiconductors such as Silicon Carbide (SiC) or Gallium Nitride (GaN) are ready to carve out a niche in applications that demand the ability to work at high voltages and temperatures while demonstrating high efficiency and relatively smaller dimensions owing to their intrinsic properties. These WBG based semiconductors offer several advantages over the equivalent silicon devices available in the market today, few of which include, lower leakage current, significantly higher operating temperatures, better conduction, and switching properties. For these reasons, the WBG devices have been identified to have a promising future in the power semiconductor industry.

Here the focus is only on the Silicon Carbide based Power devices and its applications. There has been a tremendous amount of research effort on developing power semiconductor devices with Silicon Carbide (SiC) in the pursuit of higher efficiency and smaller dimensions [1, 2]. The availability of SiC wafers on a commercial basis has led to the demonstration of many types of metal-oxide semiconductor (MOS)-gated devices that exploit its unique properties. These emerging Silicon Carbide (SiC) MOSFET power devices promise to displace Silicon IGBTs from the majority of challenging power electronics applications by enabling superior efficiency and power density, as well as capability to operate at higher temperatures [3]. Reference [4] focuses on the comparison of a SiC-based DC/DC converter and an IGBT based DC/DC converter and thus concludes that the efficiency of a SiC converter is greater than that of the IGBT converter over an output power range. An electro-thermal analysis of an automotive traction inverter platform based on SiC MOSFET and SiC IGBT technology is discussed in [5] and the results show that there is a higher total loss reduction in the SiC MOSFET model compared to the IGBT model. For all these reasons, in this paper, we are designing a cycloconverter using a SiC MOSFET as opposed to the usage of IGBT in doing the same.

In a cycloconverter, a constant voltage and frequency AC waveform is converted into another AC waveform of lower frequency without using DC link in the conversion process thus making it highly efficient [6]. A single-phase to single-phase cycloconverter consists of two full-wave converters that are linked back to back. There has been extensive research carried out to explore the several possibilities for realizing an AC variable speed drive with cycloconverter. [7] presents the different solutions and compares the performance of the cycloconverter in rolling mill drive applications. The speed control of induction motor plays an important role in industries, this can be made efficient by using various methods to control the action of the cycloconverter which will control the motor performance [8] and this paper uses the Silicon Carbide based cycloconverter for the speed control of a single-phase induction motor using PID control strategy.

The objective of this paper is to design an efficient cycloconverter using SiC MOSFET and compare the performance of that with a cycloconverter designed using IGBT. The forthcoming sections give a better understanding of the above. SiC MOSFET is modeled using MATLAB/Simulink and a novel approach to design a cycloconverter using the same is presented. An analysis of all the simulation results and comparison of the performance of SiC MOSFET with IGBT pertaining to various characteristics such as ripple factor, system efficiency and harmonic distortion is dealt with upon in the later sections Thereafter all the main results are concluded.

# SIMULINK MODEL ANALYSIS

## Silicon Carbide (SiC) MOSFET Model

An accurate SiC MOSFET Model is built using MATLAB/Simulink. Extensive research on the SiC device has demonstrated it to be a superior material to Silicon in many properties for the construction of power switching devices [9]. The SiC MOSFET as a majority carrier switch eliminates the minority carrier current tail experienced with silicon IGBTs, resulting in much lower switching losses. An added benefit of using the SiC MOSFET in place of the conventional IGBT is their overall system efficiency improvement, the capability of higher frequency operation and the reduction in size. The SiC MOSFET is modeled as shown in Fig. 1.

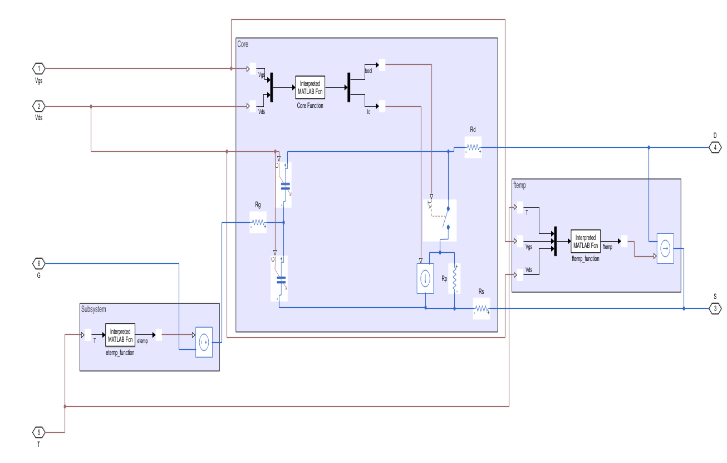


Fig. 1. SiC MOSFET Simulink Model

The above SiC MOSFET Model uses 3 main MATLAB functions, namely, the Core Design Function, ETemp Function, and the FTemp Function.

## Core Design Function

The core model which uses the Core Design MATLAB function is shown in Fig. 2.

A close up of a map

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Fig. 2. Core Simulink Model

The core function includes the SiC MOSFET characteristics with respect to the drain current and the drain-source voltage (Id -Vds). The relationship between the two is described by the following equations [10]:

In the above equations, the parameter ‘a’ represents the growth of the depletion layer and depends on the intrinsic structure of the SiC material and its properties. is the channel width modulation. K is the transistor gain which is related to the electron mobility by:

where L is the channel length, W is the channel width and Cox is the oxide capacitance. The mobility is directly proportional to the drain current Id and the transconductance gm. The threshold voltage characteristic equation for the SiC MOSFET can be written as [11]:

where,

Here, is the flat band voltage and is the interface trap voltage. is related to the work function of the metal contact before the gate-oxide (), the work function of the SiC , the Fermi potential in the bulk and the thermal voltage. The threshold voltage contains a linear temperature dependency.

## ETemp Function

The linear temperature dependency of the threshold voltage is expressed by the ideal voltage generator Etemp whose Simulink model is shown in Fig. 3.

A screenshot of a cell phone

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Fig. 3. ETemp Simulink Block

The voltage generator ETemp which is present at the gate terminal adds its contribution in opposition to the gate voltage. The Etemp function can be described as follows:

where is the slope of the temperature variation of the threshold voltage Vth which can be represented as:

where Vth2 and Vth1 are threshold voltages evaluated at T2 and T1 respectively. The standard temperature, Tstd, is 25

## FTemp Function

FTemp is a current generator and it adds its contribution in the same direction to that of the drain-source current, its Simulink model is depicted in Fig. 4. The carrier mobility increases in the working temperature range of [300–500] °K for each of the operating regions of the device such as subthreshold, linear and the saturation region. This behavior is due to the decrease in the occupied trap charge density with the rising temperature. The consequence of this is that more electrons in the channel are available at a given gate voltage, hence, when the temperature increases, a movement of Fermi level towards the bandgap can be observed. At temperatures higher than 500 °K [12], the mobility decreases since the lattice scattering dominates and begins to release the interface trap charges.

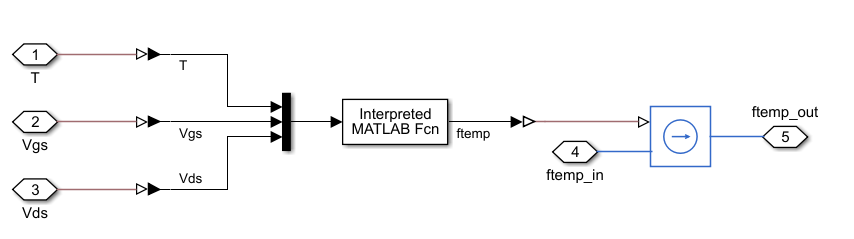


Fig. 4. FTemp Simulink Block

According to previous considerations, the main mechanisms affecting the carrier mobility of the SiC MOSFET inversion layer are the phonon and interface traps scattering. The mobility of the MOSFET strongly depends on temperature and it can be expressed as follows [13],

Here, the phonon scattering mobility depends on the temperature through the following expression,

For the interface traps, it is possible to consider a quite similar behavior, i.e.,

According to equations (12), (13) and (14), an ideal current generator FTemp can be introduced and its value can be expressed as,

Here, the two parameters ‘a’ (in equations (3), (4) and (5)) and ‘β’ (in equation (14)), are determined with a least-square fit procedure, making a regression using the device curves given by the manufacturer.

## Cycloconverter Design using IGBT

A cycloconverter for converting power at supply frequency to a lower frequency is modeled using IGBT as the switching element in Simulink. The converter has back to back connection of two full-wave rectifiers. The two-bridge type-controlled rectifiers are connected in anti-parallel direction via 4 ideal switched as represented in Fig. 5. As can be observed the conventional cycloconverter uses 2 separate converters called the P-converter and the N-converter; each performing like an H-bridge inverter. The below model is used as a standard of comparison for the SiC model which is designed in this paper.

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Fig. 5. Cycloconverter model using IGBT

The supply input to the cycloconverter is a 100V signal alternating at 50 Hz as in Fig. 6. The corresponding step-down output corresponds to a signal of 100V, alternating at a frequency of 5 Hz as shown in Fig. 7.

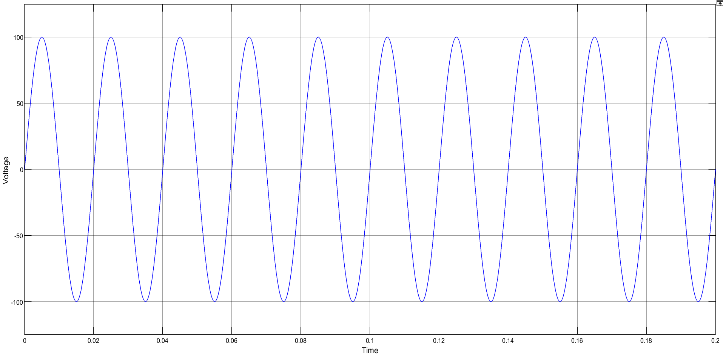


Fig. 6. Cycloconverter input

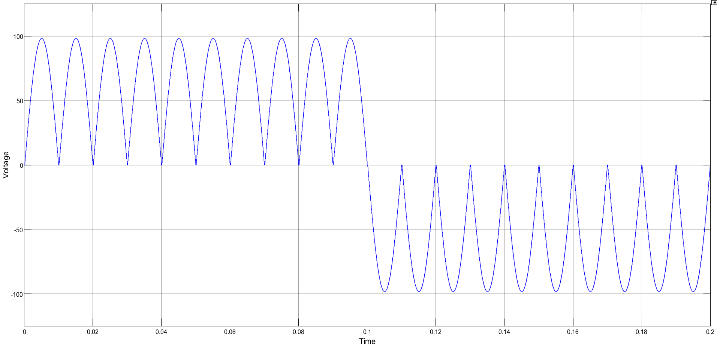


Fig. 7. Cycloconverter output using IGBT

# SIMULATION ANALYSIS

1. *Silicon Carbide (SiC) MOSFET Simulation*

The final subsystem model which will further be used in the design of the cycloconverter is as shown in Fig. 8. The proposed simulink model is validated using CREE’s C2M0025120D SiC MOSFET.

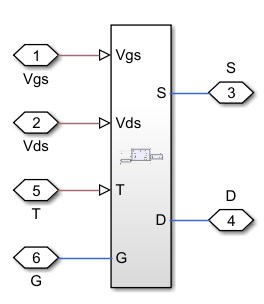


Fig. 8. SiC Subsystem

The parameters used for the design of the SiC MOSFET are obtained from the manufacturer’s datasheet, [14]. The model in Fig. 1 is simulated with all the key formulae and values plugged into the interpreted MATLAB function i.e., the core function, etemp function and the ftemp function. The output characteristics ie, the drain current vs the drain-source voltage (Id – Vds) plot at T = 25 is shown in Fig. 9.

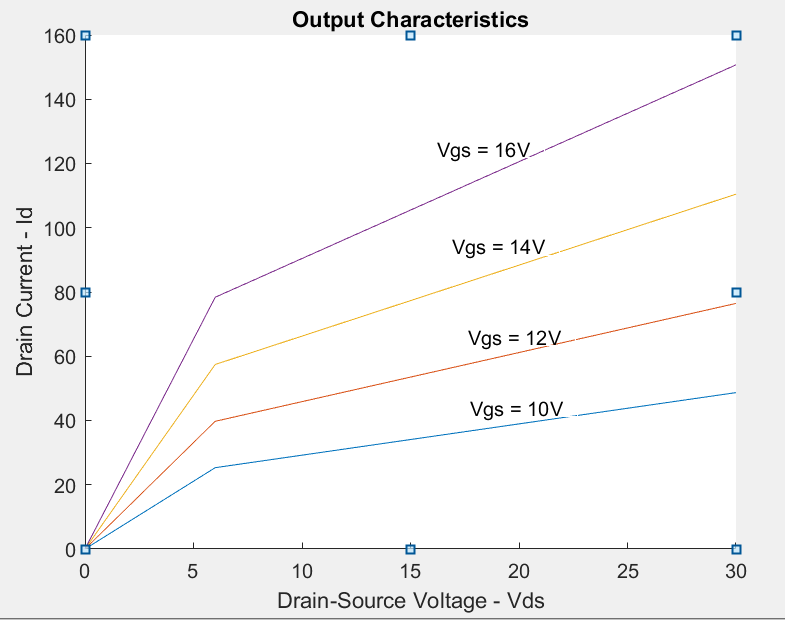


Fig. 9. Output characteristics plot

The Id – Vds plots are obtained for 4 different values of Vgs, i.e., 10V, 12V, 14V and 16V. The characteristics plot obtained from the SiC MOSFET simulation is close to that of the plot obtained from the manufacturer’s datasheet as shown in Fig. 10.

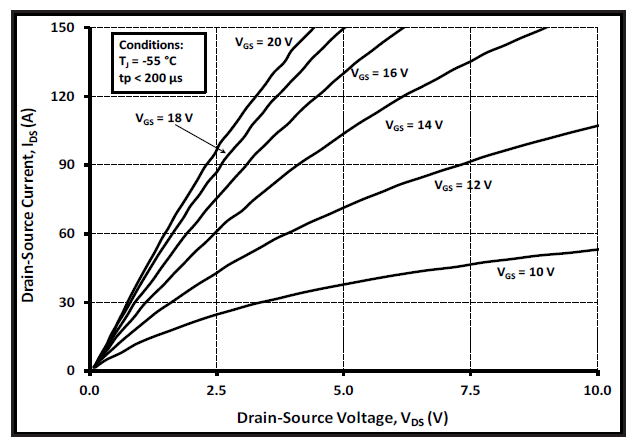


Fig. 10. Output characteristics as in the datasheet

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