Team Name: Tommasi – Bailly	Team Registration Code: 545-Av2Efl-58482

Technical Approach

Abstract *– For the Little Box Challenge we present a 13.9 in^3 inverter having 144W/in^3 power density. The key elements that enabled us to achieve this are:*

- *switching frequencies in the range of 100-1000 kHz*
- *planar inductor coil PCBs with integrated GAN 650V E-HEMT devices, drivers, heat sinks*
- *integrated planar magnetics*
- *forced air cooling*
- *boundary conduction mode (BCM) bidirectional step-up/down converters*
- *ripple mitigation using MLCC ceramic capacitors on an intermediate high voltage bus*

Our new design has a volume of 13.9 in^3 and a power density of 144W/in^3. We only had 3 months to complete it. In our previous Technical Approach we had presented a lower density 122W/in^3 device designed to meet the 5mA ground leakage limits defined in March 2015; as recommended, we included in an appendix the description of our more compact approach based on the relaxed 50mA ground current redefined in June 2015.

In order to achieve high power density, we employed several techniques:

Modularity

We adopted a simple principle: the fewer components the better. Our design uses highly integrated bidirectional step-up/step-down converter modules. Each of these half-bridge modules (HBM) is a multilayer PCB integrating a planar inductance coil with two 650V GaN E-HEMT devices by GaN Systems, including gate drivers and copper heat sinks. Fig. 1 below shows the layout of our HBM modules, with the ferrite removed.

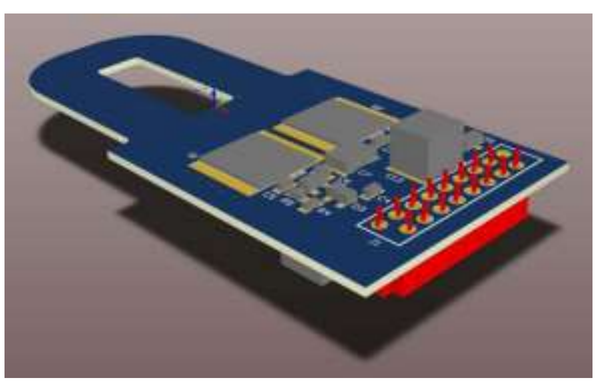

Fig. 1 – HBM layout

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Integrated planar magnetics

We experimented with tape wound inductors and litz wire, but at frequencies as high as 1MHz these were not satisfactory. Planar coils built using 8 layer PCBs were the ideal solution for us. We place these coils in their respective ferrite cores as far away as possible from the gap, to avoid copper losses induced by fringing. We thus occupy a small percentage of the available winding volume, but this leaves air space to blow cool air onto coils, cores and FETs.

The ferrite cores for the two step-down sections use 2 E-cores and a plate; the step-up section uses a single E-core and a plate. We combine all cores into a single integrated magnetics block.

We ran magnetic simulations to predict losses and find the ideal form and placement.

Forced cooling

A 35mm fan forces air through the ferrite cores, over the planar coils and onto the FET heat sinks. The magnetics have a lot of unused air space (see above), facilitating forced air cooling.

BCM

Boundary conduction mode (BCM) implies that the circuit achieves soft switching without any added inductors or MOSFETs. There are disadvantages, such as higher peak current and variable switching frequency, but at the same time BCM means reduced parts count and therefore, volume reduction. The control system keeps the frequency within 300 to 1000 kHz.

Fast wide bandgap devices

Higher switching frequencies require suitable FETs. GaN device have turn-off times far lower than SiC devices or other available MOSFET technologies. We selected GS66508 devices from GaN Systems.

Active ripple mitigation

Single-phase inverters typically use large, short-lived electrolytic capacitors to filter the input ripple directly on the DC input lines.

Our approach is to let the ripple mitigating capacitors work at higher ripple voltage on an intermediate voltage rail fed by a step-up regulator: deliberately increasing the voltage swing on the capacitors means that a much smaller capacitance can achieve the same swing in energy ($\frac{1}{2} CV^2$) as a much larger one undergoing a narrow voltage variation.

The control system sets the amount of swing of the caps (proportional to output power) and ensures that the device functions at constant power.

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Ceramic capacitors

MLCC SMD caps are far denser than film capacitor. We compared the volume of a 55uF 450V polypropylene film MKP capacitor (78 cm^3) with an equivalent bank of 2.2uF 450V MLCC capacitors. Due to nonlinearities and voltage-dependent capacitance, we had to triple the nominal capacitance of the MLCC bank to obtain comparable ripple canceling; despite this, we had a 6-fold increase in energy density compared to film (under $12cm^{3)}$. We rejected electrolytic capacitors due to their poor performance with respect to current ripple.

Our current design uses 160 MLCC capacitors of 1uF 630V, from TDK.

Highest practical switching frequency

Using Ferroxcube planar cores in 3F4 high frequency ferrite with planar PCB coils and fast GAN devices enabled us to function reliably up to 1MHz, reducing the value of capacitors and inductors and, therefore, volume.

3D printed polyamide support structure

In order to fasten and package together the HBMs, ferrite cores and fan, we use a nylon structure produced by 3D printing. Two side-PCBs hold the entire structure together mechanically; we placed capacitors and tracks in order to fill any unused space, while leaving certain areas clear to prevent disrupting airflow or magnetic flux.

EMI filter

We use an EMI filter consisting of common and differential mode chokes, and X and Y ceramic capacitors. The higher switching frequencies make it possible to use smaller components; for the common mode chokes, we used nano-crystal toroid cores from Würth.

Topology

Our circuit (see fig. 2 below) consists of a BCM step-up converter driving the intermediate ripple-mitigating voltage bus, followed by dual BCM stepdown converters and an unfolding bridge, driving the AC output in a split phase configuration.

The converters share a common positive supply. The step-up BCM converter (Q1 Q2) creates an intermediary negative voltage bus V(C2) connected to a bank of 160 x MLCC 1uF 630V capacitors C2, which is allowed to swing within the limits of the 400-450V supply voltage and a safe value for the GAN devices, around 640V. At full power, the maximum available voltage swing is used. As discussed above, the deliberately high “ripple” makes the capacitor bank act as an energy store that can mitigate or cancel ripple on the DC input.

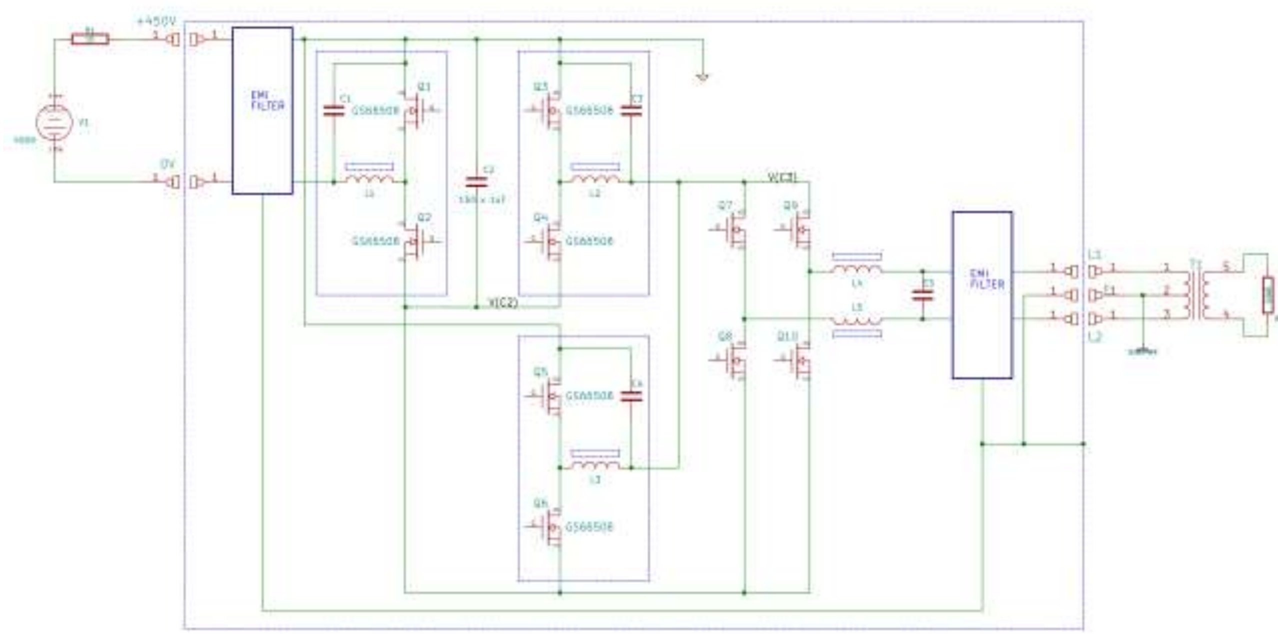

Fig. 2 - Simplified schematic

This voltage bus V(C2) feeds the two step-down BCM converters (Q3 Q4 Q5 Q6) that generate a rectified 240V_{rms} sine wave. Below 1kW, half the drivers are off, increasing efficiency.

The unfolding bridge Q7 Q8 Q9 Q10 creates the desired AC output waveform. At voltages close to the zero crossing of the AC output, in order to keep distortion low, the step-down converters are kept operating at a fixed low voltage, and the unfolding bridge is modulated.

Our device, measured according to the specification, has a volume of 13.9 in^3, which at 2kVA means a power density of 144 W/in^3.

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Appendix A: Biographical Information

Primary Contact: Michele Tommasi, mike@tommasi.org, +33-609670940

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Mike Tommasi has been active in engineering for 40 years, from power circuitry to professional audio to microprocessor based control systems to renewable energy to smartphone apps. Raised in Venice, Italy, he studied in Canada at Loyola College and McGill University, and while studying obtained his first patent for an audio sound effect system. In the 1980s, he developed some of the earliest touch sensitive graphics terminals for industrial use, and saw them adopted in the pulp and paper industry in the USA.

For several years, he was involved in bus-based computer systems such as G-64, VME, CompactPCI and ATCA. Later he switched to telecommunications infrastructure and more recently to renewable energy systems. He has just completed the development of a web app for smartphones called CriteeQ. Mike lives in southern France and is a member of the IEEE; a cofounder of the Slow Food association in France, he also enjoys writing about food and wine on blogs and in the specialized press.

Additional Team Member: Alain Bailly, ab.consult@free.fr

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Alain Bailly is an expert in applied mathematics and electronics engineering; having begun designing electronics at age 14, he later graduated from the prestigious Ecole Centrale (Paris). He has been dealing with switching power conversion ever since. Alain spent most of his industrial career in various electronics fields including high reliability space applications (Matra) as well as power semiconductors definition, marketing and testing (STMicroelectronics).

He is now active as an electronics consultant specialized in product development. He is also completing the development of a magnetic induction based slotless car racing set with DSP-driven steering and control. Alain lives in Southern France.