

Evaluation of the Powermodules' Performance of the e-Sling Inverter

Nicholas Behr, Benedict Hildisch, Roland Stärk, Anna Thumann^{1,✉}

¹Focusproject e-Sling, Institute of Machine tools and Manufacturing under supervision of Prof. Dr. Konrad Wegener, ETH Zurich

The e-Sling is a four passenger electric aircraft built by ETH students that took off in September 2022 for the first time. In this paper the focus will be set on the e-Sling's inverter and the performance of the powermodules. The power semiconductors are based on the silicon carbide (SiC) technology which enables the inverter to run on a heightened switching frequency of 15 kHz and to achieve an efficiency of about 98.5 percent. The biggest challenge with the SiC technology were the electric magnetic interferences which resulted from the fast switching times and heightened overshoots. These interferences disturbed the communication protocol of the powertrain components. After increasing the electromagnetic compatibility, the communication could be reestablished and the electric powertrain ran securely.

inverter | high voltage powermodules | silicon carbide performance | e-Sling

Correspondence: anna.thumann@cellsius.com

Introduction

e-Sling is a student project from ETH Zurich that started in September of 2020. Within two years 20 mechanical and electrical engineering students developed an electric powertrain and built it into a Sling TSi, a four passenger airplane. The e-Sling's first flight successfully took place on September 19th 2022.



Fig. 1. The e-Sling with open motor compartment

In order to meet the power, size and weight requirements the inverter of the e-Sling was newly developed with the additional aim to implement the newest silicon carbide semiconductor technology.

Further goals were to implement an optimised field oriented control containing a third harmonic injection and reaching a inverter switching frequency of 15 - 30 kHz.

	Take-off	Climb	Cruise
Power [kW]	104	87	44
Speed [RPM]	2300	2200	2000
Torque [Nm]	432	381	210

Table 1. Summarized requirements of the power profiles

Methods

After researching the current state of the market, the SiC power modules from Cissoid, Infineon and Wolfspeed were considered in the end. The following criteria were prioritized: maximum switching frequency, energy losses (consisting of switching and conduction losses), available documentation, robustness.

- *Maximum switching frequency:* A switching frequency of 15 to 30 kHz is targeted. Only Cissoid has a limitation of up to 25 kHz and accordingly would not fully meet this criterion.
- *Energy losses:* Here the direct comparison for the energy loss calculation is shown. Using the energy loss formula for mosfets shown in equation 1, the three modules were evaluated at an operating point of 600 V, 200 A, and 25 °C and at a switching frequency of 20 kHz. The detailed results can be seen in table 2. This operating setting is chosen because these values can be read directly from the data sheets of the individual manufacturers and they are reasonable because a power of 120 kW is assumed.

$$P_{loss} = (R_{DSon} \cdot I^2 + (E_{on} + E_{off}) \cdot f_{sw}) \cdot 3 \quad (1)$$

	Cissoid	Wolfspeed	Infineon
R_DSON (mOhm)	3,25	4	5,6
E_ON+E_OFF (mJ)	9,8	3,9	3,7
P_loss (W)	978	714	894

Table 2. Comparison of the contact resistance, the switching energy and the total losses from the data sheets of the modules. (1), (2) and (3)

- *Existing documentation:* An important factor for the correct implementation is the existing documentation. Here Wolfspeed is the front runner. They offer matching gate drivers for their power modules as well as additional explanations for correct commissioning and cooling. They are also the only ones to disclose the circuit diagrams of their control unit, from which the

interface from the microcontroller to the gate drivers can be read and reproduced.

- **Robustness:** Infineon is known among power semiconductor manufacturers for its robustness. This is an important consideration in the operation of an aircraft. However, robustness is also guaranteed in Wolfspeed and Cissoid, as they are operated in the proven range of their data sheets. The Wolfspeed modules are also operated far from their maximum exhausted operating point and has the further advantage that the PWM signals are transmitted differentially, which is another protection against electromagnetic interference.

The final choice fell on Wolfspeed's gate driver module CGD12HBXMP (4) and half bridge module CAB400M12XM3 (3).

Results

The e-Sling inverter weighs a total of 7 kg. After implementing the motor control a maximum switching frequency of 15 kHz could be reached in order to ensure no deadline misses.



Fig. 2. An open view of the HV section of the inverter

To evaluate the powermodules measurements were conducted on the switching operations. Figure 3 shows a single switching operation at 22 kW input power, measured between phase U and ground. An overshoot of 14 % and a switching edge of just under $2.4 \text{ kV}/\mu\text{s}$ are obtained. Thus, the overshoot is within the acceptable range of about 75 % given by experts (5). The fast switching edges however can pose a strain to the insulation of the motor. Therefore, no higher switching frequencies should be implemented unless the motor insulation is strengthened.

Measurements were also conducted on the high voltage DC (direct current) link to see the effect of the switching operations on the DC link. Fluctuations within 19 % of the high voltage could be observed occurring at the rate of the switching frequency of the inverter.

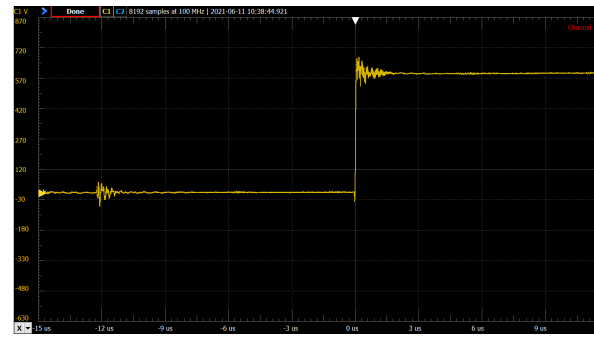


Fig. 3. Measurement of a switching operation of a semiconductor bridge from phase U to ground at an electrical input power of 22 kW

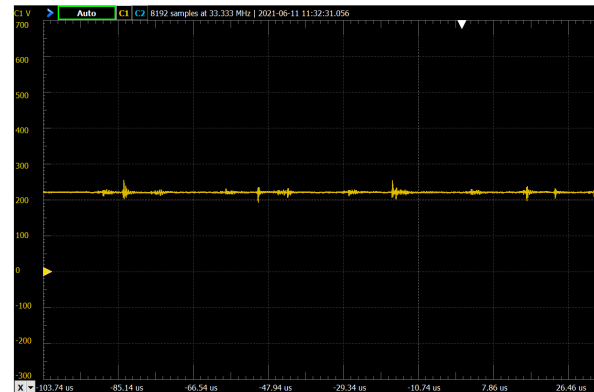


Fig. 4. Measurement of the HV DC link at 600 V with visible disturbances from the switching frequency of the inverter

When testing with other components of the powertrain, namely the electric motor, the high voltage distribution unit and the high voltage batteries, the communication network, CAN(controller area network), broke down. After many cycles of improving the electromagnetic compatibility, mainly by improving the shielding of the high voltage cables between inverter and motor, improving the spacial separation of the high voltage and low voltage cables and redistributing components attached to the CAN bus to better shielded, a secure communication could be reestablished between the components of the powertrain.

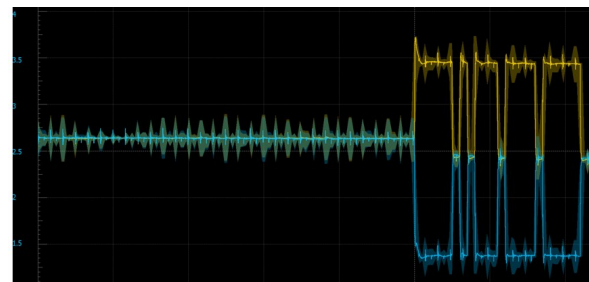


Fig. 5. Measurement of the CAN Bus with visible disturbances from the switching frequency of the inverter

A big advantage of the powermodules while testing was the Mosfet fault feature implemented in Wolfspeed's powermodules. The feature was triggered when a too high voltage or current were detected and automatically blocked the semi-conductors. This often protected to motor and inverter during testing of the motor control.

Conclusions

The e-Sling inverter is based on the silicon carbide technology which enables the inverter to run on a heightened switching frequency of 15 kHz. To increase the switching frequency, a FPGA would have to be used instead of a microprocessor and the motor insulation would have to be strengthened. The biggest challenge with the SiC technology were the electric magnetic interferences resulting from the fast switching times and heightened overshoots. These interferences disturbed the communication protocol of the powertrain components. After increasing the electromagnetic compatibility, the communication could be reestablished and the electric powertrain ran securely.

The inverter has an efficiency of about 98.5 %, the entire powertrain of the e-Sling an efficiency of about 91 %.

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