Technical approach

Team Name: OKE-Services	**Registration Code**: 545-UjK25p-58058

Introduction

This document describes the technical approach for OKE's inverter design for Google's LittleBoxChallenge. Since the project was executed by one man only, it was quite a challenge to reach the current state of development in a relatively short period of time. Therefore it is expected that further optimization can eventually result in ever smaller dimensions than described in this document.

1. Specifications

The inverter achieves a power density of 400 W/in^3.
The inverter can be simply described as a 'buck – buffer – dual half bridge' topology with an EMC filter on input and output (see Figure 1). One half bridge is HF modulated during the first half of the sinewave, the other half bridge is HF modulated during the second half of the sine. The switching frequency of both stages is 1 MHz.
Only EPC's 450 V GaN switches are used (EPC2027). The diode in the buck-stage is 600 V SiC.
The energy buffer consists of three electrolytic capacitors in parallel. These take roughly a quarter of the inverter's volume. Approximately the same space is taken by the three power inductors.
The cooling consists of a heatsink with propeller and motor. These take approximately one third of the inverter's volume.

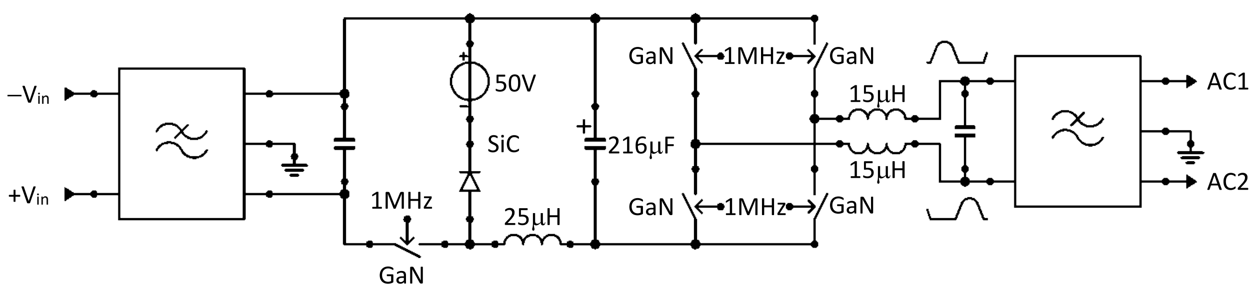

Figure 1: Inverter principle

2. 120 Hz input current/voltage ripple requirement

The requirement for the input current/voltage ripple requirement is met by using a buck regulator on the input which is connected to a capacitor bank (see Figure 1).
Commercially available high voltage capacitors achieve the highest energy density at 400 V. This matches very well with input voltage range of the inverter. The selected 400 V buffer capacitors

have 12.5 mm diameter and 35 mm length. So three of these can be mounted on a PCB of 37.5 x 37.5 mm^2. This determines the final length and width of the enclosure: 39 x 39 mm^2.

The buck-switch is built with two small GaN switches (EPC2027) in parallel. Since these switches are only 4 mm^2 (0.16 in^2) per switch the space requirement is very low. The diode is built with two small SiC diodes (C3D1P7060Q) in parallel. These diodes are in a 3 x 3 mm^2 package. The switch is at the low side and the diode at the high side. This has a number of important advantages:

- A standard very fast low side gate driver can be used
- There are no problems with high dV/dt's on the switching node.
- There are no added parasitic capacities to the switching node:
    - The housing (=substrate) of the GaN switch is at the potential of the source. Therefore no capacity will be added between switching node and heatsink.
    - The case of the SiC diode is connected to the cathode drain. So cooling the diode will not add capacity between the switching-node and $+V_{in}$.

A special inductor is designed for very low parasitic capacity in combination with an extremely high Q factor at 1 MHz. This resulted in a parallel capacity in the order of 2 pF and a Q-factor in the order of 1000 (hard to measure accurately). Due to the high Q-factor the 1 MHz ripple current through the inductor can be relatively high without causing too much losses. The core losses of the inductor is minimized by using a new ferrite grade from Ferroxcube (3F46).
The voltage control loop is implemented (in assembly code) in a simple micro controller (Sim3L) in a 6 x 6 mm^2 package. This controller scans $+V_{in}$ and $-V_{out}$ and updates the PWM at a rate of 500 kHz. The resolution of the timer of the micro controller is 10 ns. This is not good enough for directly driving the buck stage. A few discrete parts are used to improve the timer resolution for the buck-stage to 1 ns. An integrating algorithm is used to maintain constant voltage at the input while making sure that the 120 Hz ripple voltage across the buffer capacitor remains just high enough to avoid distortion of the output ac-voltage.

3. Miniaturization of components for DC-AC conversion

For the DC-AC conversion two half bridges are used. The left half bridge is HF modulated during the first half of the sine, the right half bridge is HF modulated during the second half of the sine. Each switch of the halve bridges consists of 4 GaN devices (EPC2027) in parallel. An important advantage of this type of GaN switch is that no special measures need to be taken to avoid the losses caused by reverse recovery. That saves a lot of board space and prevents EMC trouble. Unfortunately, today, there are no 450 V half bridge drivers for these devices on the market. Therefore a dedicated floating driver circuit has been designed. To minimize the additional switching node capacity which is caused by the high side driver it is located on the top side of the PCB while the switches are located on the back side of the PCB. This will also result in the shortest possible traces between the driver and the gates.
Power and drive signal are coupled to the circuit by very small transformers with very low capacity between the primary and secondary windings: 1.2 pF for the power transformer and

0.2 pF for the signal transformer. To match the delay times of the drivers the low side drivers are identical to the high side drivers.
Similar as in the buck stage, the inductors are designed for very low parasitic capacity (2 pF) in combination with an extremely high Q factor (1000) at 1 MHz.

4. Thermal management

Both GaN and SiC devices can withstand higher temperatures than silicon, but the performance decreases with temperature. Therefore it is decided to limit the maximum junction temperature to approximately 90 °C. This is achieved as follows:

- The GaN devices are mounted on the back side the PCB.
- The heatsink consists of a 36.5 x 36.5 x 2 mm^3 copper plate with 600 vertical copper fins (Ø 0.8 mm x 11.5 mm) on one side.
- Several 2 mm wide and 0.7 mm deep slots (corresponding to the position and the dimensions of the GaN switches) slots are milled in the other side of the copper plate.
- Additional slots are milled in the heatsink to isolate the solder pads in the corners of the PCB.
- The PCB is mounted directly to the heatsink with the switches sunk in the slots. The remaining (very thin) gaps are filled with conductive thermal paste (λ = 2.5 W/mK) and a high breakdown voltage (48 kV/mm).
- Since the silicon substrates of the GaN switches are good thermal conductors the increase of the junction temperature above the heat sink will be well below 20 degrees °C.
- A micro motor is mounted in between the pins which drives a 37 mm propeller close above the top of the copper fins. The motor is well ventilated and thermally isolated from the fins. Therefore it will operate just a few degrees above room temperature.
- Four 3 mm holes copper plate and the power PCB allows some cooling of the power inductors and EMC filters.
- Openings in the enclosure allow air to enter and leave the enclosure at well-defined places.
- The heatsink is thermally isolated from the enclosure

This results in a maximum heatsink temperature rise of 45 °C above ambient (at 100 W dissipation). The temperature of air that exits the enclosure is approximately 25 degrees above ambient. Since the heatsink is thermally isolated from the enclosure, the enclosure remains well below 60 °C.
The losses of the electrolytic capacitors decrease with temperature. Therefore these are mounted on the bottom of the inverter and are poorly ventilated. This allows the capacitors to heat themselves to approximately 70 degrees °C.
The first endurance tests look promising: there is no noticeable degradation of the cooling capacity after 200 hours of operation.

5. Electromagnetic Compliance (EMC)

At maximum power the HF-switches are hard-switched most of the time. To obtain acceptable efficiency at a switching frequency of 1 MHz very high dV/dt's (well above 50V/ns) are used. Without special measures this will produce noise well into the GHz bands.
The following measures are taken to keep EMC as low as possible:

- All switches and diodes have no reverse recovery. Normally this is a serious source for EMI noise.
- There are only two nodes with high dV/dt. These are kept as small as possible.
- The inverter uses two PCB's: one for the power stages and control and one for EMC filtering. These are separated properly to minimize capacitive coupling. All connecting wires between these PCB's have the return wire for the current next to it, so these connecting wires can be embedded in common mode beads.
- Special care is taken to suppress radiation of the winding of the high Q-inductors (of which one side is connected to the HF-switching node).
- Only small openings are used in the metal enclosure. This blocks high frequencies.

The filter components are mounted on the same PCB as the three buffer capacitors (but on the other side).

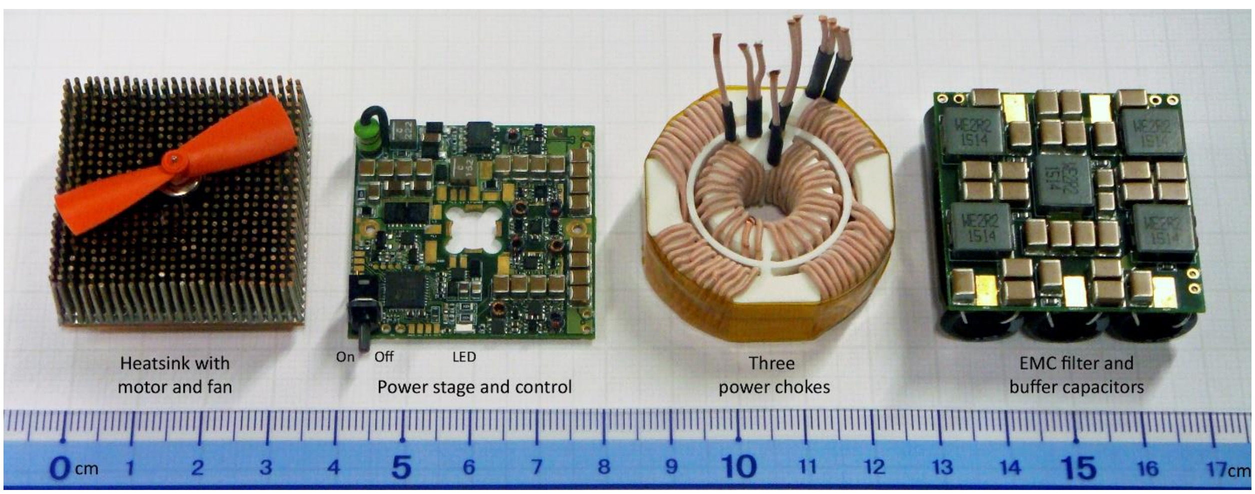

Figure 2: Photo of main sub-assemblies before final assembly (on 5 mm paper)

6. Acknowledgments

OKE-Services would like to thank the following people for their support:

- **Steve Colino** and **Renee Yawger** from EPC for arranging samples of the GaN switches
- **Marcin Kącki** from DTW for arranging and re-shaping the special ferrite cores
- **Ron Hoekstra** of iQue for implementing the firmware.

Appendix:
Biographical information

Team OKE-Services consists of one man only: Henk Oldenkamp of the one-man company OKE-Services.

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Henk Oldenkamp was born on 23rd of July 1957, and received his M.Sc. degree from the Technical University Eindhoven, Faculty of Electrical Engineering in 1988.
By then he was already running his one-man company OKE-Services, which he started in 1984.

Initially he mainly focused on wind energy, but in 1993 he switched to developing electronics for photovoltaics, especially AC-module inverters. The OK4E/OK4U was rather successful and over 100 000 units were sold, mainly in the Netherlands. Unfortunately NKF, the company that produced and distributed the micro-inverter decided to terminate its activities in the field of photovoltaics in 2003. Even today the OK4E/OK4U is still the smallest utility interactive inverter which was commercially available on the market.
Nevertheless, Henk continued his efforts to develop a cost-effective, high efficient AC-module inverter, which resulted in the OK4All. In 2009 the design of the OK4All was sold to SMA in Germany. Since then Henk has been consulting SMA.
Some of the other products developed by Henk Oldenkamp are the PV-watchdog, PV-wirefree and OKE's active bypass diode.