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A Comparative Study of Power Semiconductor Devices for Industrial PWM Inverters

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ABSTRACT

The growing demand of energy translates into efficiency requirements of energy conversion systems and electric drives. Both these systems are based on Pulse Width Modulation (PWM) Inverter. In this paper we firstly present the state of art of the main types of semiconductors devices for Industrial PWM Inverter. In particular we examine the last generations of Silicon Carbide (SiC) MOSFETs and Insulated Gate Bipolar Transistors (IGBTs) and we present a comparison between these devices, obtained by SPICE simulations, both for static characteristics at different temperatures and for dynamic ones at different gate resistance, in order to identify the one which makes the PWM inverter more efficient.

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1. INTRODUCTION

New global energy needs have led to changes in the industrial environments. Pollution restrictions, costs reductions and the rising demand for energy have been translated into efficiency requirements of the energy conversion systems and of the electrical drives. Both these systems are based on Pulse Width Modulation (PWM) Inverter [1]

PWM technique modifies timing of a pulse train in direct proportion to the voltage of control signal, whose information is transferred to the width of the pulses, in particular the magnitude and frequency of the fundamental component of the pulse train are controlled by the control signal. Low pass filtering a PWM waveform extracts the fundamental component and produces an output voltage proportional to the control signal [2]. Depending on how the pulse train is modified, it determines the specific type of the modulation. Two of the main kinds of PWM used in power electronics applications are Sinusoidal PWM (SPWM) and Space Vector PWM (SVPWM).

In SPWM a sine wave is used as control signal and it is compared with a reference triangular wave. When the voltage of the triangle wave is greater than the voltage of the input signal, the output of the comparator reaches the low level; otherwise, when the voltage of the input signal is greater than the voltage of the triangle wave, the output of the comparator is high. This method is the simplest PWM: it produces an output square wave whose fundamental component has the same frequency and magnitude proportional to the input voltage but, because of its simplicity, it has some drawbacks (for example poor quality of the output voltage, weak modulation ability on active and reactive power, higher THD) [3-4].

SVPWM are similar to the SPWM but the voltage reference is provided using a phasor. In this case magnitude and frequency of the fundamental component are controlled by the magnitude and frequency of the control vector. This modulation utilizes DC bus voltage more efficiently and generates less harmonic distortion in a three phase voltage source inverter (VSI) [2].

PWM Inverter is a power electronic DC/AC converter. In industrial applications this AC power is a three-phases AC power. The input DC voltage is obtained from the electrical grid through (active or passive) rectification, or from a DC supply e.g. storage battery or photovoltaic panel. The conversion of DC power to three-phase AC power is performed in the switched mode with Pulse-Width Modulation [5]. In particular three-phase two-levels PWM inverter can be realized using six switches, which are six power semiconductor devices driven by low voltage PWM signals that make temporary connections at high repetition rates between the two DC terminals and the three phases of the AC device, usually a motor, connected to the output of the inverter. The desired value of the AC currents is achieved by the six PWM signals.

To improve the energy requirements, we need to make the PWM inverter more efficient. There are many types of techniques to achieve that. Soft switching techniques, different topologies of inverters and many kinds of control algorithms are constantly subject matter of research. Last but not least, also the power semiconductors switches are constantly evolving because they represent the primary causes of energy dissipation: improving these devices means reducing thermal heating or the reactive losses [6].

In this paper, at first the state of art of the main types of semiconductors devices for Industrial PWM Inverters is presented. In particular we examine the last generations of Silicon Carbide (SiC) MOSFETs and Insulated Gate Bipolar Transistors (IGBTs) and we present a comparison between these devices, obtained by SPICE simulations, both for static characteristics at different temperatures and for dynamic characteristics at different gate resistance, in order to identify the device which makes the PWM inverter more efficient.

2. 4H–SiC STEP TRENCH GATE POWER MOSFET

2.1. An introduction about Power MOSFET and Trench Gate Structure

In a traditional n-channel MOSFET, lateral MOSFET, the saturation drain current, I_{Dsat}, is given by the following equation [7-8]:

$$I_{D_{sat}} = \mu_n C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2$$

where μ_n is the electron mobility, C_{ox} is the oxide capacitance, W and L are the width and the channel length respectively, V_{GS} is the gate-source voltage and V_T is the threshold voltage. Therefore, to increase the MOSFET currents, we need to made W large and L small. On the other hand, reducing L, we have a reduction of the breakdown voltage. When the body-to-drain junction is reverse polarized, the depletion region spreads into short channel, resulting in breakdown at relatively low voltage. This effect limits the lateral MOSFET in high voltage applications [9]. Planar MOSFET (Figure 1a), also known as DMOSFET (double diffused), has been developed to obtain short channel.

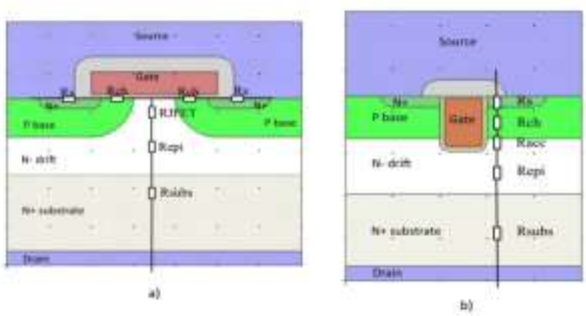


Figure 1. DMOSFET (a) and Trench Gate MOSFET (b) with R_{DS} components (*from [10]*)

The channel is formed on the surface by the double-diffusion process and the relative diffusion depth of the P body and N+ source regions control the channel length [11]. The current flows vertically, from drain to source, crossing N drift region. Due to the two adjacent P body wells, the current was affected by the JFET-effect when flows in N- drift region [10]. In the trench-gate structure (Figure 1b) the gate is etched vertically along the device and the channel is formed on the vertical sidewalls of the trench and the JFET resistance is reduced drastically [10-11].

2.2. The Silicon Carbide and the newest SiC Power MOSFET

The Silicon Carbide (SiC), as Silicon (Si), is a semiconductor material but, compared with the latter, offers: a lower intrinsic carrier concentration (9–18 orders of magnitude), a higher electric breakdown field (4–8 times) that allows a ten times reduction in drift layer thickness, a higher thermal conductivity that allows high temperature operation up to 350°C, a larger saturated electron drift velocity that allows the increasing of the switching frequency. Due to difficulty with material processing and presence of crystal defects, silicon carbide has been adopted for power devices only in the last years after the improvement of the fabrication processes. Only the 6H– and 4H–SiC poly-types are available commercially but 4H–SiC is preferred in power devices fabrication because of its high carrier mobility and its low dopant ionization energy [12].

The new generation of SiC Power MOSFET presented in [13] is developed with 4H-SiC because this material has 10X higher breakdown strength when compared to silicon, leading to realize a 10kV devices. With SiC technology R_{DS}, total current per die and switching losses per chip are improved. Furthermore, trench gate technology allows better performance in matter of conduction losses.

3. 7th GENERATION TRENCH GATE PUNCH THROUGH IGBT

3.1. An introduction about IGBT and Punch-Trough Technology

An IGBT combines the advantages of MOSFETs and BJTs. MOSFETs have high switching frequency and are voltage controlled but their internal resistance grows with the maximum applicable voltage. BJTs instead, have a low voltage drop but requires a current as input control signal. IGBT is a voltage-controlled device, it has a low voltage drop and it is fast for switching operations. If we analyse a traditional IGBT we can see that its structures are similar to that of vertical MOSFET (DMOS) where N+ interface is replaced by P+ substrate (Figure 2) [14].

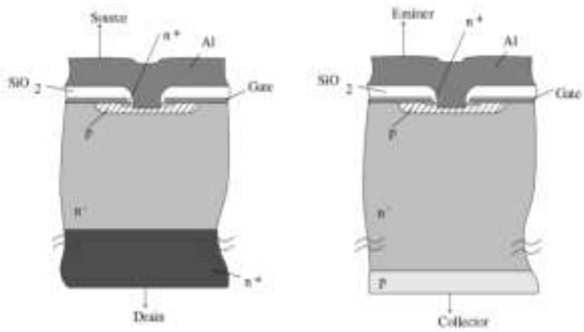


Figure 2. Power MOSFET(left) IGBT (right) (from [15])

This configuration is also called Not Punch Trough (NPT), shown in Figure 3.

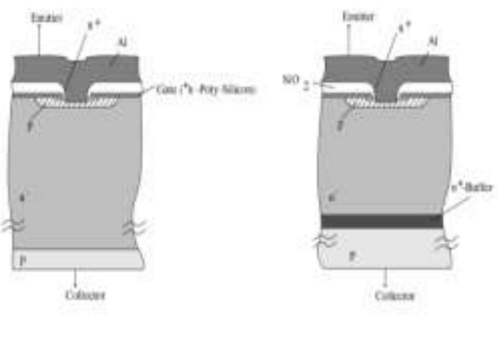


Figure 3. NPT (left) and PT (right) IGBT (from [13])

A NPT IGBT presents two main drawbacks for switching applications: it has equal forward and reverse breakdown voltages and presents a long tail current (due to the storage charge in N-drift region). To solve these problems, Punch Trough (PT) technology has been developed. PT structure is obtained adding a N+ substrate in NPT IGBT between P+ substrate and N– drift region. The new N+ region is a buffer layer that makes the P+N– diode like a PIN type diode: the carrier lifetime is reduced (consequently the tail current is reduced) and it provides a reverse breakdown voltage greater than the forward breakdown voltage despite the increase of voltage drop during the ON-state [14] [15].

3.2. The Newest generation of IGBT

The 7th generation of IGBT, as described in [16], is shown in Figure 4 and represents the newest generation of Trench Gate Punch Through IGBT.

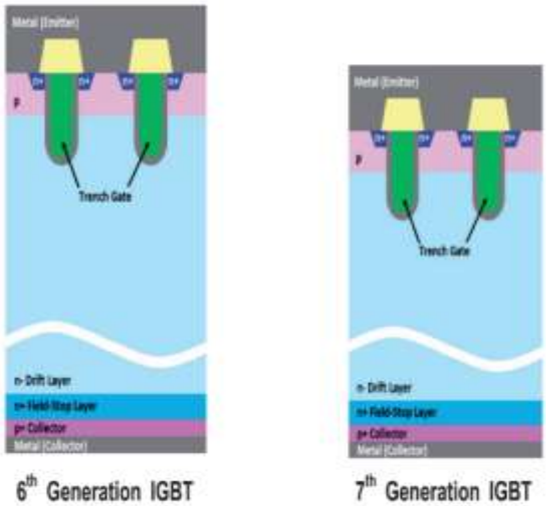


Figure 4. Cross-sections of the 6th generation IGBT (left) and the 7th generation IGBT (right) (*from [16]*).

Compared to previous trench generation, the electrical characteristics have been improved, the die size has been reduced and higher efficiency was achieved. This technology leads to a new generation of highly compact and efficient power conversion systems.

The drift layer thickness is reduced compared to the 6th generation achieving a lower on-state voltage drop and a reduction of the miller capacitor. Additionally, the trade-off relationship between on-state voltage drop and turn-off losses is improved by optimization of the surface structure. The Field Stop layer have been optimized, realizing the suppression of voltage oscillations and improving the breakdown voltage capability. The reduction of the drift layer has led to the reducing of the forward voltage of the 7th generation diode. By optimization of the local lifetime control, the 7th generation diode realized a softer switching waveform, contributing to reduction of the reverse recovery losses [16].

4. SiC-BASED MOSFET VS Si-BASED IGBT: ANALYSIS OF RESULTS

In this section we present a comparative evaluation, through static and dynamic results, obtained for SiC-MOSFET (ST STGW15H120DF2 [17]) and Si-IGBT (ST SCT20N120 [18]) with the same 1200 V voltage rating and similar current rating, 15 A of IGBT and 20 A of MOSFET. Both power devices have an intrinsic recovery antiparallel diode. To characterize the switching performance of the devices, a real test-bed is simulated using values estimated in [19-20]. The equivalent test circuit is shown in Figure 5. A 100 uH inductor is used as test load with 20 pF equivalent parallel capacitance and 3 mΩ equivalent series resistance.

4.1. Static Characterization

Figure 6 shows the transfer characteristics at various V_{CE}/V_{DS} using 10 Ω gate resistance at the junction temperature of 125 °C. Solid lines with square symbols show IGBT characteristics (I_C vs V_{GE}) and dashed lines with "x" symbols show MOSFET characteristics (I_D vs V_{GS}). Figure 7 shows the output characteristics at various gate bias using 10 Ω gate resistance at the junction temperature of 125 °C. Solid lines with square symbols show IGBT characteristics (I_C vs V_{CE}) and dashed lines with “x” symbols show MOSFET characteristics (I_D vs V_{DS}).

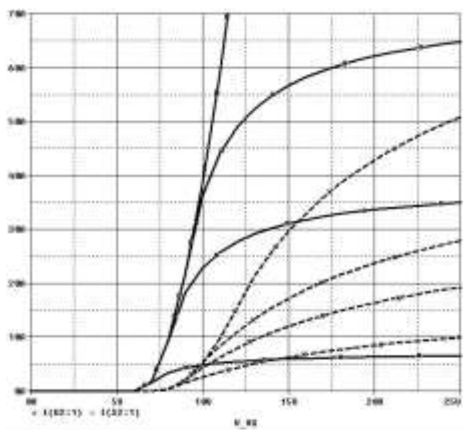


Figure 6. Transfer characteristics

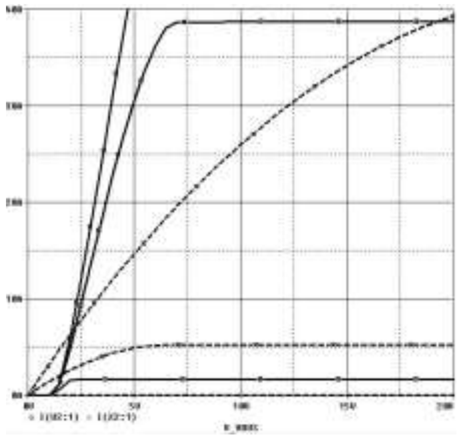


Figure 7. Output characteristics

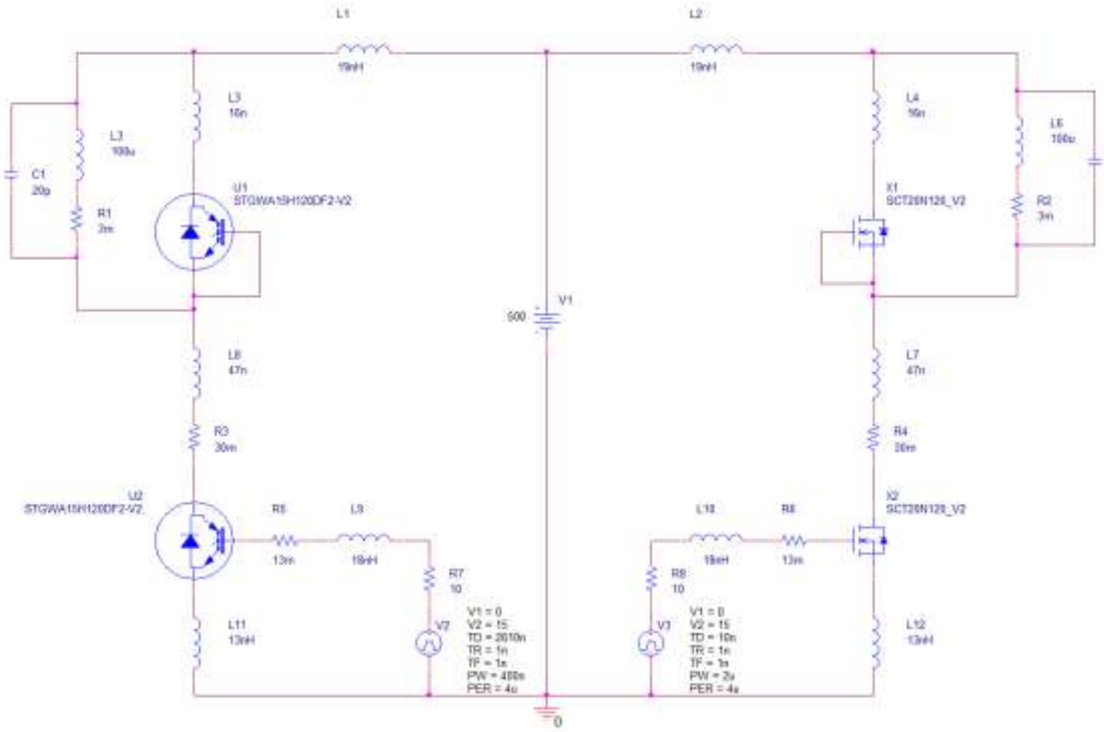


Figure 5. Test Circuit

4.2. Dynamic Characterization

The dynamic characteristics of the simulated IGBT are shown in Figures 8 and 9. In particular in Figure 8 we have highlighted the turn-on behaviour, while in Figure 9 the turn-off behaviour is highlighted. Top graphs present the driving voltage as dashed line and V_{GE} as solid line. In middle graphs collector current is shown and bottom graphs present the V_{CE}. The driving pulse had 2 µs pulse and a 4 µs period at the junction temperature of 125 °C.

Similarly the dynamic characteristics of the simulated MOSFET are shown in Figures 10 and 11. In particular Figure 10 shows the turn-on behaviour, while in Figure 11 the turn-off behaviour is highlighted.

Top graphs presents the driving voltage as dashed line and V_{GS} as solid line. In middle graphs drain current is shown and bottom graphs present the V_{DS}. The driving pulse had 2 µs pulse and a 4 µs period at the junction temperature of 125°C.

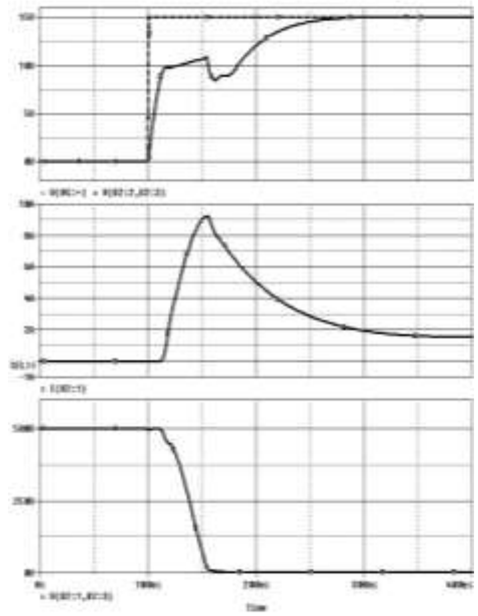


Figure 8. IGBT turn on.

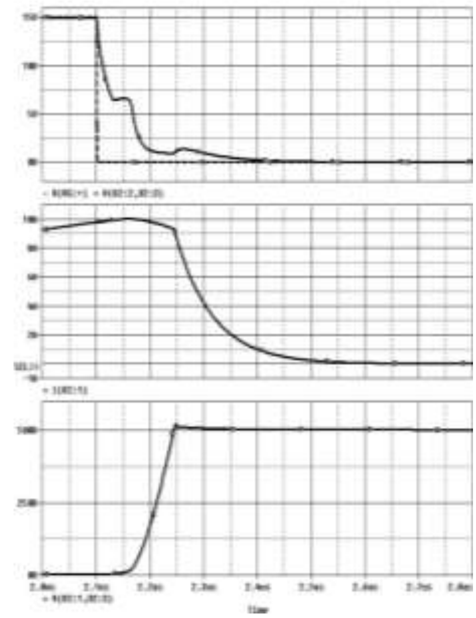


Figure 9. IGBT turn off.

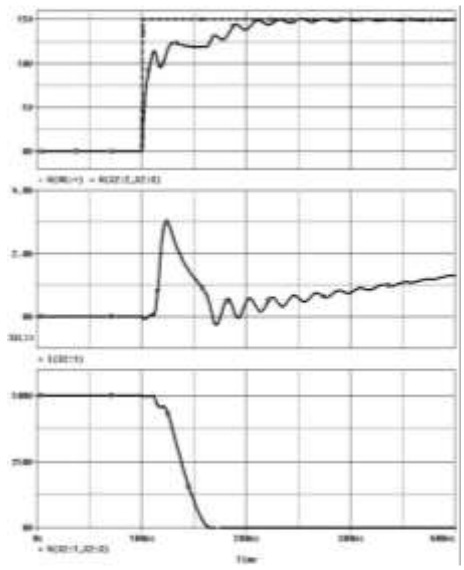


Figure 10. MOSFET turn on

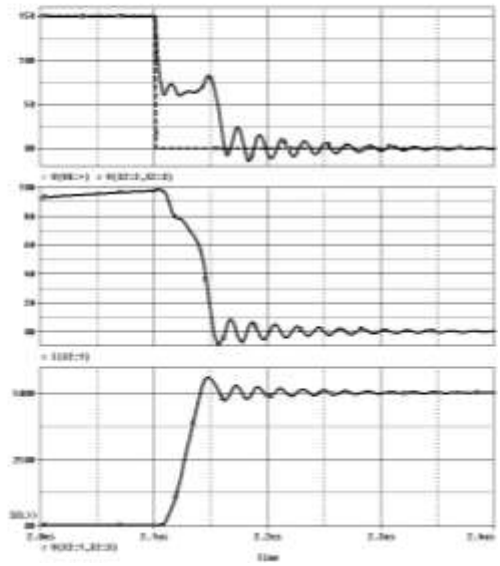
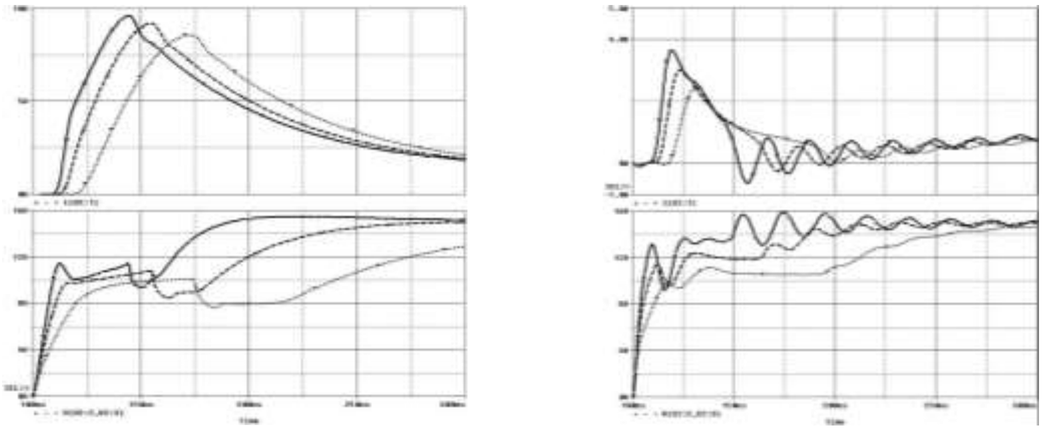


Figure 11. MOSFET turn off

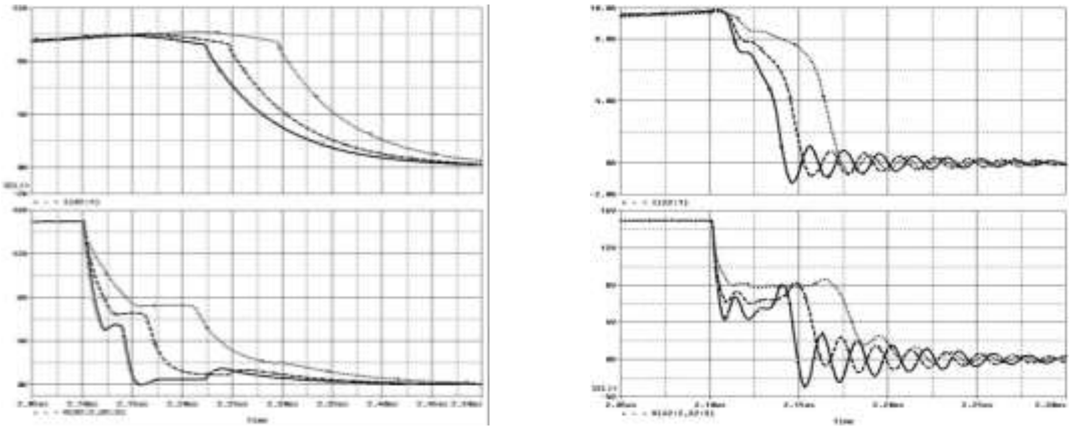
Figure 12 compares IGBT (a) and MOSFET (b) turn-on dynamics at various gate resistances. On the top the current is shown, on the bottom the V_{GE}/V_{GS}. Solid lines are referred to RG = 5 Ω, dashed lines are referred to RG = 10 Ω and dotted lines are referred to RG = 20 Ω. The higher the gate resistance, the smoother the characteristics but turn-on time increases.

Figure 13 compares IGBT (a) and MOSFET (b) turn-off dynamics at various gate resistance. On the top the current is shown, on the bottom the V_{GE}/V_{GS}. Solid lines are referred to RG = 5 Ω, dashed lines are referred to RG = 10 Ω and dotted lines are referred to RG = 20 Ω. As in turn-on dynamics, the higher the gate resistance, the smoother the characteristics but turn-off time increases.



(a) (b)

Figure 12. Turn-on comparison



(a) (b)

Figure 13. Turn-off comparison.

Finally, the energy losses as a function of gate resistance are shown in Figure 14.

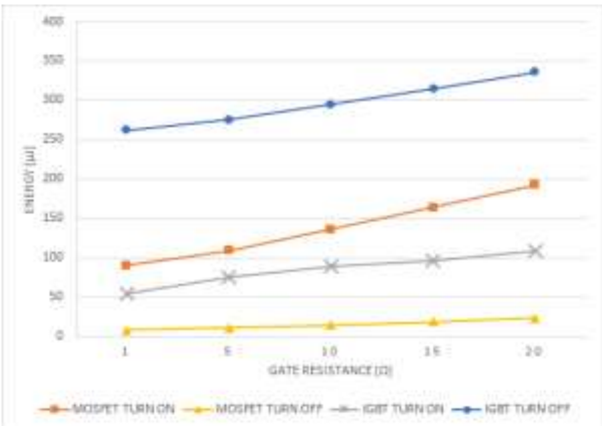


Figure 14. Switching Losses

5. CONCLUSION

In this paper, after a brief examination of the main types of semiconductors devices for Industrial PWM Inverters, we have examined the last generations of Silicon Carbide (SiC) MOSFETs and Insulated Gate Bipolar Transistors (IGBTs). SPICE simulations for static characteristics have been evaluated at different temperatures while dynamic ones have been performed at different gate resistance, in order to identify the device which makes the PWM inverter more efficient. Contrary to Si-IGBTs, no tail current was noticed for SiC-MOSFET leading to high switching capabilities for these devices. The SiC MOSFET showed superior performance in terms of switching as well as conduction loss but ringing effect may cause some problems.

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