© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Method to Reduce THD and Improve Efficiency in SiC Power Converter.

E.Fernández. V. Sala. A Paredes. L Romeral.

Motion Control and Industrial Applications Group (MCIA).
Department of Electronic Engineer, University Polytechnic Catalonia.
Terrassa, Barcelona, España.

Abstract— this paper presents a method to reduce total harmonic distortion (THD) and improve efficiency of a topology of power converter using SiC devices. The method consists of two parts: the first part finds the optimum offset angle between two carrier signals that are sent to the first stage of the V-I converter and PWM modulation for the current source inverter (CSI), to reduce the total harmonic distortion in the output currents. The V-I converter transforms the voltage source of the battery into a current source for the inverter. The V-I converter operates at 30 kHz and the CSI at 55 kHz switching. The second part consists of using SiC devices to increase the operating range in frequency, and reduce the power losses in the devices, which will improve the efficiency of the analyzed topology. Besides, a comparative study between the SiC topology and a topology with conventional Si devices was proposed, the results of simulations analyzed the power losses and THD and compared with the purpose of validating the method proposal.

Keywords—SiC, CSI, FOC Control, Surface Mounted Permanent Magnet Synchronous.

I. INTRODUCTION

The use of SiC semiconductor devices in various studies [1],[2],[3] open new lines of investigation into these elements on developing traction systems for electric vehicles, where their application can benefit and solve various problems identified in systems using devices conventional of Si as it losses power, low frequency of activation and too large cooling systems [4],[5]. The SiC devices have several properties that are presented in [6], the use of these elements in power converters for working at high frequency, high temperature and reduce power losses (Fig.1) in compared with conventional Si devices, making them very interesting for application in electric traction systems.

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

Usually an electric traction system is formed by high-voltage battery, a power converter topology. The topology more used is the voltage source inverter (VSI) by research presented in [7]-[9], these topology incorporate a DC / DC booster. The DC / DC plays an important role in the stabilization of voltage for feeding the three-phase converter.

Nowadays, various studies present other emergent topologies [10]-[12]. In [13] the authors present the topology of CSI with a power converter V-I that controls the stabilization of the current, the input and the regeneration of the current for the battery of high voltage [13],[14]. The authors using the implementation of this topology insulated gate bipolar transistors (IGBTs) with reverse-blocking (RB) capability to low frequency of switching (15 kHz and 7.5 kHz). The result shows that the THD is high and the technique of modulation used is the simple signals of carrier without offset angle.

Several investigations analyze and present methods to minimize losses [15], the topology most analyzed is the VSI topology but with conventional silicon devices and works to low frequency, using this devices and low frequency of switching the current are distorted and the THD increase. The method of control used in [16], extends the base speed and improves the efficiency, but they use Si conventional devices and the power losses are higher in the analysis they develop.

In general, in most of the literature consulted it is noted that the tendency is to develop topologies of power converters at a low frequency of operation that causes distortion in the currents, this increases the THD and losses.

The present paper contributes to search topologies of converters implemented with silicon carbide devices that work at higher switching frequencies to obtain greater efficiency and improve applications focused on electric traction systems. Besides, the implementation and the finding of the best offset angle between the carrier signals of PWM and V-I converter to obtain a reduction of THD in the proposed topology.

The paper is organized as follows: first, a study about power converter topology and methodology used to develop the proposed method are presented in section II. The operation and finding of offset angle between the carrier signals is analyzed in III. Section IV presents the study comparative of power losses of the topology with conventional devices of silicon. The results of simulation are presented in V. Finally, section VI concludes this paper.

II. TOPOLOGY OF POWER CONVERTER AND METHODOLOGY PROPOSED.

A) Analysis of Topology.

The topology proposed for the analysis is presented in Fig.2. The topology uses a V-I converter to regulate the current input and a three-phase CSI that generates the three-phase currents.

Fig 2. Topology of power converter proposed for the study.

In researches [17]-[18], it is indicated that the CSI converter as an ideal for work at high frequency, the input inductor converter would be smaller, as the filter capacitors, semiconductors SiC offering a high blocking voltage and low resistance state. The CSI converter has an inductor component and uses it as energy storage, in addition to certain advantages compared to the VSI topology as described in [8]-[19] as the high voltage capability, as short-circuit protection, and sinusoidal output voltage due to the effect of the output filter capacitors AC, which are much smaller in capacity.

The V-I converter has two transistors, two diodes, and an output coil, if implemented with SiC devices. The analysis of the modes of operation of this converter in the first place performed when the SiC MOSFET are in an ON state and then when they are in an active state OFF.

In the first state (Fig. 3) when the MOSFETs T_1 and T_2 are turned ON under this condition the battery voltage is applied to the converter and charging the inductor, in this mode a current I_{out} and a voltage V_{out} are obtained $V_s = V$ Battery [12]. The return of the current through the activation MOSFET T_2 , the Diodes D_1 , D_2 at this moment are in reverse bias therefore do not activate.

Fig 3. Converter V-I converter in the first state.

In the second state Fig. 4, the MOSFETs are turned off and the current flows through the diodes D_1 and D_2 , this mode can be implemented in the case when the current converter returns to recharge the high voltage battery $V_s = -V$ Battery [11].

Fig 4. Topology DC/DC converter in the second state.

B) Proposed Methodology

A PWM modulation is used for the CSI and for the V-I converter. A second carrier is compared with the control PI implemented to obtain a constant current output, the main objective is to find a phase angle between the carrier signals to obtain the minimum THD in the output PWM currents, the scheme of the study proposed and the way of linking the two carrier signals is depicted in Fig.6.

The design of the control PI for the current in the V-I converter is summarized as follows: The circuit shown in Fig. 5 is a flow of current and voltage that are generated when you place a load RC. Also for the analysis considered the internal resistance of the SiC MOSFETs ($R_{ds} = R_{on}$), inductance (R_L) and capacitance (R_C).

Fig 5. Analysis of DC/DC bidirectional power converter MOSFETs On.

The equations that are obtained in the function of the circuit of input shown in Fig. 7 are described as follows:

$$V_{in}(t) = V_{Ron_1} + V_L + V_o + V_{Ron_2} \quad (1)$$

$$V_{in}(t) = R_{on_1} I_L(t) + L \frac{di_L(t)}{dt} + R_L I_L(t) + V_o + R_{on_2} I_L(t) \quad (2)$$

$$V_{in}(t) = 2R_{ds} I_L(t) + L \frac{di_L(t)}{dt} + R_L I_L(t) + V_o \quad (3)$$

$$L \frac{di_L(t)}{dt} = V_{in}(t) - 2R_{ds} I_L(t) - R_L I_L(t) - V_o \quad (4)$$

Fig 6. Schematic of operation and methodology proposed.

The value can be expressed in terms of R_{load} and R_c by the following equation:

$$V_o = \frac{R_{Load}R_c}{R_{Load}+R_c}i_L(t) + \frac{R_{Load}}{R_{Load}+R_c}V_c(t) \quad (5)$$

Substituting (5) into (4) we have:

$$L \frac{di_L(t)}{dt} = V_{in}(t) - 2R_{ds}I_L(t) - R_L I_L(t) - \frac{R_{Load}R_c}{R_{Load}+R_c}i_L(t) - \frac{R_{Load}}{R_{Load}+R_c}V_c(t) \quad (6)$$

$$L \frac{di_L(t)}{dt} = V_{in}(t) - \left[2R_{ds} + R_L + \frac{R_{Load}R_c}{R_{Load}+R_c} \right] i_L(t) - \frac{R_{Load}}{R_{Load}+R_c}V_c(t) \quad (7)$$

$$\frac{di_L(t)}{dt} = \frac{V_{in}(t)}{L} - \left[\frac{2R_{ds} + R_L + \frac{R_{Load}R_c}{R_{Load}+R_c}}{L} \right] i_L(t) - \frac{\frac{R_{Load}}{R_{Load}+R_c}}{L} V_c(t) \quad (8)$$

The equation that is obtained from the output circuit is given by the following expression:

$$C \frac{dV_c(t)}{dt} = V(t) - i_L(t) \quad (9)$$

$$C \frac{dV_c(t)}{dt} = \frac{R_{Load}}{R_{Load}+R_c}i_L(t) - \frac{1}{R_{Load}+R_c}V_c(t) \quad (10)$$

$$\frac{dV_c(t)}{dt} = \frac{\frac{R_{Load}}{R_{Load}+R_c}}{C}i_L(t) - \frac{\frac{1}{R_{Load}+R_c}}{C}V_c(t) \quad (11)$$

From equations (8) and (11), you can set the equation of state space mode or activation ON.

$$\dot{X}(t) = AX(t) + B \quad (12)$$

$$y(t) = CX(t) + D \quad (13)$$

Theses equations can be expressed in the matrix form:

$$\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dV_c(t)}{dt} \end{bmatrix} = \begin{bmatrix} \frac{2R_{ds} + R_L + \frac{R_{Load}R_c}{R_{Load}+R_c}}{L} & -\frac{\frac{R_{Load}}{R_{Load}+R_c}}{L} \\ \frac{\frac{R_{Load}}{R_{Load}+R_c}}{C} & -\frac{1}{C} \end{bmatrix} \begin{bmatrix} i_L(t) \\ V_c(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in}(t) \quad (14)$$

$$\begin{bmatrix} \frac{V_o(t)}{dt} \\ I_{in}(t) \end{bmatrix} = \begin{bmatrix} \frac{R_{Load}R_c}{R_{Load}+R_c} & \frac{R_{Load}}{R_{Load}+R_c} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_L(t) \\ V_c(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} V_{in}(t) \quad (15)$$

With this system, we can proceed to calculate the transfer function of the output current with respect to the input.

The modulation used in the CSI power converter is the simple PWM with logic mapping digital circuit and the schematic of the implementation is presented in Fig. 7

Fig 7. Technique of Modulation for CSI.

III. METHOD FOR FINDING THE ANGLE OFFSET OPERATION

This section presents the stages of development to get the angle of offset between the two signals of carrier. The frequency of CSI power converter is fixed to 55 kHz. The V-I power converter is tested in values every 5 kHz up to the maximum (55 kHz). Simultaneously the angle of offset between the carriers' signals is increased every 10 degrees until reaching the 100 degrees of offset. For each angle and value of frequency a result of THD in PWM is obtained.

The goal is to analyze all the results obtained by determining a zone where the lowest THD PWM is obtained. The offset angle is moved to different frequencies until the maximum angle offset. Fig 8 shows some examples of the signal carrier.

Fig 8. Signals carriers to different frequencies and angles. a) Fcsi=55 kHz, Fv-i=10 kHz, angle=0°; b) Fcsi=55 kHz, Fv-i=25 kHz, angle=20°; c) Fcsi=55 kHz, Fv-i=30 kHz, angle=50°; d) Fcsi=55 kHz, Fv-i=50 kHz, angle=90°.

The results obtained from THD by simulation between all the frequency ranges and angles are presented in Fig.9a and represents the different values of THD obtained and are analyzed on a surface. To determine the value of each point where the THD is minimum, the contour of the analyzed surface is used (Fig.9b).

Fig 9. Results of analysis. a) Surface with results of THD, b) Countour to determine the values of angle and frequency with lower THD

Select the zone where the V-I converter has the minimum THD and the angle of operation (30 kHz and 50 grades), this zone must have the highest switching frequency since it is working with SiC devices. In the map, there are other areas where the THD is low but found at low switching frequencies. The objective is to select the zone with the highest switching frequency. To validate the data, we select three points of the map and obtain the results shown in Table I and Fig.10.

Table I
Analysis of differents points

F _{V-I}	F _{csi}	Angle	THD PWM
5 kHz	55 kHz	0°	82.98%
30 kHz	55 kHz	50°	65.33%
40 kHz	55 kHz	70°	74.37%

Fig 10. Results of analysis THD of three points.

From the results obtained in the analysis it can be established that by varying the angle of offset between the carrier's signals, a reduction of the THD can be obtained in the modulated output currents. The parameters, for using in the simulations, are 30 kHz in the V-I converter and 55 kHz in the CSI, the angle of offset between the signal carrier is 50°.

IV. ANALYSIS OF POWER LOSSES AND EFFICIENCY

For the calculation of losses in the CSI the important rule is that there must always be at least one switch forward biased

in each half bridge of the converter [20]. The loss conduction P_c is expressed as,

$$\text{Mosfet: } P_{CON} = I_{out}^2 (R_{DS}) \quad (17)$$

$$\text{Diode: } P_{CON} = (V_T I_{out} + R_T I_{out}^2) \quad (18)$$

Where V_T is the voltage threshold and R_T is the dynamic resistor.

The Mosfet and diode switching power losses can be calculated with the next expression:

$$P_{SW} = \frac{1}{\pi} \int_{sw} (E_{ONI} + E_{OFFI} + E_{OFFD}) \frac{V_{DC} I_{out}}{i_{REF} V_{REF}} \quad (19)$$

V_{ref} and I_{ref} are the DC voltage and load current amplitude at which the switching energy losses given in the datasheet were measured.

The results of power losses in the topology proposed are presented in the Table II. The results and efficiency are compared with the same topology but with Si devices to low frequency (10 kHz and 5 kHz) and are shown in Fig.11.

Parameter	Losses in SiC Topology	Losses in Si Topology
Conduction Mosfet+ diodes CSI	57.94W	76.39W
Switching Mosfet +diodes CSI	23.78W	21.6W
Conduction Mosfet+ diodes V-I	19.19W	32.99 W
Switching Mosfet +diodes V-I	18.44W	14.14 W
Total Power Losses	119.35W	145.12W

Fig 11. Power losses and efficiency in SiC Topology vs Si Topology.

Efficiency is improved and power losses in the topology with SiC devices are reduced. The use of this technology reduces the power losses and increases the range of operation of frequency.

V. RESULTS AND SIMULATIONS.

This section describes the different results obtained in simulation made in Matlab-Simulink. The first part presents the results of PI control in the V-I converter. Next, the results obtained in the topology analyzed and a topology with silicon devices are performed. The values of THD and currents are presented and compared by validating the method proposed.

The parameters used for the simulations are presented in the table III.

In Fig.12, the results of tuning PI control in the V-I converter are shown in simulations.

TABLE III
Parameters of Simulation

Parameter	SiC Topology	Si Topology
Power	2.5 kW	2.5kW
Voltage	300V	300V
Current of Input	20A	20A
Inductor	20uH	200mH
Devices	19.19W	32.99 W
Load	2Ω	2Ω
Frequency V-I	30 kHz	10 kHz
Frequency CSI	55 kHz	5 kHz
Offset Angle Carrier	50°	0°

Fig 12. Result of PI control in the V-I converter. a) PI tuning control; b) Current of input to CSI

The currents, waveforms, and THD comparison between the method proposed in the topology SiC with angle offset between carrier signals and the conventional topology with devices of silicon without angle offset are shown in Fig. 13 and Fig. 14.

VI. CONCLUSIONS

This paper describes a method to reduce THD and improve the efficiency in SiC topology of a power converter. The proposed method shows results that by varying the angle of offset between the carrier signals a reduction of the THD can be obtained in the modulated output currents. The methodology proposed for obtained the offset angle between carrier signals and Pi control in the V-I converter is convenient for this type of topology since the THD is reduced from 10.52% to 5.27%, compared to the same topology but implemented with conventional silicon devices and without phase angle. The use of silicon carbide devices reduces the power losses and improves the efficiency of topology of this

power converter in comparison with the silicon conventional and is novel for future applications in electric traction systems.

Fig 12. Results in topology SiC with offset angle between signal carriers . a) Currents of output; b) Anlisy of THD.

Fig 12. Results in topology Si without offset angle between signal carriers . a) Currents of output; b) Analysis of THD

ACKNOWLEDGMENT.

This work was supported in part by the Spanish Ministry of Economy and Competitiveness under the TRA2016-80472-R Research Project.

REFERENCES

- [1] 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.
- [2] 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.
- [3] 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
- [4] Wrzecionko, B.; Bortis, D.; Kolar, J.W., "A 120 °C Ambient Temperature Forced Air-Cooled Normally-off SiC JFET Automotive Inverter System," in Power Electronics, IEEE Transactions on , vol.29, no.5, pp.2345-2358, May 2014.
- [5] Murakami, Y.; Tajima, Y.; Tanimoto, S., "Air-cooled full-SiC high power density inverter unit," in Electric Vehicle Symposium and Exhibition (EVS27), 2013 World , vol., no., pp.1-4, 17-20 Nov. 2013.
- [6] M. Zdanowski, D. Pefitsis, S. Piasecki and J. Rabkowski, "On the Design Process of a 6-kVA Quasi-Z-inverter Employing SiC Power Devices," in IEEE Transactions on Power Electronics, vol. 31, no. 11, pp. 7499-7508, Nov. 2016.
- [7] Haizhong Ye, Y. Yang and A. Emadi, "Traction inverters in hybrid electric vehicles," 2012 IEEE Transportation Electrification Conference and Expo (ITEC), Dearborn, MI, 2012, pp. 1-6.
- [8] F. Xu, L. Chen and N. Narayanachar, "Traction inverter evaluation method based on driving cycles for electric and hybrid electric vehicles," 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, 2016, pp. 1-6.
- [9] D. G. Woo, D. M. Joo and B. K. Lee, "On the Feasibility of Integrated Battery Charger Utilizing Traction Motor and Inverter in Plug-In Hybrid Electric Vehicles," in IEEE Transactions on Power Electronics, vol. 30, no. 12, pp. 7270-7281, Dec. 2015.
- [10] Siwakoti, Y.P.; Fang Zheng Peng; Blaabjerg, F.; Poh Chiang Loh; Town, G.E., "Impedance-Source Networks for Electric Power Conversion Part I: A Topological Review," Power Electronics, IEEE Transactions on, vol.30, no.2, pp.699,716, Feb. 2015.
- [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] H. Zhu, D. Yu, W. Zhu and Z. Zhou, "DC-Link Voltage Regulation of Bidirectional Quasi-Z-Source Inverter for Electric Vehicle Applications," 2016 IEEE Vehicle Power and Propulsion Conference (VPPC), Hangzhou, 2016, pp. 1-5
- [13] L. Tang and G. J. Su, "Boost mode test of a current-source-inverter-fed permanent magnet synchronous motor drive for automotive applications," 2010 IEEE 12th Workshop on Control and Modeling for Power Electronics (COMPEL), Boulder, CO, 2010, pp. 1-8.
- [14] Z. Wu and G. J. Su, "High-performance permanent magnet machine drive for electric vehicle applications using a current source inverter," 2008 34th Annual Conference of IEEE Industrial Electronics, Orlando, FL, 2008, pp. 2812-2817.
- [15] W. Hassan and Bingsen Wang, "Efficiency optimization of PMSM based drive system," Proceedings of The 7th International Power Electronics and Motion Control Conference, Harbin, 2012, pp. 1027-1033.
- [16] Bharat Singh Parihar and S. Sharma, "Performance analysis of improved power quality converter fed PMLDLC motor drive," Electrical, Electronics and Computer Science (SCEECS), 2014 IEEE Students' Conference on, Bhopal, 2014, pp. 1-6.
- [17] G. J. Su, L. Tang, and Z. Wu, "Extended Constant-Torque and Constant-Power Speed Range Control of Permanent Magnet Machine Using a Current Source Inverter," the 5th IEEE Vehicle Power and Propulsion Conference (VPPC'09), pp. 109-115, Sept. 7-11, 2009, Dearborn, MI.
- [18] Gui-Jia Su; Lixin Tang A Current Source Inverter Based Motor Drive for EV/HEV Applications, SAE International 2011.
- [19] Von Malottki, S.; Hameyer, K., "Extended base speed range by using a current-source-inverter-fed IPMSM for automotive application," in Power Electronics and Applications (EPE'14-ECCE Europe), 2014 16th European Conference on , vol., no., pp.1-8, 26-28 Aug. 2014.
- [20] F. Shang, A. P. Arribas and M. Krishnamurthy, "A comprehensive evaluation of SiC devices in traction applications," 2014 IEEE Transportation Electrification Conference and Expo (ITEC), 2014.