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Optimized rad-hard DC/DC converters for HEP applications

Nils H. van der Blij,[*] Sokratis Koseoglou, Georgios Bantemits, Giacomo Ripamonti and Stefano Michelis

CERN,
Espl. des Particules 1, 1211 Geneva 23, Switzerland

E-mail: Nils.Hans.van.der.Blij@CERN.ch

Abstract: The development of 48 V compatible DC/DC converters that are tolerant to high magnetic fields and radiation helps to reduce the cost and weight of the cabling, power supplies and cooling of High Energy Physics (HEP) experiments. In this paper, a new, optimized and compact bPOL48V module is presented aimed at 48 V to 5–12 V power conversion. This new module, which is available for purchase and as a reference design, reduces the size by 93% compared to previous designs while exhibiting similar efficiency. Furthermore, a framework for optimizing and comparing converter topologies is also introduced, which identifies the 3-level buck topology as a promising topology for future research and development. Moreover, experimental validation of different optimized converters is also provided. The experimental results show that the 3-level buck topology is promising for 48 V to 5 V conversion stages, and that the Berkeley buck topology is promising for the development of 48 V to 1 V conversion stages.

Keywords: Radiation-hard electronics; Voltage distributions

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[*]Corresponding author.

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Contents

1 Introduction

Traditionally, the on-detector low-voltage electronics are directly powered from power supplies positioned many meters away, or powered from a 12 V bus that is locally stepped down via two power electronic stages [1, 2]. In order to reduce the power dissipation, cost and weight of the cabling and power supplies, it would be advantageous to increase the bus voltage to 48 V [3]. However, this would require new compatible DC/DC converters capable of withstanding the high magnetic fields (4 T) and high radiation doses (hundreds of MRad) of HEP experiments.

Previously, a conversion stage was introduced, capable of stepping down the voltage from 48 V down to 12 V [4, 5]. However, these (previous) implementations, named "bPOL48V", were not able to step down the voltage below 12 V, were rather bulky, and were not easy to cool due to the hovering air core inductor design.

This paper mainly focuses on three topics. Firstly, a new compact and efficient bPOL48V module is presented that utilizes the same active components as the previous design. Secondly, an optimization framework is created and utilized for the comparison and selection of power electronic converter topologies for future developments. Lastly, prototypes are developed and tested in order to verify the results of the optimization framework.

2 Efficient and compact 48 V conversion stage

The bPOL48V design is based on a buck topology, the main advantages of which are its simplicity and low number of active devices [4, 5]. The main components of the bPOL48V design are the controller (named GaN_Controller), commercial GaN power stage and the filtering components.

2.1 Preceding high-current bPOL48V design

The first reference design of bPOL48V is shown in figure 1 on the left, and its efficiency curves for an output voltage of 12 V are shown in the same figure on the right. This converter reference design has a size of 43 mm × 49 mm × 27 mm, or a volume of 56889 mm^2, including the air-core inductor and connectors. The custom 220 nH air core inductor has been built using Litz wire on a 3D printed toroidal plastic core.

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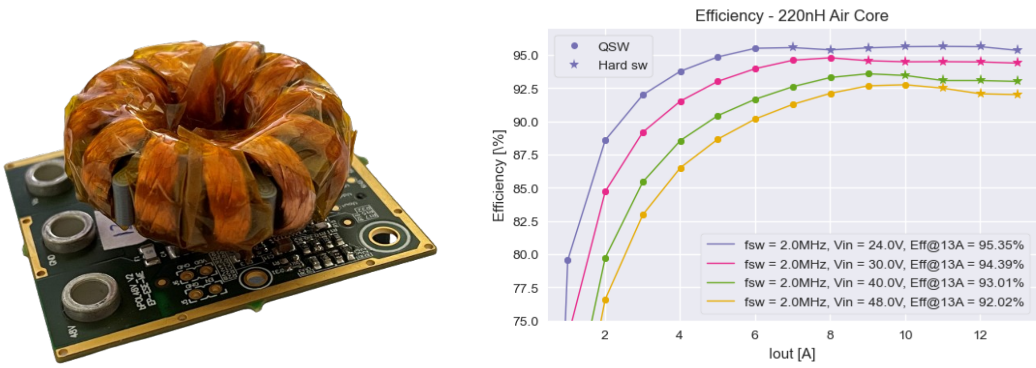

Figure 1. Preceding high-current bPOL48V design and its efficiency for an output voltage of 12 V. In this figure QSW indicates the soft switching region.

The GaN_Controller and GaN power stage were extensively tested for radiation tolerance with respect to Total Ionising Dose (TID), Displacement Damage (DD) and Single Event Effects (SEE). Overall, both the controller and GaN power stage showed no significant degradation due to radiation up to 228 MRad for TID, 88.8 MeV·cm^2/mg LET for SEE, and 2.23·10^{14} p/cm^2 for DD [4, 5].

2.2 New compact and efficient bPOL48V module

Using the same core components, a compact and efficient buck module was developed for output voltages ranging between 5 V and 12 V. Consequently, this module is compatible with a conventional 3-stage power distribution scheme and future 2 stage distribution scheme, where a second stage (iPOL5V) steps down the voltage from 5 V [6]. This compact module, shown in figure 2 to the left, utilizes M.2 PCI Express connector for easy integration and accommodates a custom designed and optimized 250 nH air-core PCB inductor. This module achieves a total height of only 3 mm by utilizing a cutout in the module's PCB and connecting the PCB inductor via castellated holes (present on both PCBs). Moreover, the module occupies only 24 mm × 55 mm × 3 mm, or a volume of 3960 mm^2, including the air-core inductor and connector. Please note that this is a 93% decrease in volume compared to the previous reference design.

Due to the cutout in the PCB, this module is only compatible with the developed custom PCB inductor. Therefore, a second "ferromagnetic" module without a cutout was developed in order to improve compatibility with other (ferromagnetic) inductors. This module, which is shown in figure 2 in the middle, has the same surface area of the previous module (24 mm × 55 mm), but its height and efficiency are highly dependent on the inductor that is used for the design. In this paper, on the ferromagnetic module, a 1 µH inductor (MPX1D1264L1R0) is integrated.

Experimental results for the efficiency of both modules are shown in figure 2 on the right. From this figure it is seen that, even though the maximum current is limited to 10 A (due to thermal constraints), only around 2 % is lost in efficiency compared to the previous reference design. Besides these differences, the different designs perform identically.

Overall, these results show that the developed modules are highly compact while minimizing the effect of the reduced volume on their efficiency. These modules are available as reference designs, or they can be purchased and plugged into the target application.

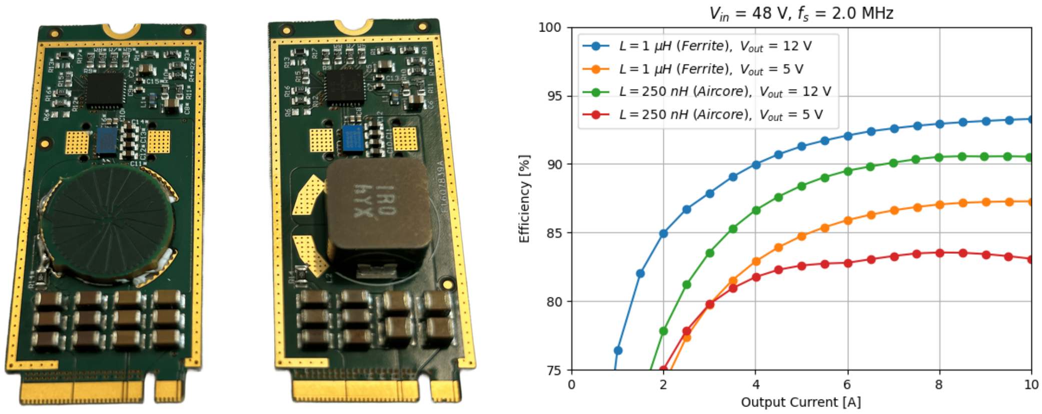

Figure 2. Compact and Efficient bPOL48V modules that are optimized for PCB inductors (left) and ferromagnetic inductors (middle), and their efficiencies (right).

3 Optimization framework for conversion topologies

In order to compare and select power electronic converter topologies for future developments, an optimization framework was developed. This optimization framework utilises object oriented programming and pymoo (a Multi-Objective Optimization library in python) to find pareto optimal solutions for converter designs [7]. This paper focuses on optimizing a conversion stage from 48 V to 5 V with an output current of 6 A, and a voltage ripple on the input and output of less than 1 %. The optimization algorithm can change which GaN devices are used, the inductance and size of inductors, the capacitance and size of capacitors, and the switching frequency. The optimization algorithm also automatically designs a custom PCB air-core inductor for the given inductance and size (similar to the inductor from the previous section).

Before analyzing and comparing several converter topologies using the optimization framework, certain topologies can be excluded via qualitative discussion. Firstly, the losses in the magnetic components form (one of the) primary sources of losses since air-core components need to be used. Furthermore, the coupling coefficient of air-core magnetic components is relatively low. Therefore, since they will have poor performance, topologies that utilise more complex magnetic components such as transformers or coupled inductors are excluded from consideration. Secondly, switched capacitor and resonant style conversion topologies are generally not considered because they provide only limited control over their voltage gain (and thus output voltage).

Although other topologies can also be implemented in the optimisation framework in the future, in this paper the buck, buck-boost, double buck, 3-level buck and interleaved buck topologies are compared. The double buck topology here refers to two cascaded buck converters that produce the output voltage in two stages, while the other topologies are commonly known topologies [8]. The optimisation (loss and area minimisation) results for these different converter topologies are shown in figure 3.

From figure 3 it is clear that, from the investigated topologies, the 3-level buck topology is more efficient as long as the available surface area is more than 280 mm^2. Furthermore, the buck converter performs reasonably well due to its low complexity and low component count (allowing for a larger inductor).

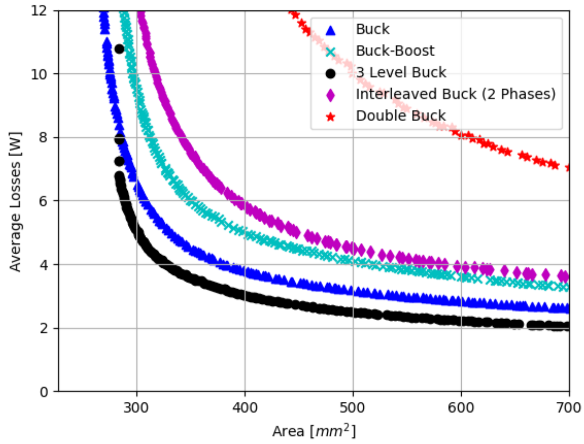

Figure 3. Optimization results comparing different topologies for stepping down 48 V to 5 V.

4 Experimental verification

To validate the results from the optimization framework (presented in the previous section) and to provide a more thorough topology comparison, several converter prototypes were built. These converter prototypes form (non-rad-hard) reference designs by utilising commercial GaN switches, gate drivers, and a STM32 microcontroller. The STM32 microcontroller measures local voltages and provides controlled Pulse Width Modulation (PWM) signals for each prototype's gate drivers.

Prototypes for buck, 3-level buck, double buck, 5-level buck and Berkeley buck converters are shown in figure 4. In this case, the double buck converter references to two cascaded buck converters, and the Berkeley buck converter's topology is given in figure 6 on the left [9].

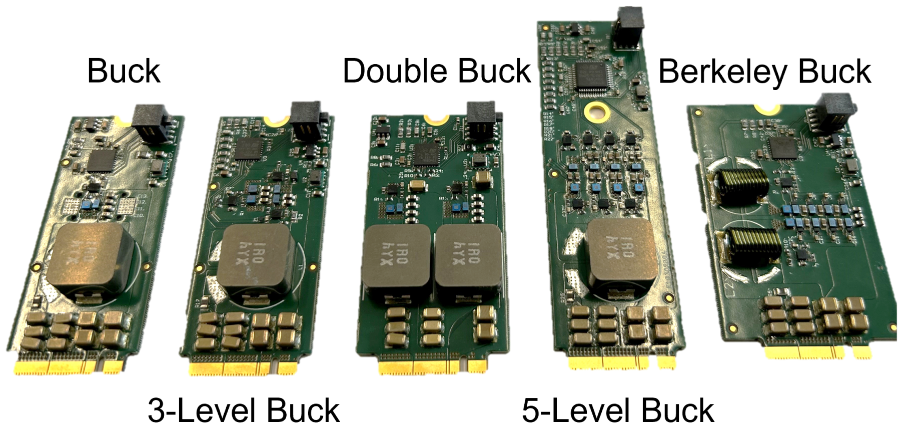

Figure 4. Non-rad-hard converter topology prototypes using commercial components.

Each individual prototype's switching frequency was optimized for efficiency via trial and error. The resulting efficiency curves for the prototypes is shown in figure 5. In these results the Berkeley buck converter prototype is not shown, as it is not as suitable for stepping down to 5 V due to the choice in the number of levels (together with duty cycle limitations).

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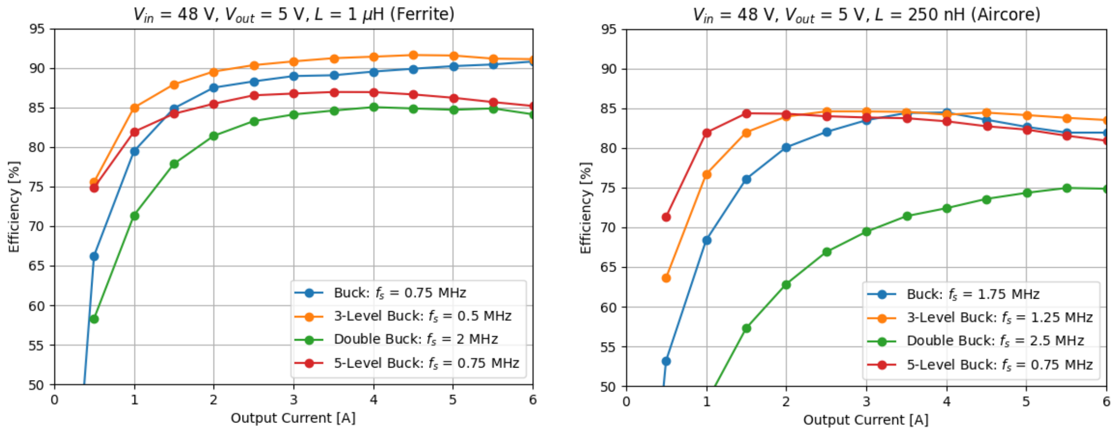

Figure 5. Efficiency of the converter topology prototypes with ferromagnetic inductors (left) and aircore PCB inductors (right), at their optimal switching frequency.

Ideally, a single conversion stage should step down the voltage from 48 V down to the final voltages around 1 V. In reality most conversion topologies are limited by a practically achievable minimum pulse width (of around 40 ns). However, the 5-level buck converter and the Berkeley buck converter do not suffer (as much) from this limitation. Since the Berkeley buck topology is not a well-know topology definition its circuit is shown in figure 6 to the left.

Experimental results for the efficiency of these two conversion topologies are shown in figure 6 to the right. Please note that these results are very preliminary and highly unoptimized. Please note that the dip in efficiency at 3 A is caused by a transition into the hard switching region. However, it shows that such a conversion stage could be feasible and reasonable in the future, considering that otherwise two conversion stages are cascaded that each have an efficiency of about 70–80%, leading to an overall efficiency below 60%.

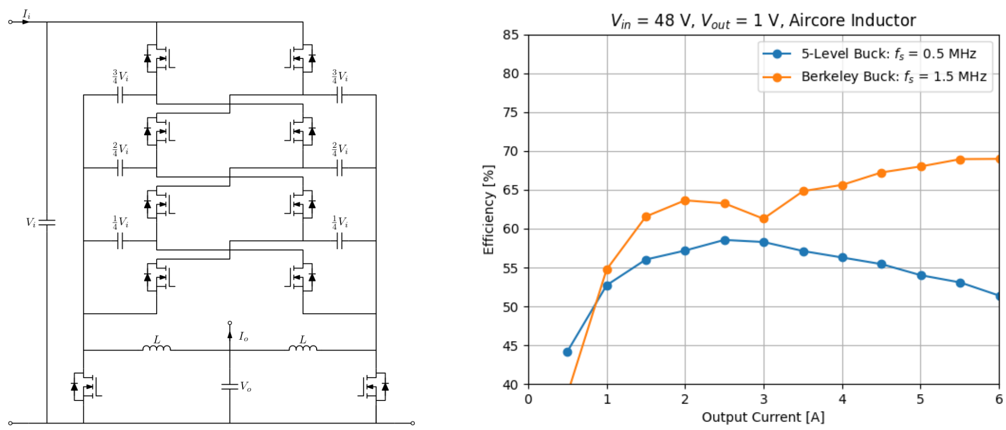

Figure 6. Preliminary experimental results for the efficiency of the 5-level buck and Berkeley buck prototypes when stepping down from 48 V to 1 V.

Overall, from the optimisation and experimental results it is shown that the 3-level buck topology is interesting for future research and development into a 48 V to 5 V conversion stage. On the other hand, the Berkeley buck topology looks most interesting for future research into a 48 V to 1 V conversion stage.

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5 Conclusions

This paper demonstrates the successful development of two compact, efficient and rad-hard DC/DC converters tailored for HEP applications. The new air-core bPOL48V module reduces the volume by 93% compared to the previous reference design, while maintaining high efficiency, making it a viable solution for power distribution environments with high magnetic fields and radiation. Furthermore, a optimization framework was developed that provides a robust tool for analyzing, comparing and selecting power conversion topologies for future developments. Moreover, several experimental prototypes were built to validate and extend the topology comparison provided by the optimisation framework. The optimisation and experimental results show that the 3-level buck topology and the Berkeley buck topology are the most promising topologies for future R&D. This research paves the way for the next generation of DC/DC converters that can meet the evolving demands of HEP experiments.

Acknowledgments

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