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Analysis of Power Converters with Devices of SiC for Applications in Electric Traction Systems.

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***Abstract*—this article presents the analysis of two topologies of power converters. Voltage Source Inverter (VSI) and Current Source Inverter (CSI) proposals for traction system applications, these topologies are implemented with silicon carbide devices. The use of SiC semiconductors allow working at high switching frequency (100KHz), increase the working temperature range and decreasing power losses during conduction and activation of the semiconductors.**

The objective is analyze these topologies and select the one that provides the best performance and behavior at high frequency to improve it on a electric traction system.

***Index Terms*—SiC, CSI, VSI, High Frequency, PWM, FOC.**

I. INTRODUCTION

Nowadays, research about more efficient power converters topologies has improved considerably on the development of electric vehicles traction systems. The use of new materials in the design of semiconductor devices has contributed to open up new lines of research and development of this type of technologies in traction systems for hybrid and electric vehicles.

Recent researchs [1,2] have shown that the silicon carbide is a very promising electronic material especially for use in semiconductor devices with high ranks of work at higher temperatures, high power and higher frequencies.

Silicon Carbide SiC, are gaining importance in power converters design, considering your their efficiency working at high frequency and high temperature, reducing power losses during activation and conduction, compared with the conventional silicon elements (Fig. 1) where its work and performance is below the SiC devices [3].

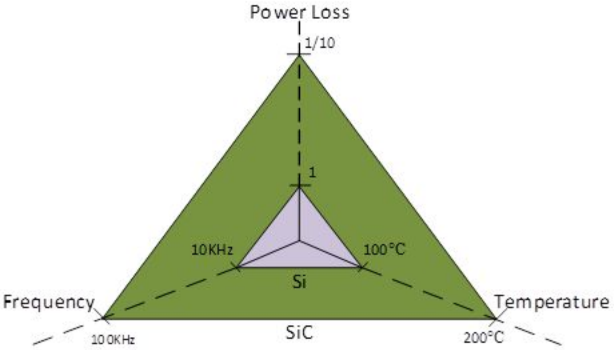


Figure 1. Comparison of work elements ranges SiC vs Si.

The implementation of these devices in topologies for electric traction system VSI and CSI, can improve the operation mode, performance and efficiency considering the advantages and operating ranges of SiC devices, this will allow to develop more compact traction systems with smaller passive components and reduce the power losses in semiconductors.

This paper presents the analysis of VSI and CSI topologies with silicon carbide devices at high switching frequency (100 KHz). The paper is organized as follows: Section II describes the features of the topologies VSI and CSI used for the development of electric traction systems. Section III presents to design of the topologies VSI and CSI with devices of SiC, modulation techniques, control technique and analysis of power loss in the each topologies. Section IV presents the results of simulations and conclusions.

II. TOPOLOGIES VSI AND CSI IN ELECTRIC TRACTION SYSTEM

The topologies with higher demand implementation on hybrid and electric vehicles traction systemas are the VSI and CSI, the less demanded are topologies with impedance networks.

A. Voltage Source Inverter VSI.

The VSI (Fig. 2), is the more used topology on hybrid and electric vehicles traction systems due to the voltage type energy storage devices in it. This topology use a large capacitor in the DC bus with the aim of filtering the current input, keeping a constant voltage level [4], the manufacturers has opted for this topology type, based on their production costs and to be tested technology in several vehicles present on the market.

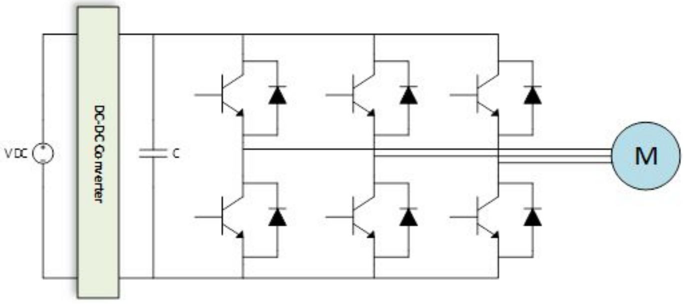


Figure 2. Voltage Source Inverter Topology.

Among problems identified in this topology is that the activation of the power transistors in the same branch must be done at time intervals and both cannot be active at the same time because this can cause damage to the converter, therefore it is necessary a dead time between activations which will bring some distortion of the AC output current, which increases the motor torque ripple [4].

Also it has been found that the output voltage generates high dv/dt by PWM modulation, has a negative impact on the motor causing electromagnetic interference and noises motor insulation degradation due to the voltage surges resulting from these rapid voltage transitions, and produce high frequency losses in the windings and cores of the motor furthermore, for the VSI to operate from a low voltage battery, a bidirectional boost converter is needed [5].

B. Current Source Inverter CSI.

The CSI topology (Fig. 3) has an inductor component for using it as energy storage, has the high voltage capability, has short-circuit protection, and sinusoidal output voltage due to the effect of the output filter capacitors AC, which are much smaller in capacity [6].

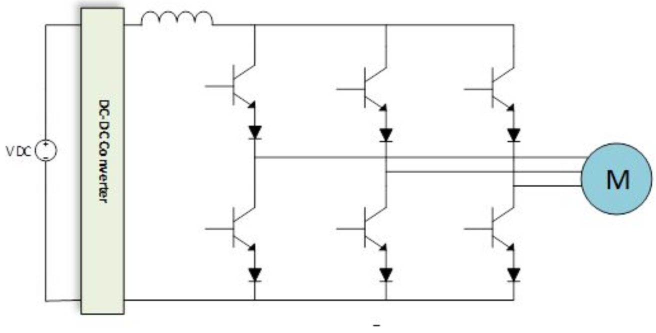


Figure 3. Current Source Inverter Topology.

This topology has been gaining ground on the development of applications for electric vehicles traction systems [7], with this topology is possible to get high power density and the use of this topology increases the option to implement high frequencies above 100 KHz, allowing the usage of SiC, and will reduce the size of the input inductor [8].

The CSI offers many significant advantages for electric vehicle applications: CSI does not need anti-parallel diodes in the switches, provides an action of short circuit protection, provides sinusoidal voltages to the motor due to the effect of AC output filter capacitors and can increase the output voltage to a higher voltage source to activate the motor to operate at higher speeds level.

But some problems have had an influence on this topology which is not consolidated on the commercial development of electric traction systems.The first problem is that the battery charging with conventional topology CSI does not allow the return of the current, therefore a DC/DC bidirectional converter is necessary to solve this problem [5,9]; the control loss of the motor current and speed in the low speed region where the back electromotive force (EMF) of the motor is substantially lower than the battery voltage [9], the lack of power semiconductors with switch states enabling block voltages in both directions, this involves the use of diodes in series generating increased in the conduction losses [5,9].

The advantages of VSI and CSI topologies are detailed in Table 1, these must be considered when is wanted to find a topology which adapts to new conditions and operating ranges.

Table 1. Advantages of VSI and CSI topologies.

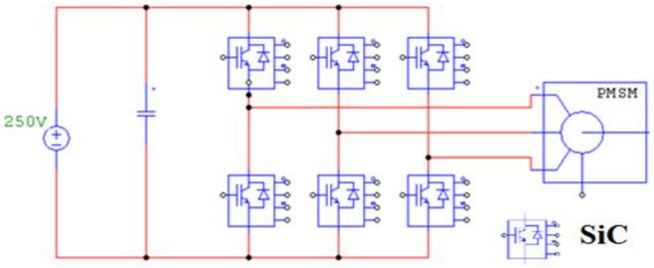
	VSI	CSI
Advantages	More used in traction systems	Short-circuit protection
	Topology Bidirectional	Sinusoidal output voltage
	Reduce Cost	Works high frequencies reduce the inductor

III. TOPOLOGIES VSI VS CSI WITH SIC DEVICES

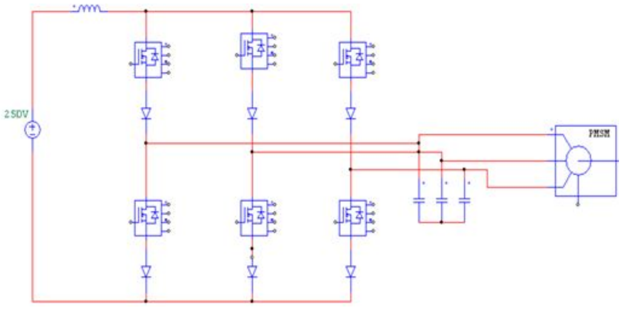
This section describes the design of the VSI and CSI topologies with silicon carbide elements and the selection of these devices, the modulation techniques and control applied in each topology and the power losses, the simulations are made using PSIM.

A. VSI and CSI SiC Topologies .

The Voltage Source SiC inverter (Fig. 4a), consists of six Mosfet devices made of Silicon Carbide and capacitor filter for the input current, this power converter controls a permanent magnet motor (PMSM). The Current Source Inverter SiC (Fig. 4b) has 6 SiC MOSFET in series with 6 Schottky SiC diodes and an input inductor.



a. VSI.



b. CSI

Fig. 4. VSI and CSI Topologies.

The switching devices selected for these designs are the SiC Mosfet SCT30N120 produced by the manufacturer ST, Mosfet SiC is rated for 1200 V with a breakdown voltage, HiP247 package and the diode Schottky SiC C2D10120A from CREE for the case of CSI topology, the features of these devices are presented in the table 2.

The development of these topologies with SiC selected devices are implemented on PSIM simulator using the thermal module package where the characteristics of the devices mentioned before where entered..

Table 2. Parameters of Mosfet SiC SCT30N120 and diode Schottky SiC C2D10120A.

SiC Mosfet Parameters	
VDS	1200V
ID Drain current (continuous) at Tc= 25 °C	45A
Rds	$90m\Omega$
Tj	25°C to 200 °C
Switching Loss Parameters	
Turn-on switching losses	$500\mu J$
Turn-off switching losses	$300\mu J$
SiC Diode Parameters	
Vrm	1200V
IF(TC=135°C)	14.5A
Qc	61nC

B. VSI and CSI SiC Modulation Techniques and Control

A. Modulation Technique.

A great number of modulation techniques have been presented to implementing in these types of converters [10-13], the main objective of modulation techniques is to obtain current or voltage waveforms where the losses are minimal, and this feature also allows to reduce the common medium voltage and harmonics minimization[14].

There are two modulation strategies that can be applied for these type of converters, the SPWM and space vector modulation SVPWM. On SPWM technique (Fig.5) the amplitude modulation index m_a is defined as the relation between the peak amplitude of modulating control signals and the amplitude of the carrier signal [14].

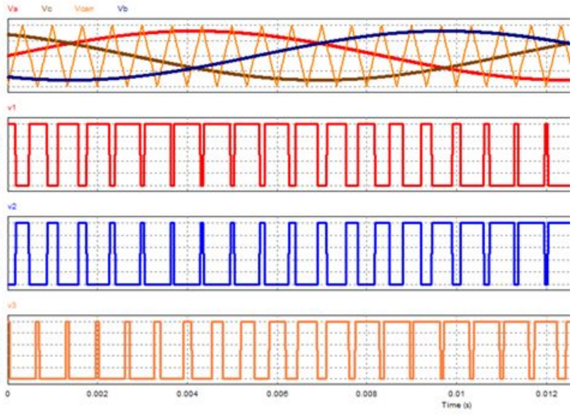


Fig.5. SPWM modulation technique.

In SPWM the signals are a set of three-phase sinusoidal balanced signals responsibles of setting the amplitude, frequency and phase of the inverter output, the PWM phase modulation scheme based on carrier It is shown in Fig. 6. The SPWM modulation technique is selected for the analysis of this study.

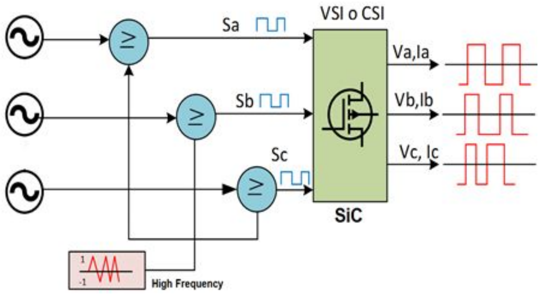


Fig. 6. SPWM modulation scheme based on carrier.

B. Control.

The control system that shape it the power converter and electric motor that is selected is the Field Oriented Control FOC, this algorithm allows control of the speed of a Permanent Magnet Synchronous Motor (PMSM) and has been used widely in the Electric Drives Industry in the recent years [15].

The FOC control, proposed in the 1970s by Hasse [16] and Blaschke [17], is based on an analogy to the mechanically commutated dc brush motor. In this motor, due to the construction of excitation and armature winding, flux is controlled by the exciting current and torque is independently controlled, by adjusting the armature current. So the flux and torque currents are electrically and magnetically independently [18].

In the FOC Control for VSI and CSI topologies (Fig.7) vector current and voltage are calculated by measuring the rotor speed and the value of the flux and torque.

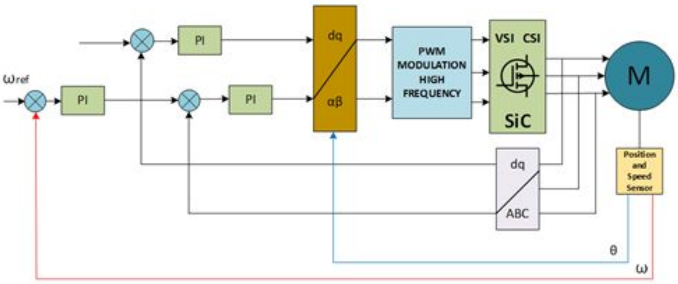


Figure 7. Diagram of the proposed control FOC for PMSM with topologies VSI and CSI with SiC devices.

External PI controller sets a reference current Iq based on speed setpoint of the machine, This is compared with actual current isq, generating an error signal which goes through a PI controller that generates the reference Vsq, for flux control, error is calculated between the reference value Idref and the measured value Ireal generating the reference Vsd, by the second PI controller [15].

C. Power Loss.

In this secction present an analysis of power losses for conduction and switching in the devices SiC.

The conduction power loss on VSI topology in the Mosfet and diode SiC can be determined with the next expressions:

Mosfet:

$$P_{con} = R_{on} i^2 \left(\frac{1}{8} + \frac{mcos\phi}{3\pi} \right) \tag{1}$$

Diode:

$$P_{con} = \frac{1}{2} \left(V_D \frac{i}{\pi} R_{on} \frac{i^2}{4} \right) - mcos\phi V_D \frac{i}{8} + R_{on} \frac{i}{\frac{2}{3}\pi} \tag{2}$$

Where I is the current peak, Ron is the on-resistance, VD is the diodes voltage drop M is modulation index and cosϕ is the power factor.

The switching losses of the Mosfet and diode SiC, can be calculated with the next expressions:

Mosfet:

$$P_{sw} = f_{sw} \left(E_{on} + E_{OFF} \right) \frac{Vi}{V_{Nom} i_{Nom}} \tag{3}$$

$$P_{sw} = f_{sw} E_{rr} \frac{Vi}{V_{Nom} i_{Nom}} \tag{4}$$

The EON is the turn-on energy losses in power MOSFET and EOFF is the switch-off energy losses.

For the calculation of losses in the CSI the important rule is that there must be always at least one switch forward biased in each half bridge of the converter. The loss conduction Pc is as in the next equation:

$$P_{con} = 2 \left(i_{DC} V_{ds0} \right) + i_{DC}^2 \left(R_{ds} \right) \tag{5}$$

The IDC is the value of current, VDS is the voltage drain-source and RDS is the resistance drain-source. The values are rated diode referred to the series diodes of the power modules, and the inverses diodes can be ignored.

To calculate the switching losses, the alternating blocking state voltages of the switching devices which coincide with the converter's output voltages have to be taken into account. Thus the average total switching losses can be calculated by:

$$P_{sw} = \left(E_{on} + E_{OFF} \right) f_{sw} \tag{6}$$

$$P_{sw} \approx E_{onD} f_{sw} \tag{7}$$

The Eon is the turn-on energy losses in power MOSFET and EOFF is he switch-off energy losses in the MOSFET, and is similar for the diode in equation (7).

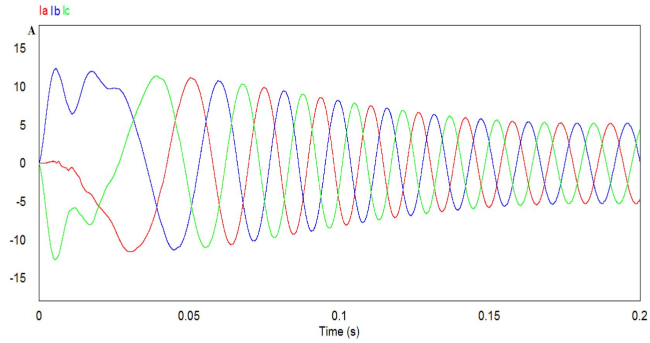
IV. SIMULATIONS AND RESULTS

In this section the results of the simulations developed in PSIM are presented. In the first part the results of topology VSI with SiC devices, losses in conduction and the switching power losses and results of control are presented, in the second part the results of topology CSI with SiC devices. The parameters for simulations and features in voltage and current of operation of the devices SiC are shown in the table 3.

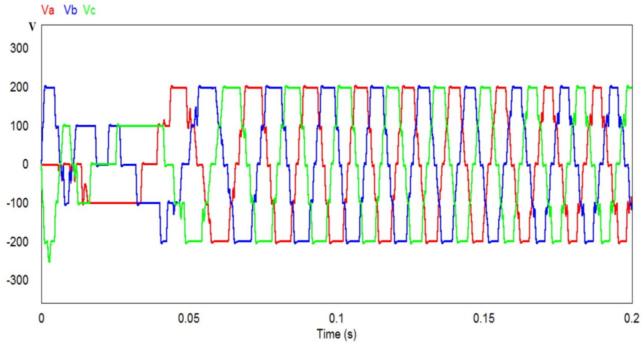
Table 3. Parameters of simulation for VSI and CSI Topologies SiC.

Parameter	*VSI*	*CSI*
Power Density	2.2Kw	2.2Kw
Frequency	100KHz	100KHz
Vdc	250V	250V
Load	PMSM	PMSM
Power Transistor:	*Mosfet*	*Mosfet*
Voltage and Current	1200v, 45A	1200v, 45A
Rds	90mΩ	90mΩ
Temperature	200 ^{o}C	200 ^{o}C
Model	SCT30N120	SCT30N120
Power Diode:	VRRM=1200v	VRRM=1200v
	I=14.5A, 170 ^{o}C	I=14.5A, 170^{o}C
	C2D10120A	C2D10120A

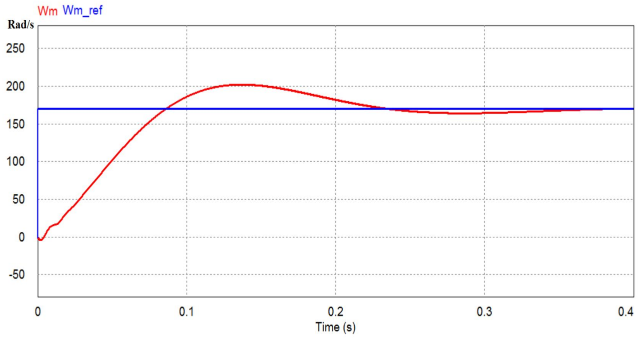
In the figure 8 are shown the currents and voltages of VSI SiC topology and Speed control of PMSM.



a. Currents



b. Voltage



c. Speed

Fig. 8. Currents, voltage of VSI SiC topology and Speed control of PMSM.

The conduction and the switching power losses in VSI SiC topology are shown in the figure 9.

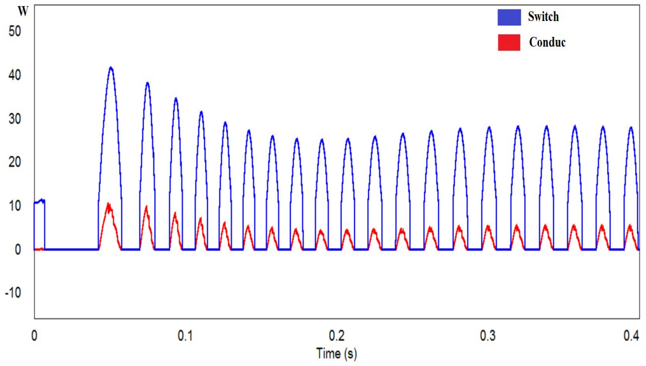
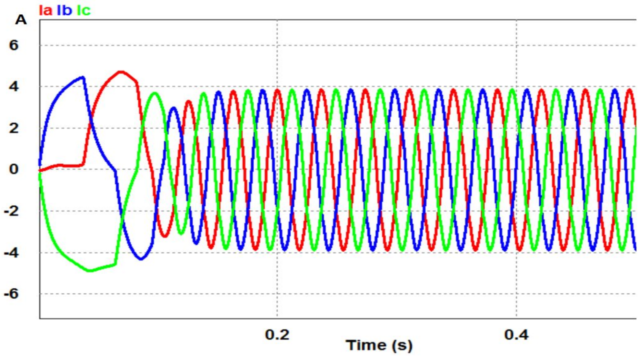
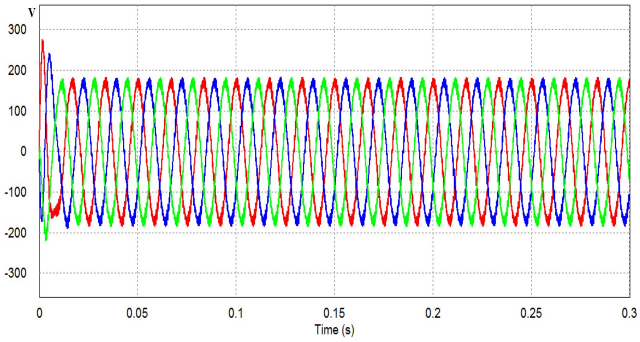


Fig. 9. Power losses due to conduction and switching in VSI SiC topology.

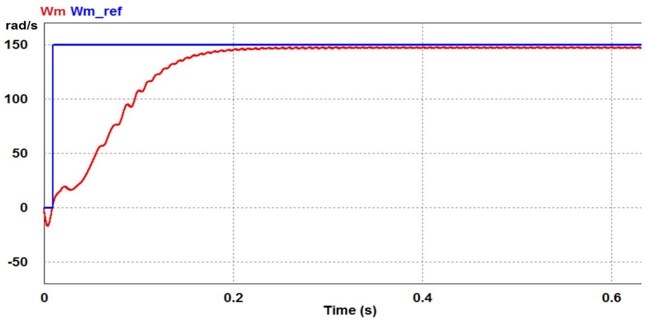
In the Fig. 10 are shown the results of current and voltage simulations of CSI SiC topology and Speed control of PMSM.



a) Currents of Stator.



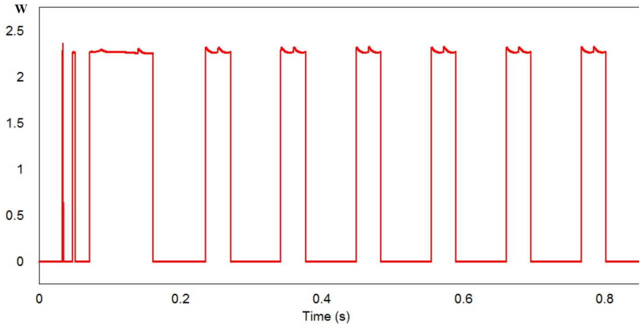
b. Voltage



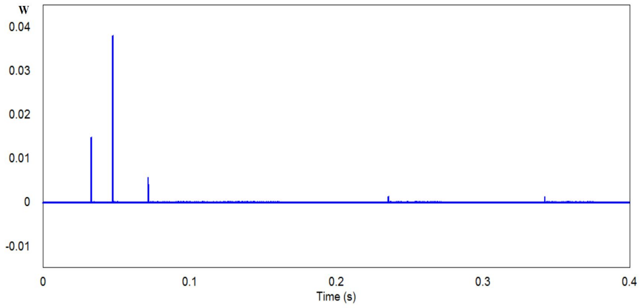
c. Speed

Fig. 10. Currents, voltage of CSI SiC topology and Speed control of PMSM.

The conduction and the switching power losses in CSI SiC topology in the MOSFETs are shown in the figure 11.



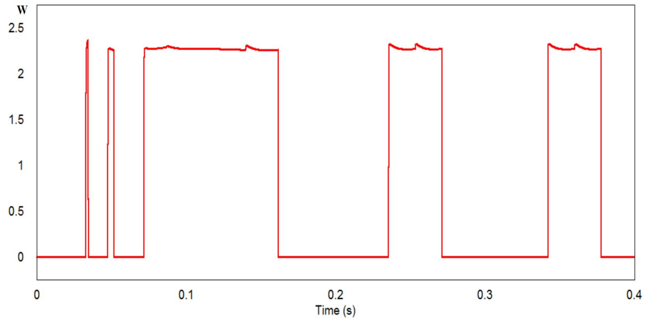
a. Loss by conduction.



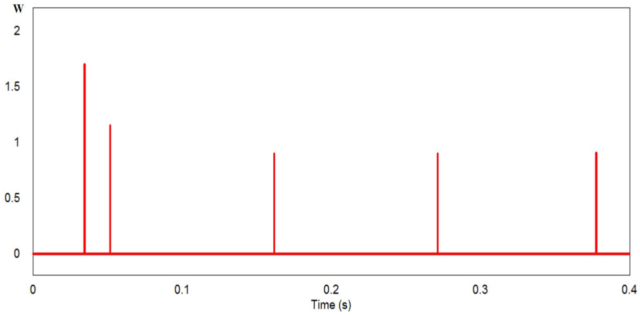
b. Loss by switching.

Fig. 11. Conductions and the switching power losses in MOSFETs SiC of the Topology CSI.

The conductions and the switching power losses in CSI SiC topology in the diodes are shown in the figure 12.



a. Loss by conduction.



b. Loss by switching.

Fig. 12. Conductions and the switching power losses in Diodes SiC of the Topology CSI.

The power losses in the CSI topology is smaller compared to the VSI topology, this would imply a better efficiency of CSI topology with elements of SiC working at 100 KHz in the figure 13 the power losses and perfomance are analyzed. These results are presented on the basis of the values obtained in the simulation, in the future can be validated with the development and implementing these topologies. The total power losses in the CSI topology are 68.61W and the VSI topology are 241.4W and represent 3.89% and 8.45% performance in each topology.

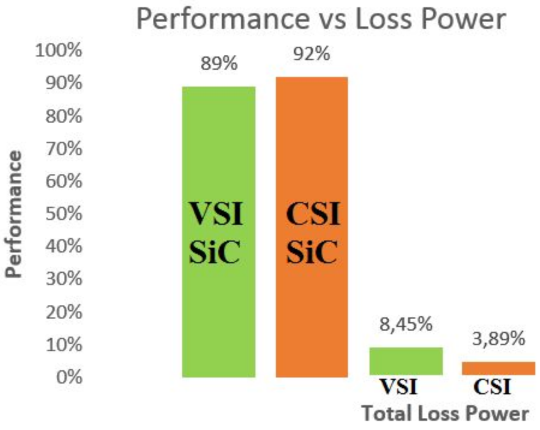


Fig. 13. Power loss in each topology vs performance.

CONCLUSIONS

This paper describes design, analysis and simulation of two topologies VSI and CSI with devices of Silicon Carbide at high switching frequencies (100 KHz), according to the results obtained the CSI topology with SiC devices is better to work at higher frequencies in comparison to the VSI SiC topology, this could contribute to obtain electric traction systems more efficient and compact with higher power density.

The use of SiC devices inside these topologies proposals allow to work at high frequency and temperature, this can minimize the size of the passive elements in each topology and getting systems smaller traction systems with better performance, and these devices reduce activation and conduction losses compared to conventional silicon IGBT topologies presented in several papers comprising in the literature.

The modulation technique applied to this study, SPWM to high frequency allows to obtain current and voltage responses; other methods can be applied that could improve the performance of these topologies, one of these methods would be the use of a space vector modulation (SVM) for each topology.

The technique FOC Control implemented for these SiC topologies is best adapted to electric traction systems, the development and implementation of algorithms used are not complex and offer a fast and effective response, they are also cheap and yield acceptable within traction systems.

It is concluded that the use of SiC devices in VSI and CSI topologies for the application on traction systems are attractive topologies that reduce activation and conduction losses, reduces high frequency harmonics and sizes of passive elements in each topology.

ACKNOWLEDGMENT

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REFERENCES

[1] Fei Shang; Arribas, A.P.; Krishnamurthy, M., "A comprehensive evaluation of SiC devices in traction applications," in Transportation Electrification Conference and Expo (ITEC), 2014 IEEE , vol., no., pp.1-5, 15-18 June 2014.

[2] Jahdi, S.; Alatise, O.; Fisher, C.; Li Ran; Mawby, P., "An Evaluation of Silicon Carbide Unipolar Technologies for Electric Vehicle Drive-Trains," in Emerging and Selected Topics in Power Electronics, IEEE Journal of , vol.2, no.3, pp.517-528, Sept. 2014.

[3] Kumar, K.; Bertoluzzo, M.; Buja, G., "Impact of SiC MOSFET traction inverters on compact-class electric car range," in Power Electronics, Drives and Energy Systems (PEDES), 2014 IEEE International Conference on , vol., no., pp.1-6, 16-19 Dec. 2014.

[4] Haizhong Ye; Yinye Yang; Emadi, A., "Traction inverters in hybrid electric vehicles," in Transportation Electrification Conference and Expo (ITEC), 2012 IEEE , vol., no., pp.1-6, 18-20 June 2012.

[5] Gui-Jia Su and Lixin Tang, A Current Source Inverter Based Motor Drive for EV/HEV Applications, SAE International, 2012.

[6] Zhiqiao Wu; Gui-Jia Su, "High-performance permanent magnet machine drive for electric vehicle applications using a current source inverter," in Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE , vol., no., pp.2812-2817, 10-13 Nov. 2008.

[7] Hak-Jun Lee; Sungho Jung; Seung-Ki Sul, "A Current Controller Design for Current Source Inverter-Fed AC Machine Drive System," Power Electronics, IEEE Transactions on , vol.28, no.3, pp.1366,1381, March 2013.

[8] Adamowicz, M.; Morawiec, M., "Advances in CSI-fed induction motor drives," Compatibility and Power Electronics (CPE), 2011 7th International Conference-Workshop , vol., no., pp.276,282, 1-3 June 2011.

[9] Gui-Jia Su; Lixin Tang, "Current source inverter based traction drive for EV battery charging applications," in Vehicle Power and Propulsion Conference (VPPC), 2011 IEEE , vol., no., pp.1-6, 6-9 Sept. 2011.

[10] Keliang Zhou; Danwei Wang, "Relationship between space-vector modulation and three-phase carrier-based PWM: a comprehensive analysis [three-phase inverters]," in Industrial Electronics, IEEE Transactions on , vol.49, no.1, pp.186-196, Feb 2002.

[11] Xupeng Fang; Mingjie Zhu; Zhiqiao Chen; Jie Liu; Xinwei Zhao, "Current-fed Z-source inverter modulation," in Electrical Machines and Systems (ICEMS), 2011 International Conference on , vol., no., pp.1-6, 20-23 Aug. 2011.

[12] Yun Wei Li; Bin Wu; Xu, David; Zargari, N., "Space Vector Sequence Investigation and Synchronization Methods for PWM Modulation of a High Power Current Source Rectifier," in Power Electronics Specialists Conference, 2007. PESC 2007. IEEE , vol., no., pp.2841-2847, 17-21 June 2007.

[13] da Silva, E.R.C.; dos Santos, E.C.; Jacobina, C.B., "Pulsewidth Modulation Strategies," in Industrial Electronics Magazine, IEEE , vol.5, no.2, pp.37-45, June 2011.

[14] F. Z. Peng, “Z-source inverter,” IEEE Trans. Ind. Appl., vol. 39, pp.504-510, Mar/Apr 2003.

[15] Bevilaqua, M.A.; Nied, A.; de Oliveira, J., "Labview FPGA FOC implementation for synchronous Permanent Magnet Motor Speed Control," in Industry Applications (INDUSCON), 2014 11th IEEE/IAS International Conference on , vol., no., pp.1-8, 7-10 Dec. 2014.

[16] K. Hasse, ‘‘Drehzahlgelverfahren fur schnelle Umkehrantriebe mit strom-richtergespeisten Asynchron-Kurzchlusslaufermotoren,’’ Reglungstechnik, vol. 20. no. 2, pp. 60–66, 1972.

[17] F. Blaschke, ‘‘The principle of field-orientation as applied to the transvector closedloop control system for rotating-field machines,’’ Siemens Rev., vol. 34, no. 1,pp. 217–220, 1972.

[18] Leon, J.I., "High-Performance Motor Drives," in Industrial Electronics Magazine, IEEE , vol.5, no.3, pp.6-26, Sept. 2011.