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Optimized Rad-Hard DC/DC Converters for HEP Applications

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DC/DC converters that are tolerant to high magnetic fields and radiation are needed to improve the power distribution scheme of High Energy Physics (HEP) experiments. This paper presents 2 topics: firstly, an optimised rad-hard production-ready module for 48V to 5V-12V conversion (including) a custom PCB air core inductor, and secondly the outcome of a R&D program for developing next generation DC/DC converters. In this context, a framework for analysing, optimizing, and comparing different conversion topologies has been developed. Furthermore, the most promising topologies for input voltages up to 48 V (Buck, 3-Level Buck, and Berkeley Series Capacitor) are experimentally validated.

Summary (500 words)

The High Luminosity Large Hadron Collider (HL-LHC) experiments at CERN necessitate DC/DC converters capable of withstanding high magnetic fields and high radiation doses. Due to this harsh environment commercial, automotive, and aerospace grade silicon components cannot be employed.
This paper focuses on a conversion stage stepping down from 48 V to 5 V, split into two parts: the development of a production-ready rad-hard module that can be distributed to the HEP community, and the research and development for next generation of DC/DC converters.

A highly efficient and compact rad-hard buck module has been developed. The module, shown in Figure 1, occupies only 5280 mm^3 (24 x 55 x 4 mm) and utilizes an M.2 PCI Express connector for easy integration. A custom air-core PCB inductor is optimized specifically for this module. The main advantages of PCB inductors are the low NRE for custom designs and fast production times.
Figure 2 shows the efficiency curves for the optimized buck module, for both the air-core PCB inductor and a low-profile ferromagnetic inductor. These curves show that despite the low volume of the buck module, efficiencies of over 90% can be achieved. If there are enough request from the HEP community this module can be put in production and distributed to users.

In the framework of the EP funded WP5.2 R&D program, for the next generation of DC/DC converters several converter topologies are qualitatively compared. It is discussed and shown that, since no ferromagnetic components can be used, topologies with transformers or coupled inductors will be disadvantageous if the converter's volume should be minimized. Furthermore, it is discussed that topologies with a single magnetic component and/or multiple voltage levels are likely preferred.
Quantitative analysis, optimization, and comparison of selected topologies are performed using an object-oriented framework, which is shown in Figure 3. In this framework classes are created for various converter components (e.g., power devices, inductors, capacitors etc.). Furthermore, conversion topology classes are created that are composed of these components. An overarching multi-objective optimization routine is then established that minimizes losses and PCB area for these topologies.
The optimization routine is then executed for a conversion stage with an input voltage of 48 V, an output voltage of 5 V, and an output current of 6 A. The variables of the optimization include, but are not limited to, the switching frequency, the size(s) of the inductor(s), the capacitor type(s) and size(s), and the selection of GaN power devices. The results (pareto fronts) of the optimizations for the PCB area and average losses (over the whole operating range) for various converter topologies are given in Figure 4.

Based on qualitative and quantitative analyses, three conversion topologies are chosen for experimental testing: Buck, 3-Level Buck, and Berkeley Series Capacitor converters. Prototypes are built using commercial GaN power devices and an STM32 microcontroller. This paper will detail the experimental results of testing the prototypes, which are shown in Figure 5. Furthermore, the experimental results are compared to the results of the optimization routine (showing strong congruency).

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