Comprehensive design optimization of a wind power converter using SiC technology

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***Abstract*— This paper proposes the joint electro-magnetic and electro-thermal design optimization of a three-phase two-level voltage-source inverter, referring to the specific operational conditions of wind power conversion applications. The reference power level is 12 kW and the devices have a nominal voltage rating of 1.2 kV, typical values of small-scale wind turbines. Novel silicon carbide (SiC) devices are used to enable higher switching frequencies and operational temperatures, yielding in turn higher power density, without penalty on efficiency. Specifically, with relevance to commercial products, the paper focuses on the salient features of SiC and discusses their impact on system performance, elaborating on the associated bespoke design needs to yield optimum results in terms of inverter performance and power density, both volumetric and gravimetric. The study is of relevance primarily to on-ground systems, but also includes novel insight and results of straightforward spin-off transfer to a number of transport applications, including upcoming hybrid and fully electric naval and avionic applications.**

Keywords*— *renewable energy; wind power conversion; voltage source inverter; silicon carbide (SiC); small-scale wind turbine.

I. INTRODUCTION

In view of the benefits they offer in terms of size and weight reduction, it is a trend to use permanent magnet synchronous generators (PMSG) in small-scale wind conversion systems, with power ranges up to indicatively a few hundred kW's. As there is no reactive power circulation, the conversion system is a simple 3-phase diode rectifier with dc-dc boost converter connected to an inverter, as schematically illustrated in Fig. 1. [1, 2]. In this work, the focus is on the inverter stage. Among the various candidate topologies, the two-level (2L) three-phase (3P) voltage source inverter (VSI) is the typically preferred option for small-scale wind turbine applications, the main advantages being simpler hardware construction and control complexity, fewer switches count, less drive and protection circuits and more even thermal stress among the various switches [1].

Fig. 2 shows a typical yearly wind-speed distribution profile and the corresponding wind turbine output power for a commercial 10 kW nominal rating small-scale wind turbine [3, 4]; it is notable that the system spends most of its operational time at relatively low wind speeds and load conditions. Design optimization must consider this important aspect.

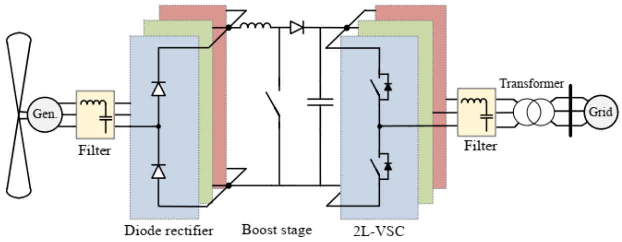


Fig. 1. Two-level grid-connected voltage-source power conversion system for wind turbines application.

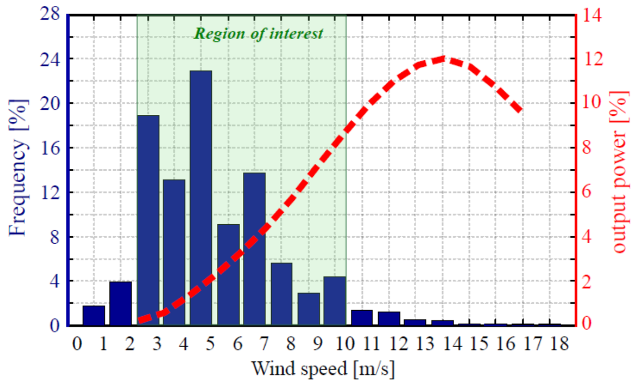
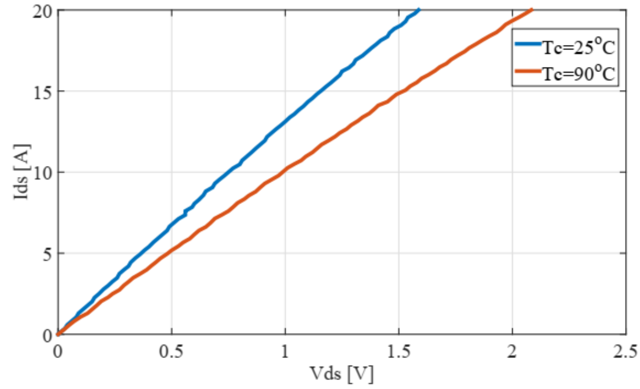


Fig. 2. Illustration of wind speed distribution probability and corresponding power conversion system operational point.

II. SiC DEVICE CHARACTERISTICS

The devices used in this study are packaged in a commercial power module (CCS020M12CM2 from Wolfspeed [5]), including a power MOSFET with anti-parallel Schottky diode for current free-wheeling. Fig. 3 a) and b) show the MOSFET and diode output characteristics, respectively, measured at two diffferent baseplate temperatures, 25 and 90°C. As can be seen, the effect of temperature on the on-state performance becomes more pronounced at higher current levels; however, diode conduction startes already at current levels between 5 and 10 A and can help contain current and temperature related decrease of performance compared to reliance on the MOSFET body-diode and synchronous rectification.



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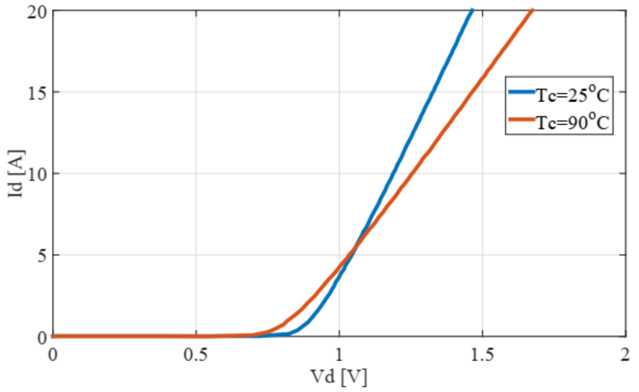

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Fig. 3 Temperature dependence of MOSFET output characteristics (the gate-source bias voltage is VGS=18 V), a), and Schottky diode forward characteristics, b).

As far as the switching performance is concerned, Fig. 4 shows the measured turn-on, turn-off and total switching energy as a function of power module case temperature, for two different values of the switched current, 10 and 20 A, respectively. Again, a certain dependence of the switching efficiency on the load conditions is noticeable; however, the extremely contained dependence on temperature is also remarkable: this is an important connoting characteristic of SiC devices against their silicon (Si) equivalents (e.g., IGBTs), which can be taken advantage of in the pursued system design optimization.

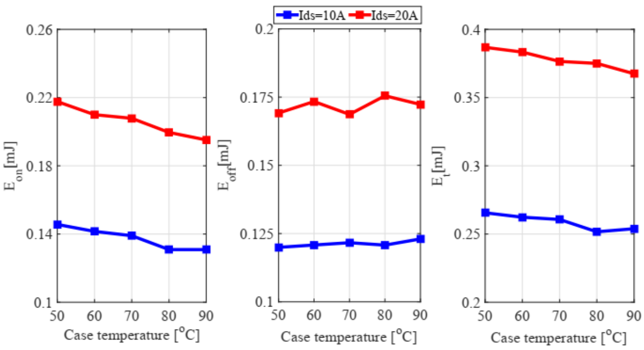


Fig. 4. Measured switching energy versus baseplate at different drain currents.

III. System level performance and design optimization

The experimental results in this section were produced by means of a prototype inverter, its parameters are show in Table I, and its setup shown in Fig. 5 a), which uses a heatsink mounting both heating resistors and cooling fans (detailed view in Fig. 5 b)). This way it is possible to decouple the output load test condition (i.e., the power losses) from the operational temperature: at low load, the heating resistors can be used to produce a higher baseplate temperature as required; at high load, the fans can be turned on to achieve lower baseplate temperatures.

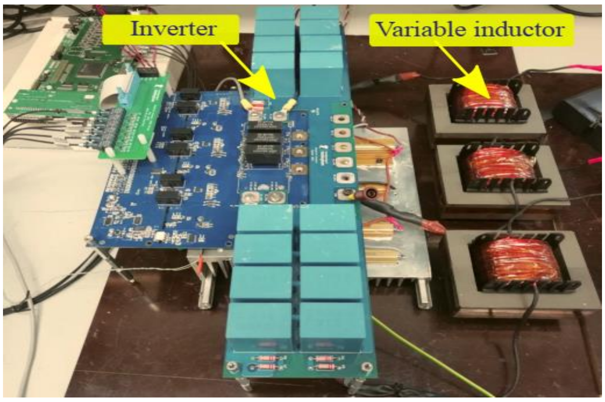
TABLE I. Converter parameters and test conditions

Parameter	Value
Input power rating, P_{in}	12 kW
DC-link voltage, V_{DC}	720 V
DC-link capacitor C_{DC}	56 µF
Filter inductance L_f	Variable (1.1-2.7) mH
Grid phase voltage, V_g	230 V
Switching frequency, f_{sw}	16-32 kHz
Dead-time	500 ns

A. Switching Frequency and Filter Design

With the aim of maximizing the power density of the inverter, it is meaningful to explore the trade-off between switching frequency and efficiency. Fig. 5 a) shows the measured data for the system under analysis: as the output load increases, the overall losses are increasingly dominated by conduction and so, the effect of switching frequency progressively becomes negligible; however, an important difference in efficiency is registered at the lower load conditions. Remembering the opening discussion about wind distribution and most frequent operational conditions (Fig. 2). At 400 W output power which represents the starting wind turbine power, about 5% efficiency drop in the performance curve is observed when moving from 16kHz to 32kHz switching frequency and the implication of poor low-load efficiency is that a non-negligible increase in yearly energy waste can result, as quantitatively shown in Fig. 6 b), whereas, by considering the operation of the wind turbine in the wind speed range from 3m/s to 7m/s which has a highly probable working chance, this subsequently leads to about 53% difference in the lost energy by increasing the switching frequency from 16 kHz to 32 kHz.

So, to enable optimum efficiency versus power density trade-off, the inverter was re-designed with variable switching frequency (fs) modulation: the nominal value is 32 kHz, decreasing in steps to 16 kHz as the load decreases. Saturable output filter inductors were designed based on Kool Mu 60 E-core with litz wire to ensure compliance with the maximum admissible harmonics generation profiles even at the lower frequencies [6]. The results for efficiency and energy saving are given in Fig. 7 a) and b), the annual cumulative lost energy for SiC inverter with fixing switching frequency is about 224.6 kWh, and in contrast, 128.7 kWh for the inverter with variable switching frequency. This results in a total lost energy saving up-to 42.69% by adopting a variable switching frequency technique.



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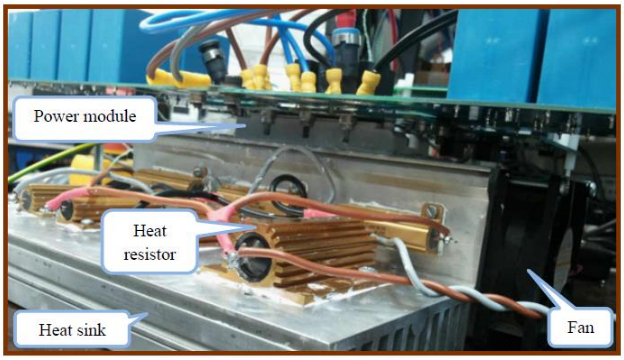

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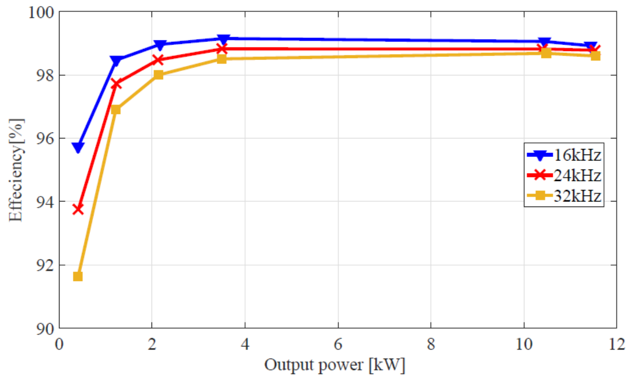
Fig. 5. Prototype inverter setup with detail of output filter inductors, a); detail of heatsink equipped with heating resistors and cooling fans, b).

B. Heat-sink Design

The implication at system level of the device switching performance discussed in Section II is well illustrated by Fig. 8 a), which reports the efficiency as a function of module baseplate temperature: overall system efficiency is not significantly dependent on temperature, at least within the considered range, indicating the possibility to reduce the heatsink size without immediate penalty, the efficiency drop was 0.19% (less than 22W) over a whole range of heat-sink temperatures (from 50 ºC to 90 ºC).

The achievable amount of decrease of overall volume is quantified in Fig. 8 b): as these results clearly point out, a minimum exists, which depends on the pair of variables fs and heat-sink temperature, which, for optimum results, need to be set as a pair, rather than independently (i.e., at a different target heat-sink temperature will correspond a different optimum fs value). Preliminary validation results of the proposed heat-sink design are shown in Fig. 9 a). Fig. 9 b), on the other hand, shows a final very important result: the maximum value up to which it makes sense to increase the heat-sink temperature is limited at about 240-245 °C; beyond this value, the increase in semiconductor losses becomes a limiting factor and no further heat-sink volume shrinkage is viable. These results base on a physical semiconductor device model validated up to very high temperatures [7].



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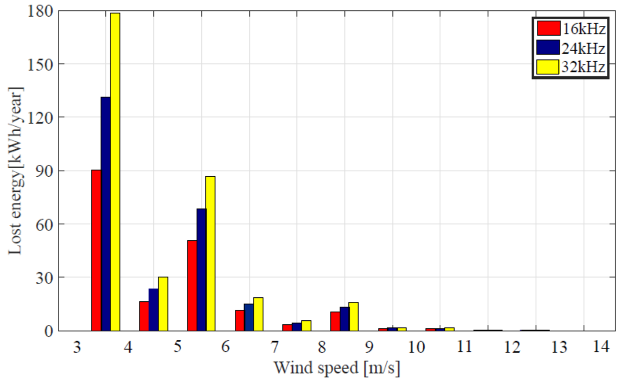

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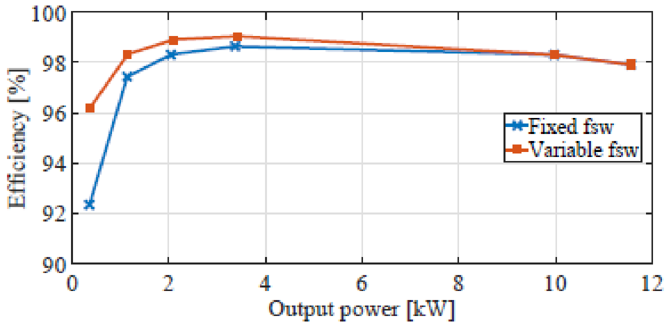
Fig. 6. Measured efficiency as a function of output power at three different switching frequencies with standard output filter, a); corresponding calculated yearly energy waste, b).



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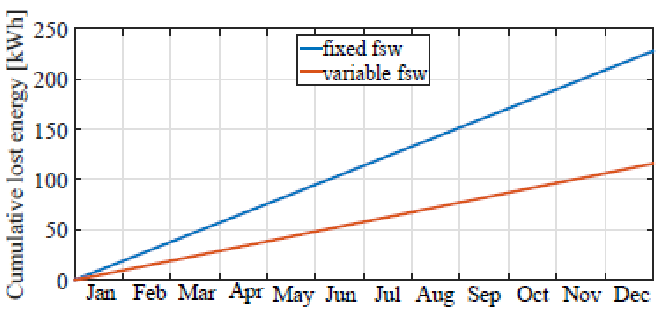

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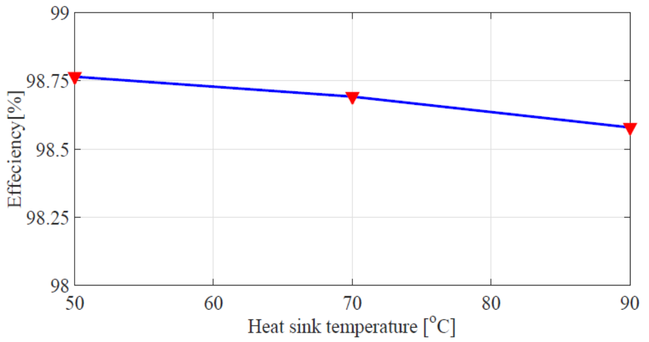
Fig. 7. Measured efficiency with saturable inductor and varying fs (and comparison with fixed 32 kHz fs), a); corresponding cumulative yearly energy waste (and comparison with fixed 32 kHz fs), b).



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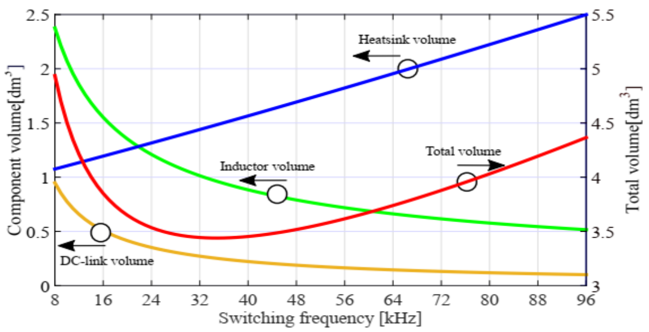

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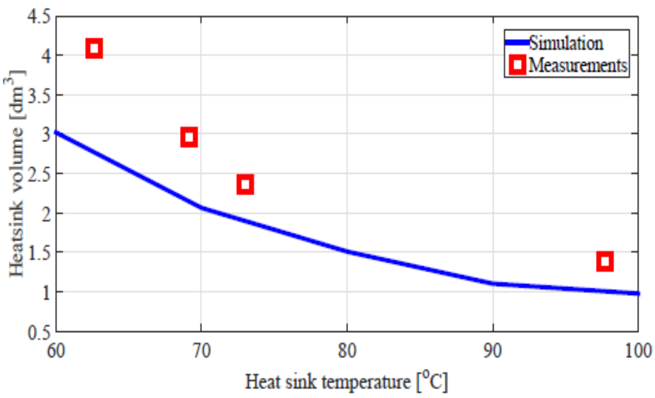
Fig. 8. Measured inverter efficiency as a function of heatsink temperature, a); trade-off filter/heatsink size and determination of optimum frequency for target heat-sink temperature of 90 °C, b).

IV. Conclusion

With the aim of maximizing the power density of the inverter, a combined heat-sink and output inductor-filter volume were reduced by increasing the heat-sink temperature from 60 °C to 90 °C, and choosing the optimum switching frequency at 32 kHz for minimum converter volume. To enable optimum efficiency versus power density trade-off, the inverter was redesigned with variable switching frequency, the nominal value is 32 kHz, decreasing in steps to 16 kHz as the load decreases. Saturable output filter inductors were used to ensure compliance with the maximum admissible harmonics generation profiles even at the lower frequencies. This enables to 37.8% increase in the inverter power density and saving up to 42.7% of the lost energy per year.



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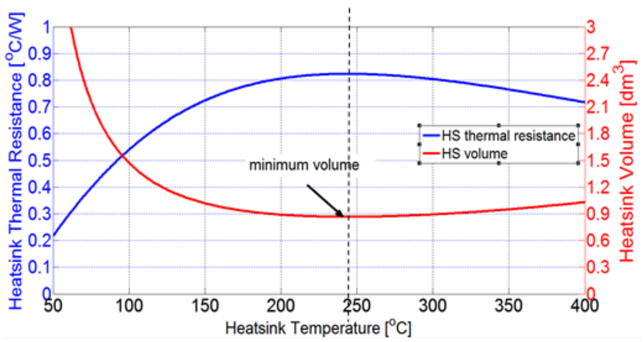

b)

Fig. 9. Analytical and experimental estimate of heatsink volume reduction with increasing temperature, a); assessment of potential for reduction over broader temperature scale, indicating an optimum operational temperature around 245 °C.

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