Experimental Analysis of the Application of Latest SiC Diode and CoolMOS Power Transistor Technology in a 10kW Three-Phase PWM (VIENNA) Rectifier

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Abstract. This paper presents the experimental analysis of the switching behavior of the combination of latest SiC diode and CoolMOS power transistor technology in a 10kW three-phase/switch/level unity power factor PWM (VIENNA) rectifier module. The focus is placed on the determination of the transient turn-off overvoltages and of the switching power losses at switching speeds in the range of 400V/10ns and 30A/10ns. The goal is to design a unit with an ultra high power density of 10kW/l and a height of only 1-U (44.4mm).

1 Introduction

State of the art boost rectifier systems do employ conventional high-(warp-)speed IGBTs and/or power MOSFETs in connection with ultrafast soft recovery diodes. However, the use of IGBTs does limit the maximum switching frequency to f_P = 25...50kHz in case a high system efficiency should be achieved. Power MOSFETs would alleviate this problem, however, the relatively high on-state resistance of conventional power MOSFETs does impair the efficiency of the rectifier at the lower end of a wide input voltage range (e.g. $U_{N,l\text{-}l}$ = 320 ... 530V) due to the increasing rms value of the transistor current.

Infineon Technologies AG now has recently introduced the 2nd generation of low on-resistance CoolMOS power transistors and a novel Silicon Carbide (SiC) Schottky diode with a blocking capability of 600V, which is claimed to have no reverse recovery properties [5]. The combination of these components is ideally suited for realizing a highly efficient high-frequency boost-type topology in a hard switching mode of operation.

In this paper this new semiconductor technology should be employed for improving the power density of an existing 10kW/25kHz three-phase/switch/level boost-type PWM rectifier system (**Fig.2**(a), [1]) from ρ = 1.8kW/l to ρ = 3kW/l for conventional air-cooling and/or to ρ > 10kW/l for water-cooling; the latter with a significantly increased switching frequency of about 250 … 500kHz (cf. **Fig.1**).

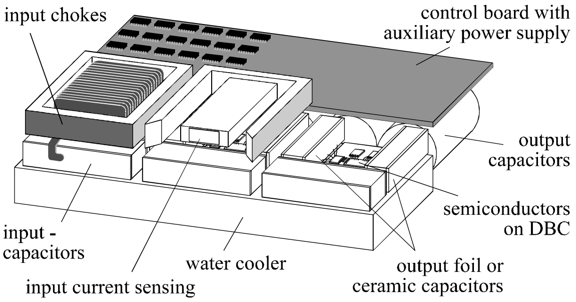

Fig.1: Outline of the rectifier module showing a power density of ρ > 10kW/l at a switching frequency of f_P = 250 … 500kHz.

In **section 2** the experimental analysis of the switching behavior of the CoolMOS power transistor in combination with a SiC diode are presented. There, the focus is on the transient turn-off overvoltages, the power transistor turn-on and the turn-off losses as well as on the limitations of the measurement setup. **Section 3** shows the switching losses in a graphical form and presents a simple method with high accuracy for the calculation of the average values of switching power losses over a mains period. Also a brief comparison to the published datasheet values is given. **Section 4** does discuss advantages, drawbacks and limitations of the power semiconductor combination employed and does give details on the planned continuation of the research on the rectifier system.

2 Experimental Analysis of the CoolMOS power transistor and the SiC Diode

In **Fig.3** the schematic of the measurement setup for the determination of the switching behavior is depicted. The measurement circuit is realized on a standard double-sided printed circuit board which has been designed for a 2-U high power density (ρ = 3kW/l) unit. The experimental analysis of the 1-U rectifier module depicted in Fig.1 will be treated in a future paper. All the measurements are done without using any overvoltage limitation (DRC) circuits or

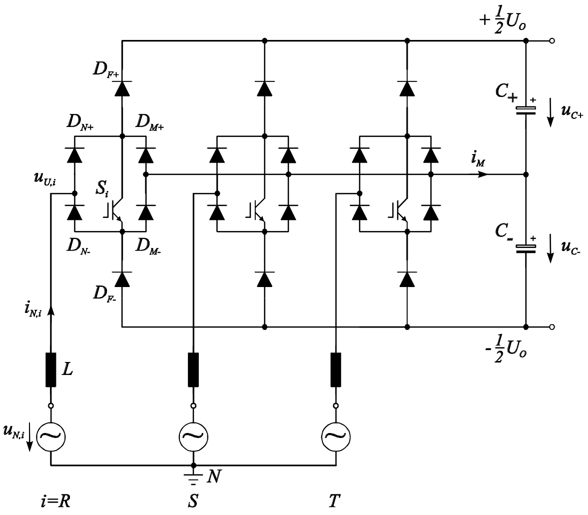

Fig.2: Topology of the three-phase/switch/level PWM (VIENNA) rectifier system.

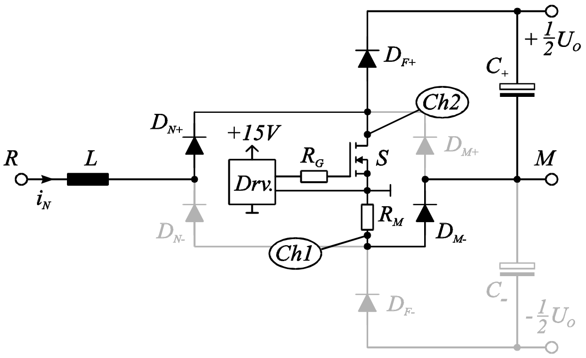

Fig.3: Measurement setup for the evaluation of the switching behavior of the CoolMOS power transistor *S* (SPW47N60C2) in combination with a SiC freewheeling diode D_{F+}; D_{F+} is realized as parallel connection of two diodes of type SDB06S60. The components shown in gray are not placed on the switching behavior evaluation board.

RC snubbers across the semiconductor components. **Table 1** shows a detailed listing of the components used for the experimental analysis described in this paper.

The power MOSFET *S* is driven with a pulse sequence having a low pulse width and a repetition rate of only $f_P \approx$ 1Hz. The power semiconductor components are mounted on an aluminum carrier. The temperature of the carrier is controlled to a constant value of 25°C or 125°C which also does define the power semiconductor junction temperature with respect to the low frequency and low pulse width of the pulse sequence depicted in **Fig.4**. The input current i_N is increased up to an adjustable threshold where the power transistor is turned off for 4µs. Subsequently the power transistor is turned back on for again 4µs. The detailed investigation of the switching behavior is done using this final turn-on pulse.

The results of the experimental investigation of the turn-on and turn-off behavior are depicted in **Fig.5(a)** … **(l)** for transistor currents of i_S = 10, 20 and 30A and junction temperatures of T_j = 25°C and T_j =125°C.

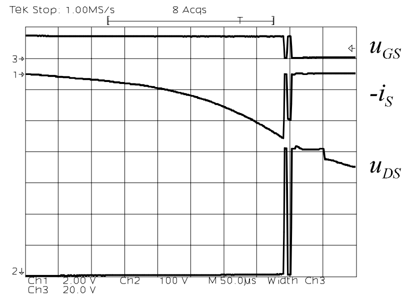

Fig.4: Pulse sequence employed for the evaluation of the switching behavior of the CoolMOS power transistor in combination with the SiC freewheeling diode. Top: u_{GS} @ 20V/div; middle: $-i_S$ @ 20A/div; bottom: u_{DS} @ 100V/div. The detailed investigations are done at the end of the sequence (last turn-on and turn-off).

Part	Type / Value
S	Infineon SPW47N60C2
D_{F+}	2x Infineon SDB06S60
D_{N+}, D_{M-}	Int. Rect. HFA15TB60
C_+	2x 150µF / 450V + 220nF / 630V
L	700µH iron powder core
R_M	T&M Research SDN-414-10 0.0968Ω, 2GHz
R_G	5 Ohm, SMD MiniMelf
Drv.	Optocoupler drive Agilent HCPL 3120
Ch1	Tektronix TDS 544A 500MHz 1.0m coaxial cable
Ch2	Tektronix TDS 544A 500MHz 1:10 voltage probe 350 MHz
R-M	Input voltage 55Vdc
$+{}^1/_2\, U_O$	Output voltage 400Vdc

Tab.1: List of components and equipment employed in the measurement setup.

The transient turn-off overvoltage shows a maximum value of 480V (cf. Fig.5(e)) at an output voltage of $\frac{1}{2}U_O$ = 400V and a switched transistor current of i_S = 20 A and T_j = 25°C. Increasing or decreasing the values of the switched current does not increase the overshoot of the drain to source voltage, therefore, no additional overvoltage limitation circuit needs to be installed (in case of a low inductance circuit layout). The drain to source voltage has a maximum rise time at turn-off of t_r = 10ns at a junction temperature of T_j = 25°C (cf. Fig.5(e)) what does result for a change of the voltage level of 400V in a turn-off voltage

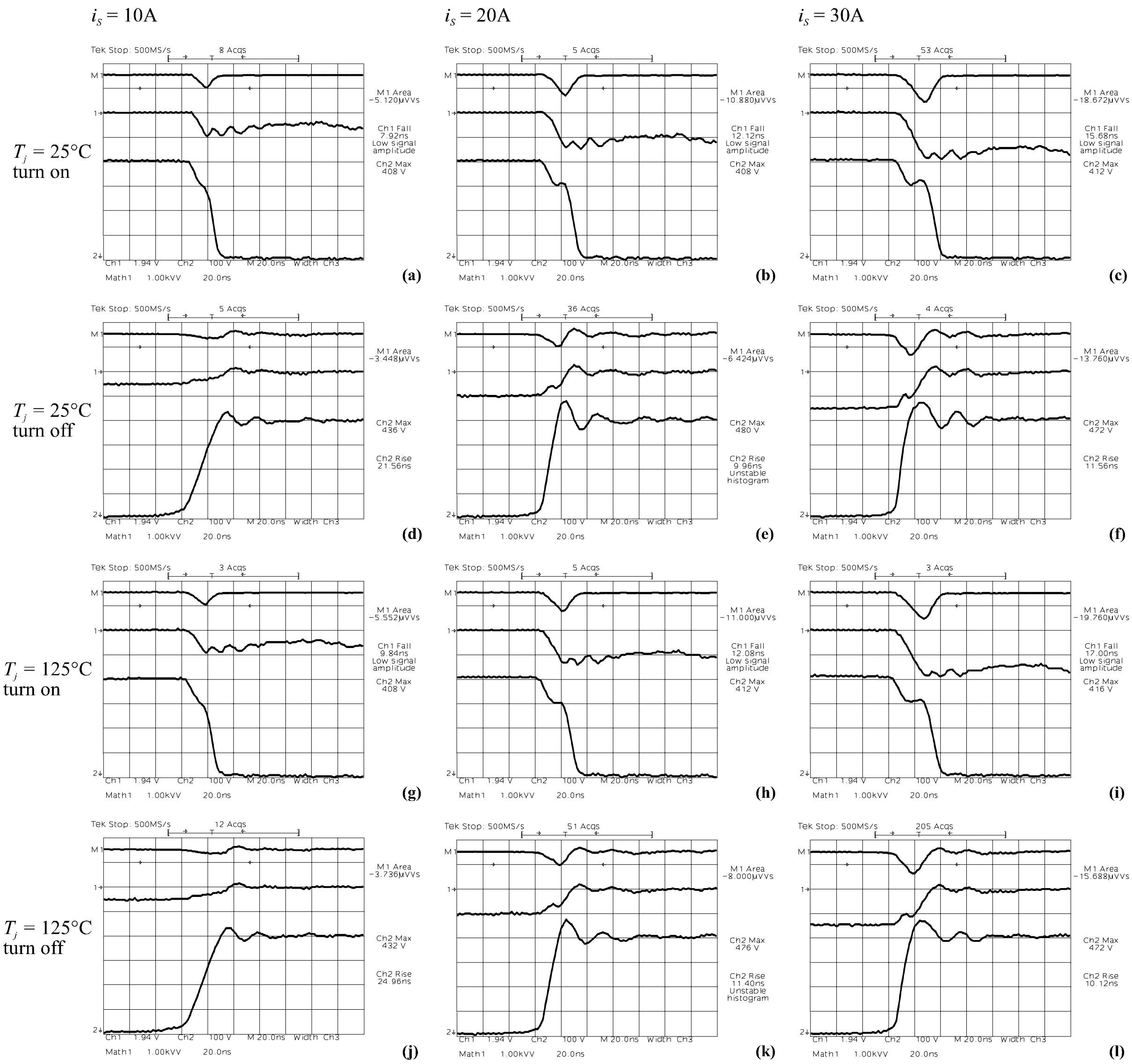

Fig.5: Experimental analysis of the Infineon power transistor SPW47N60C2 in connection with two SiC freewheeling diodes SDB06S60 connected in parallel for application in a three-phase/switch/level PWM (VIENNA) rectifier system. Test parameters according to Table 1. **(a)** … **(f)**: junction temperature T_j = 25°C; **(g)** … **(l)** T_j = 125°C; **(a)**, **(b)**, **(c)** and **(g)**, **(h)**, **(i)**: turn-on of the power transistor S; **(d)**, **(e)**, **(f)** and **(j)**, **(k)**, **(l)**: turn-off of the power transistor S. **(a)**, **(d)**, **(g)**, **(j)**: power transistor current being switched i_S = 10A, **(b)**, **(e)**, **(h)**, **(k)**: i_S = 20A, **(c)**, **(f)**, **(i)**, **(l)**: i_S = 30A. Top trace: negative switching power loss $-p_s$ (10kW/div), middle: negative power transistor current $-i_S$ (20A/div), bottom: power transistor drain to source voltage u_{DS} (100V/div).

slope of 40kV/µs(!). The maximum current slope at turn-on is in the range of 2A/ns, at turn-off approximately at 1.5A/ns. It should be pointed out that the SiC Schottky diodes are free of any recognizable reverse recovery effects. A detailed analysis of the turn-on and the turn-off power losses will be given in section 3.

The determination of the switching power losses is very near to the bandwidth limits of the measurement setup employed. It is important to note that, e.g. for the current rise time of 2A/ns a piece of wire of 1cm length (10nH/cm) does result in an inductive voltage drop of 20V. In the case at hand current measurement is by a coaxial shunt of 0.1Ω with a bandwidth of 2GHz (cf. **Fig.6**, [7]).

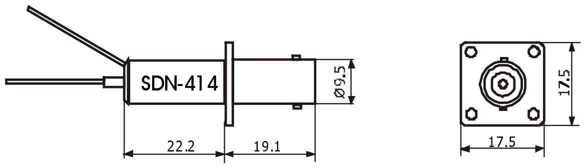

Fig.6: Shunt employed for transistor current measurement [7].

3 Calculation of the Power Losses

The transistor turn-on and turn-off energy losses are shown in **Fig.7** in dependency on the switched current and the corresponding junction temperature. The relation between the switched transistor current and the switching energy cannot be approximated with sufficient accuracy in a linear way but by a polynomial of second order. The resulting quadratic relations are shown in Fig.7 in combination with the underlying formulas. The formulas are based on the measurements at a junction temperature of T_j = 125°C because there is only a minor variation of the switching losses with the junction temperature. The switching energy value given in the Infineon datasheet [4] for i_S = 47A and for the same value of the gate drive resistor (R_G = 5Ω) at turn-on is $w_{S,on}$ = 1.3mJ as compared to $w_{S,on}$ = 380µJ resulting in the case at hand (Fig.7). The published turn-off energy is with $w_{S,off}$ = 700µJ at i_S = 47A and R_G = 5Ω which is approximately twice the value shown in Fig.7 ($w_{S,off}$ = 330µJ). These differences could originate from the different measurement setups, e.g. two SiC diodes in parallel are employed in the case at hand and therefore twice the junction capacitance, in contrast to only a single diode used in the Infineon measurement setup. Furthermore, the measurements are extremely sensitive to parasitic inductances of the PCB used for the wiring of power semiconductors. The switching energy losses published by Infineon should be used in case of an unavailable test environment for dimensioning in order to ensure a sufficient safety margin.

For the determination of the average value of the switching power loss of a power transistor of the three-phase/switch/level PWM rectifier we assume a constant switching frequency f_p and a purely sinusoidal shape of the switched current within the mains period. The average value of the switching power loss then can be calculated [2] using

$$i_S = \hat{I}_N \sin(\varphi_N) \tag{3}$$

$$w_S = k_2 i_S^2 + k_1 i_S + k_0 \tag{4}$$

$$P_S = \frac{1}{\pi}\int_0^{\pi} f_P w_S(\varphi_N) d\varphi_N \tag{5}$$

as

$$P_S = f_P\left(k_2 I_{N,rms}^2 + k_1 I_{N,avg} + k_0\right). \tag{6}$$

Table 2 shows a detailed listing of the estimated partial losses at different input voltages (U_N = 320, 400, 480V line-to-line) of a 500kHz water-cooled rectifier system according to Fig.1. The current values are calculated according to [2], the switching loss values according to equation (6) with k_2 = 0.0783µJ/A^2, k_1 = 4.3946µJ/A and k_0 = 0µJ at turn-on and k_2 = 0.0983µJ/A^2, k_1 = 2.4043µJ/A and k_0 = 0µJ at turn-off at a junction temperature of T_j = 125°C (Fig.7). The parallel connection of the two SiC diodes is modeled as an ideal diode with a forward voltage drop of U_D = 0.8V and a series resistor of R_D = 75mΩ [5].

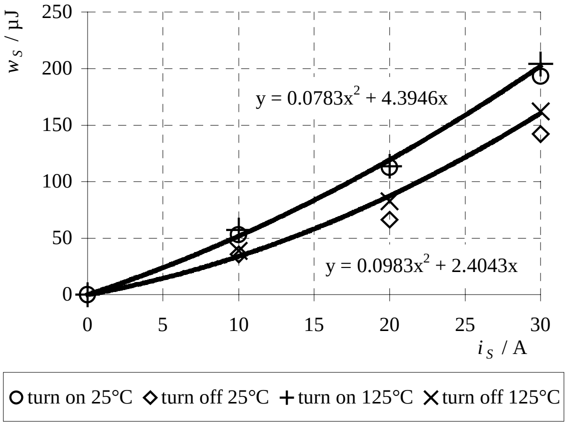

Fig.7: Measured values of the transistor turn-on and turn-off energy losses w_S dependent on the switched current i_S and the junction temperature T_j. Furthermore shown: second order trend lines and corresponding formulas ($y = w_s$ [µJ], $x = i_s$ [A]) for the measurements at T_j = 125°C.

Taking into consideration the power losses given in Table 2 an estimation of the efficiency of a three-phase rectifier system of P_O = 10.5kW output power and f_P = 500kHz switching frequency could be in the range of η = 92 … 94%. For this high switching frequency in any case a water-cooled heatsink has to be provided. A conventional forced air-cooled heatsink would have to have a thermal resistance of less than 0.05K/W what would result in a system power density of less than 1kW/l. For a conventional system with a switching frequency of f_P = 48kHz the efficiency would be in a range of η = 97 … 98%. Exact values of the efficiencies for both, a conventional air-cooled 48kHz and a water-cooled 500kHz unit, based on measurement on not just a bridge leg but on a whole three-phase system, will be published in a future paper.

Special attention has to be paid on the practical realization of the input inductors for a system operating at 500kHz switching frequency. While low to medium conversion frequency units usually do employ iron powder core inductors and a solid or litz wire winding configuration with vacuum potting, an input choke for a 500kHz unit has to employ a ferrite core. Consequently, because of the lower maximum flux density of the ferrite core the volume of the input inductors does not decrease linearly with increasing converter switching frequency. Accordingly, an estimation of a frequency increase from 48kHz to 500kHz (factor of 10) yields only a volume reduction by a factor of 5 (from 84cm^3 to about 18cm^3). In order to achieve a reasonable resonant frequency of the input inductors of at least 10

Input power	$P_N =$	11000	11000	11000	W
Input voltage	$U_{N,l\text{-}l} =$	320	400	480	V
Input current	$I_{N,rms} =$	19.85	15.88	13.23	A
Output voltage	$U_O =$	800	800	800	V
CoolMOS current	$I_{S,rms} =$	13.25	8.80	5.43	A
	$I_{S,avg} =$	8.70	5.13	2.75	A
CoolMOS @125°C	$R_{ds,on} =$	0.12	=	=	Ω
Conduction loss	$P_{S,C} =$	21.06	9.28	3.54	W
Switching frequency	$f_P =$	500	=	=	kH
Turn on sw. loss	$P_{S,on} =$	54.68	41.28	33.03	W
Turn off sw. loss	$P_{S,off} =$	40.84	29.57	22.92	W
CoolMOS total loss	$P_S =$	116.6	80.1	59.5	W
SiC diode	$I_{DF,rms} =$	10.45	9.35	8.53	A
	$I_{DF,avg} =$	4.58	4.58	4.58	A
2x SiC Diode	$R_D =$	0.075	=	=	Ω
@125°C	$U_D =$	0.8	=	=	V
SiC diode loss	$P_D =$	11.86	10.22	9.13	W

Tab.2: Listing of the partial losses the CoolMOS and the SiC diode of a 10kW/500kHz water-cooled rectifier module according to Fig.1. The values listed are for a single CoolMOS and for a single SiC diode and therefore have to be multiplied by a factor of 3 or 6, respectively in order to obtain the total semiconductor losses of the rectifier system.

times the switching frequency, f_R > 5MHz, there, e.g. a helical wound flat copper coil with a baked-on thermal epoxy insulation [6] should be employed instead of a quasi-planar winding configuration. This single layer technology allows a higher utilization of the winding window and does give better AC properties in terms of parasitic capacitance, skin- and proximity effects as compared to solid round wires, foil windings or litz wire windings.

4 Conclusion

As shown in this paper the application of latest power semiconductor technology, CoolMOS power transistors in combination with SiC Schottky diodes does allow the realization of 10kW boost-type three-phase PWM rectifier switching frequencies of 500kHz in a hard switching mode of operation for applications where power density but not efficiency is the main issue. However there are a few open questions remaining which have do be answered before starting a product development. An extremely high rate of change of the transistor voltage - up to 100kV/µs could be achieved using a gate drive circuit with sufficiently high output current. This certainly would cause problems in connection with limiting radiated EMI in a frequency range of 30MHz … 2GHz. Furthermore, the extreme rate of change of the voltage would cause significant noise on the rectifier control board and one has to notice that an optocoupler employed for the gate drive of the MOSFET usually is guaranteed to reliably operate only up to typically 15kV/µs (e.g. Agilent HCPL 3120). Additionally, a common measurement equipment is very near to its limits for the design of converters employing CoolMOS power transistors and SiC diodes. These problems are in the focus of the continuation of the research on converter modules of ultra high power density at the ETH Zurich.

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