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Introduction of SiC MOSFETs in Converters based on Si IGBTs

A Reliability and Efficiency Analysis

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Abstract— Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) have the potential to increase the power density in power electronics converters compared to the currently used silicon (Si). Their benefits are higher efficiency, higher switching speeds, and higher operating temperatures. Moreover, SiC MOSFETs, which are normally-off, offer the possibility to directly replace Si Isolated-Gate-Bipolar-Transistors (IGBTs) in already existing converter designs with minimal circuit changes. Nevertheless, as an emerging technology, the reliability performance remains to be investigated. A reliability analysis has been performed based on a full-bridge resonant converter rated at 60 kW for modern Electrostatic Precipitator (ESP) power supplies. This analysis shows that introducing SiC devices will increase the lifetime of the converter while reducing the losses. The investment costs of replacing the Si IGBTs with SiC MOSFETs can thus be covered with the reduction of the losses over the economical operational lifetime. Furthermore, a theoretical analysis on how introducing SiC MOSFETs could increase the power density of the converter while maintaining the efficiency and the reliability. Finally, an analysis on introducing redundancy as a way to improve the reliability of the system has been performed.

Keywords—Silicon Carbide (SiC), Reliability, MOSFETs, IGBTs, Multichip Module, Reliability Engineering.

I. INTRODUCTION

Silicon Carbide (SiC) offers three main potential benefits compared to the currently used silicon (Si) [1], [2]. These benefits are higher efficiency, higher switching frequency and higher temperature of operation [3]. Over the past few years, there has been a special emphasis on SiC Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) [1]. The benefits of using SiC MOSFETs compared with Silicon (Si) Isolated-Gate-Bipolar-Transistors (IGBTs) has been identified in many applications such as aeronautics [4], automotive [5], wind turbine [6] and, soft

switching converters [7], [8]. The SiC MOSFET is currently under mass production, mainly due to the fact that it is comparably uncomplicated to replace Si IGBTs with SiC MOSFETs. One of the main reasons for this is that the gate-driver unit of a Si IGBT can easily be modified for use with SiC MOSFETs. Finally, the replacement of Si-IGBT technology with SiC MOSFET technology in the 900 V – 1.7 kV range is beneficial in terms of efficiency. However, if the efficiency is not the main target, a combination of higher switching frequency and higher temperature operation results in smaller passive components and cooling system, respectively. This may result in a higher power density as well as a considerable costs reduction.

However, the SiC technology is fairly new and numerous studies on the reliability of SiC MOSFETs have pointed out several issues arising from imperfections in oxide quality, threshold stability, and body-diode ruggedness (among others) [9]–[12]. With the recently introduced 3rd generation of SiC MOSFETs from Wolspeed, which is the leader on the market, the oxide layer stability and body-diode ruggedness seem to have improved [13]. Manufacturers are also considering new package designs in order to decrease the stray inductances in the package so as to fulfill high switching speed requirements and, therefore, taking full advantage of the SiC properties [14]–[17]. New package concepts are also considered for high-temperature operation. A promising reliability analysis on SiC MOSFET power modules considering parallel

connection as well as gate-voltage dependency has recently been presented in [18].

This study aims at comparing the reliability and the efficiency of a resonant converter topology using SiC instead of Si devices with the reference case using Si IGBTs. Consequently, an identical converter with SiC MOSFETs has also been evaluated. The comparison of these two identical converters will permit to identify how the benefits in efficiency impact the reliability. Furthermore, an analysis on how much the switching frequency can be increased while maintaining the efficiency and the reliability is also presented. Finally, introducing redundancy in the overall system is investigated. The three different topologies are finally compared through a Life Cycle Cost Analysis based on 20 years of lifetime.

II. THE RESONANT CONVERTER

The converter topology investigated in this paper is a full bridge LCC resonant converter as shown in Fig. 1. It is part of an industrial power supply. An illustration of the whole system with one converter unit is shown in Fig. 2.

Fig. 1: Full bridge converter with resonant tank

The electrical parameters of the resonant converter and the devices under investigation are stated in Table I. The devices chosen are both rated 1.2 kV and 300 A and are built with a 62 mm package based on Si technology. The calculations are made based on a case where the load is constant.

TABLE I. CONVERTER ELECTRICAL CHARACTERISTICS

Resonant Converter	
Power Rating	60 kW
Input Voltage	540 Vdc
Output Current	150 A RMS
Switching Frequency	25 kHz
DC Capacitance 1	AVX FFVE6B0666K
DC Capacitance 2	AVX FFLI6B0687KJE
Resonant tank Capacitance	AVX FAX86-9443--B
Blanking Time	2 μ s
Power Semiconductor Devices (1.2 kV, 300 A)	
Si IGBT module	FF300R12KT4
SiC MOSFET module	CAS120M12BM2

The reliability study focuses on the lifetime of the semiconductors as well as the capacitors (dc and resonant). The failure (FIT) rates of the transformer and the inductors are not considered in this study since they are much lower than the other two components and will have negligible impact on the reliability of the system. The resonant tank capacitor lifetime will be unchanged for the Si and the SiC variants providing that the power rating at the load is similar. However, increased losses in the semiconductors for the Si IGBT reference case compared to the SiC MOSFETs case results in higher current in the input dc capacitors, thus higher operation temperatures. Therefore, a slight increase of the FIT rate for the dc capacitors is expected for the Si IGBT case.

Fig. 2: Modern ESP power supplies based on LCC resonant converter

III. SiC MOSFET MODULE – FIT RATE CALCULATION

The SiC MOSFET power module investigated in this study is configured as a half bridge. This power module is built with parallel connection of 6 SiC MOSFET chips and, 6 anti-parallel SiC Schottky diodes per switch position, as shown in Fig. 3.

Under the assumption of an exponential distribution, the mean time to failure (MTTF), defined as the inverse of the FIT rate for the SiC MOSFETs and SiC Schottky diodes are given by the manufacturer for a single chip. The failure rates are shown in Table II. For the Si IGBT, the module FIT rate is provided by the manufacturer and is stated in Table III.

Fig. 3: SiC MOSFET module – internal configuration

Therefore, for the SiC MOSFET, a reliability calculation in order to derive the FIT rate of the power module must be performed. In that case it will be assumed that when one of the chips fails, the module fails entirely. Thus, the calculation consists of a series connection of all the single chips contained in the module. Accordingly, the FIT rate of the module is calculated using

$$\lambda_{Module} = \sum_{i=1}^n \lambda_{MOSFET} + \sum_{i=1}^n \lambda_{Schottky} \quad (1)$$

where λ_{MOSFET} and $\lambda_{Schottky}$ are the FIT rates of a single MOSFET chip and a single Schottky diode chip, respectively. Additionally, n is the number of chips which is equal to 12 for the SiC power module. The representative diagram of the SiC MOSFET module is shown in Fig. 4. The figure shows the series connection from a reliability perspective, which implies that if one chip fails, the complete power module fails. Table III shows the

calculated FIT rate for the SiC MOSFET module and the FIT rate for the Si IGBT as given by the manufacturer. It can be observed that the FIT rate of the SiC MOSFET power module is almost half that of the Si IGBT power module.

TABLE II. FIT RATE OF THE SiC MOSFET CHIP AND THE SiC SCHOTTKY DIODE.

Device (chip)	Failure rate, λ (valid field fail per billion device hour)
SiC MOSFET	3.03
SiC Schottky	0.10

Fig. 4: Reliability block diagram for the SiC MOSFET module

TABLE III. FIT RATE OF THE SiC MOSFET MODULE (CALCULATED) AND Si IGBT

Device	Failure rate, λ (valid field fail per billion device hour)
SiC MOSFET module	37.56
Si IGBT module	75

IV. RELIABILITY OF THE RESONANT CONVERTER

From the reliability data derived in the previous section, one can estimate the reliability of the resonant converter. In order to limit the scope of the study to the power module comparison, the investigated components are the semiconductor devices in the half-bridge, the dc capacitors C_r in the dc-link, and the resonant capacitor C_s (c.f Fig. 2). The dc-link capacitors are composed of the parallel connection of three AVX FFVE6B0666K and two AVX FFLI6B0687KJ. In this study, the FIT rate of the total converter is calculated using (2), as a series connection of all the components from a reliability perspective. Thus, if one single component stops working, the complete system fails. Table IV shows the efficiency and the FIT rates of the full bridge resonant for the reference case and the SiC MOSFETs case. Note that the efficiencies are only considering the semiconductor devices at this stage. The reliability data for the capacitor are provided by the manufacturer. They are temperature dependent (thus

loss dependant). As a consequence, the capacitor FIT rate is slightly higher in the Si case.

$$\lambda_{LCC} = \sum_{i=1}^{n_{devices}} \lambda_{MODULE} + \sum_{i=1}^{n_{cap1}} \lambda_{DC_cap_1} + \sum_{i=1}^{n_{cap2}} \lambda_{DC_cap_2} + \sum_{i=1}^2 \lambda_{res_cap} \quad (2)$$

Furthermore, since the SiC MOSFET based converter has lower losses, the heat sink temperature will be reduced. A reduction of system costs can be obtained by either reducing the heat sink size or increasing the switching frequency and therefore, reducing the size of the passive components. If the heat sink size is maintained, the switching frequency can be increased up to 3.3 times (82.5 kHz) in order have the same efficiency as the reference case. This will enable a considerable reduction in the size of the passive components in the resonant tank and the dc-link. A size reduction of the passive components results in a reduction of the total cost of the converter. Furthermore, in a second step, the overall converter design can be modified in order to reduce its volume. Thus, the space taken by the converter on site will be reduced.

TABLE IV. FIT RATE OF THE SiC MOSFET CHIP AND THE SiC SCHOTTKY DIODE.

Technology	Power loss [W]	Efficiency [%]	FIT, λ [fail per billion device hour]	MTTF [years]
Si IGBT module (ref. case)	1200	98	199.3	572.78
SiC MOSFETs module	350	99.48	124.42	917.45
SiC MOSFETs Redundant	175	99.71	-	1376.2

V. REDUNDANT SYSTEMS

Another possibility to improve the reliability of the system is to introduce redundancy. An example of how this redundancy can be achieved in this application is presented in Fig. 5. In fact, since each single converter is rated at 60 kW, it is possible to connect two or three units in parallel in order to increase the power rating or increase the possibility to fulfill the load requirement in case one converter fails. In fact, the higher efficiency and higher reliability of the SiC-based converter can allow cutting down costs (lower losses, and longer interval in between maintenance).

Fig. 5: Example of parallel connection of two low voltage units

The reliability of such a system can be calculated using the parallel connection representation. The MTTF of parallel systems with two identical components can be calculated according to (3) [19]. The MTTF is stated in Table IV.

$$MTTF_s = \frac{3}{2\lambda} \quad (3)$$

VI. LIFE COST ANALYSIS

In the life cost analysis of this study, three cases are considered. The focus of the comparison concerns only the low-voltage unit of the resonant converter as the main difference between the converters is the switching semiconductor devices. The first one, taken as reference case is the Si IGBT converter currently commercialized. The second case is the SiC MOSFET based converter and, the third a parallel connection of two SiC-based low voltage units. The costs are given in Swedish crowns and stated in Table V. As it can be seen, the reliability for the SiC converter with redundancy is 2.5 times higher than for the reference case. Therefore, the outage costs per year are further reduced for this case. Moreover the redundancy results in a power loss reduction of 50 % compared with the SiC MOSFET based converter without redundancy which leads to a total savings of a further 4000 SEK per year based on an electricity rate of 0.4 SEK/kWh (Average 2016) [20].

As it can be seen in Table V, the net present sum is lower for both SiC MOSFET based converter. I.e. that the additional investment costs are covered by the energy savings mostly, but also, by the fact that

the outage costs per year are lower, and the preventive maintenance is done less frequently. The net present value (NPV) for the SiC MOSFET single converter is 32.5 % lower than for the Si IGBT case. The case with redundancy has an almost identical NPV. This is mainly due to the large investment cost and the relatively short duration of the economic lifetime of this product. However, considering the noticeable reliability improvements, increasing the economic lifetime of the product would be the natural step forward.

TABLE V. INVESTEMENT COSTS – CONVERTERS

Converter	Si IGBT	SiC MOSFET	SiC MOSFET redundancy
Investment Costs	30 000 SEK	45 000 SEK	2 x 45 000 SEK
Loss / year	12 MW	4 MW	2 MW
Electricity Costs – due to losses	4800 SEK	1600 SEK	800 SEK
Outage Costs / year	Negligible	Negligible	Negligible
Preventive Maintenance	5 years	10 years	10 years
Costs / maintenance (estimation)	5000 SEK	5000 SEK	5000 SEK
Interest Rate	5 %	5 %	5 %
Economic Lifetime	20 years	20 years	20 years
Net Present Sum	105 895 SEK	71 494 SEK	105 725 SEK

In this application, the redundancy is attractive in terms of power loss. Both single and redundant converters result in a lower NPV calculated over 20 years. However, the case without redundancy is economically more attractive due to the consequent savings brought by this solution. Finally, the next step towards the integration of SiC devices into converter designs made previously with Si is the reduction of the system passives by increasing the switching frequency. The power density can be further increased by allowing a higher temperature of operation. In this way, the benefits of SiC can be fully used and SiC will become even more economically interesting.

VII. CONCLUSION

In this paper, a reliability and efficiency analysis has been presented when introducing SiC MOSFETs in order to replace the Si IGBTs. The reliability of an identical single system was improved by 1.6 times and the efficiency by a factor of 3. Moreover, including redundancy in the system can further improve the reliability and lower the losses. The reliability is 2.5 times better than the reference case and the losses are 6 times lower. Furthermore, a life cycle cost analysis is performed, revealing that replacing Si IGBTs by SiC is economically interesting since the investment costs can be fully covered by the reduction of losses over the economic lifetime of the product. Finally, introducing redundancy will only be interesting if the converter expected lifetime is increased. This can clearly be considered in accordance to the improvement of the reliability.

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