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DC-DC Conversion Powering for the CMS Tracker at SLHC

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DC-DC Conversion Powering for the CMS Tracker at SLHC

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Abstract

A tracker powering scheme based on DC-DC converters close to the detector modules can supply more power through thinner cables. This will allow to satisfy the increased power demands of tracking systems at the SLHC. This article describes the development of DC-DC converters for upgrades of the CMS pixel and tracking systems and addresses system integration issues.

Key words: CMS, SLHC Upgrades, Tracking Systems, Power Distribution, DC-DC Conversion

1. Introduction

Tracking systems based on silicon sensors require an efficient, reliable and low mass power distribution to the front-end electronics inside the detector volume. The total power consumption of the front-end electronics in the current CMS tracker amounts to about 30 kW. Although an attempt has been made to minimise the amount of material in the supply cables, allowing for cable losses similar to the front-end power consumption, these cables already fill up the available space in the cable trenches and constitute a significant fraction of the material budget inside the tracking volume.

Future pixel and strip tracking systems will most likely need even more power than the current systems. The channel count will grow due to the need for additional pixel layers and higher granularity in the whole system. Furthermore, expanded functionality, most notably additional logic to provide tracking information to the first level trigger, will require extra power. Significant power savings per channel can be achieved by moving to sub-0.25 μm ASICs. But even if this could be used to keep the total power roughly at the current level, the reduced supply voltage implies substantially increased supply currents. Since cable losses rise quadratically with current, significantly increased cross sections would be needed which neither fit in the existing cable trenches (actually it would be highly desirable to re-use the current cabling to the detector) nor are they acceptable inside the detector volume where the material budget should rather be decreased. Clearly, an improved powering scheme is needed.

The strategy is very simple. Since power P is voltage V times current I, a certain amount of power supplied at r times the voltage will require only $1/r$ of the current: $P = V \cdot I = (rV) \cdot (I/r)$. This will reduce the cable losses $P_{loss} = R \cdot I^2$ by a factor r^2 and allow to either supply more power through the same cables or preferably even to reduce the cable cross sections in order to save on material. Two quite distinct schemes of implementation of this strategy are under discussion [1]. In a *DC-DC Powering Scheme*, low-mass DC-DC converters are placed inside the detector volume. They derive the supply voltage V required by the front-end ASICs from an increased voltage rV at a correspondingly reduced current. In a *Serial Powering Scheme*, r detector modules are powered in series with a total voltage drop of rV at the current required by a single module. Shunt regulators have to be introduced in order to provide each module with the correct voltage and to be able to react to the failure of single modules in the chain.

The choice between these two schemes is not obvious. Compared to current tracking systems, DC-DC powering adds just one new component (the converters) with minor modifications to the rest of the system and without introducing new interdependencies. The switching noise of the converters, however, is a concern in this scheme. Serial powering avoids switching noise at the price of having many modules coupled in each chain, implying different ground potentials at each module as well as the need to introduce additional circuitry which keeps the voltage at each module constant under load variations in the chain and provides safety against single module failure. Neither in powering efficiency nor in its material budget is one scheme clearly better than the other. The CMS tracker Collaboration has chosen DC-DC Powering as the baseline for the tracker upgrade mainly because the changes to the well tested and understood current system design are minimal and factorisable. Since the R&D for DC-DC powering is still ongoing, serial powering is kept as a back-up.

2. DC-DC Converters

DC-DC converters are available in many different types. For a tracker powering system a step-down converter is needed which can be implemented in a low mass design. Inductor-based converters use a coil as an intermediate energy storage and can supply currents up to several amps, sufficient to supply one or even several modules. Capacitor-based converters charge a number of capacitors in series and discharge them in

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parallel. They are typically limited to a few 100 mA at most and are best suited to be integrated into the front-end ASICs, with external capacitors. There are more types like piezoelectric transformers which are still in an early R&D phase. The R&D work presented in this article is focussed on inductor-based converters. Mainly for material budget reasons, the most simple converter of this type, known as *buck converter*, has been chosen. Figure 1 shows the schematics. Transistors $T1$

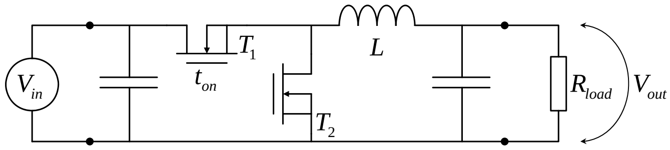

Figure 1: Simplified schematics of a DC-DC buck converter. Transistors $T1$ and $T2$ are operated by a pulse width modulation logic which is not shown.

and $T2$ are switched on and off in an alternating way such that current from the input side is only flowing for a time t_{on} within the period T, while the inductance L of the coil keeps the current flowing to the load even when $T1$ is off and $T2$ is on. The duty cycle $D = t_{on}/T$ therefore determines the conversion ratio for the current and correspondingly for the voltage. For a lossless converter $V_{out} = DV_{in}$. In this case, the conversion ratio r introduced earlier is simply $r = V_{in}/V_{out} = 1/D$ and typical values range from 2 to 10. The switching of the transistors is controlled by a pulse width modulation logic (not shown in the figure) which adjusts the output voltage to the desired value. A capacitor at the converter's input supplies the switched current while keeping the input current to the converter approximately constant. Another capacitor at the converter's output stabilises the output voltage. The remaining noise ripple at the converter output is driven by the current ripple at the inductor

$$\Delta I_L = \frac{V_{out}(1-D)}{Lf}. \qquad (1)$$

The switching frequency $f = 1/T$ has to be chosen as a compromise between noise ripple (falls with frequency) and switching losses in the transistors $T1$ and $T2$ ($\sim V_{in}^2 I_{out} f$). The latter appear during switching when there is both current and voltage across a transistor at the same time. For practical inductance values L of a few 100 nH the optimum frequency is typically in the range of a few MHz. Besides the switching losses, the efficiency $\eta = P_{out}/P_{in}$ of the converter is mainly determined by resistive losses in the inductor and the transistors as well as the equivalent series resistance of the input and output capacitors. Typical η-values range from 60 to 90%. Note that there will also be a current ripple at the converter input and that the converter represents a negative impedance load to its power supply. Both issues have to be addressed in a careful system design.

Given their operation principle, the application of DC-DC converters in a tracking system raises a number of issues. Switching noise could couple into the detector modules both conductively through the cables and through radiative electromagnetic coupling. The latter is of particular concern since air-core inductors have to be used (any ferrite would saturate in the 4 Tesla magnetic field inside the tracking volume). Air-core coils, however, besides being more bulky are also better antennas than their ferrite-core counterparts. Both mechanisms of switching noise coupling can lead to increased noise in the detector modules and thus reduce their signal-to-noise ratio. Radiation hardness is another concern since the converters will be exposed to severe radiation levels. For an integrated luminosity of 3000 fb^{-1} and at a radius of 20 cm the expected ionising dose is above 1 MGy and the fluence of charged particles corresponds to several 10^{15}1-MeV-neutron-equivalent/cm^2. Therefore, the MOS transistors in the DC-DC converters have to be at the same time radiation tolerant (which asks for thin oxides) and capable of switching rather high voltages of the order of 10 V, requiring thick oxides. The choice of the ASIC process is therefore not obvious. In order to save on the overall material budget, the converters need to be low-mass and also rather efficient. Any inefficiency will require additional supply cable cross-section and also an increase of cooling power. Evidently, the converters need to be of minimal size to ease integration close to the detector modules.

The R&D work presented in this article was started with commercial ASICs like Enpirion's EQ5382D [2]. This ASIC has a switching frequency of 4 MHz and can deliver up to 0.8 A. The maximum input voltage is 7 V. It was equipped with a custom made air-core toroid of about 6 mm diameter and 600 nH of inductance as well as other required passive components on a two layer PCB of $12\times19\text{cm}^2$. Figure 2 shows a photograph of this prototype, called *AC2*. Using these readily available com-

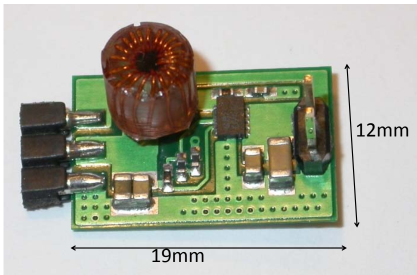

Figure 2: Picture of a DC-DC converter prototype (*AC2*).

mercial, non-radiation-hard converters it was already possible to optimise the design for low mass, low space, low noise and to perform initial system tests [3].

The development of a radiation tolerant ASIC is pursued by a group at CERN [4]. They have identified two candidate ASIC technologies which according to single transistor irradiation tests could be sufficiently radiation tolerant to survive radiation levels around the ones mentioned above for the full SLHC lifetime, with one technology being a bit better than the other. Prototyping in both technologies in underway. In the following first results of a prototype called *AMIS2* will be shown. While it was optimized for a switching frequency of 1 MHz, the frequency can actually be varied from 0.6 MHz to 4 MHz. It can supply up to 3 A and has a maximum input voltage of 12 V.

3. Lab Tests

The efficiencies of the converters have been measured for a fixed output voltage V_{out} as a function of input voltage V_{in} and output current I_{out}. In general, efficiency drops with increasing I_{out} due to ohmic losses in the inductor and the transistors and it drops with increasing V_{in} due to increasing switching losses and also ohmic losses due to the increased current ripple ΔI_L. For $V_{in} = 6$ V, $V_{out} = 1.2$ V, and $I_{out} = 0.8$ A efficiencies of 71% and 69% were measured for the commercial *AC2* ($f = 4$ MHz) and the radiation tolerant *AMIS2* ($f = 1.3$ MHz), respectively. The frequency dependence of the efficiency of the *AMIS2* converter has a maximum at the design value of $f = 1$ MHz, with a significant fall-off towards higher frequencies caused by increasing switching losses and also towards lower frequencies due to increased current ripple ΔI_L and corresponding losses.

For the measurement of the conducted noise spectrum the converter was powered through a Line Impedance Stabilisation Network (LISN). The output noise currents were measured both for differential and common mode with a calibrated pick-up coil and a spectrum analyser. As an example, Fig. 3 (a) shows the differential mode spectrum for the *AC2* converter. The switching frequency and its higher harmonics are clearly visible. The

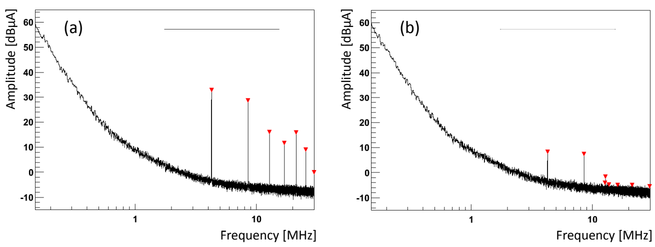

Figure 3: Output noise spectrum in differential mode of the *AC2* converter without (a) and with (b) a π-filter at the output for $V_{in} = 5.5$ V, $V_{out} = 1.3$ V, and $I_{out} = 0.5$ A.

impact of such a noise spectrum on a given detector system will depend on its frequency dependent susceptibility. Nevertheless, since the spectrum measurement provides the full frequency dependence and is much quicker than a full read-out test of a detector system it represents a valuable tool in the optimization of DC-DC converters. Figure 3 (b) shows the spectrum of the same converter equipped with a π-filter in the output. The conductive noise is much reduced.

The radiated noise of the converters has been measured on a scanning table equipped with a B field probe. It is dominated by emission from the inductor due to the current ripple ΔI_L. In order to minimise radiation a toroid inductor has been chosen. Still, the measurements show that the electromagnetic fields are not fully contained in the toroid and, in fact, have a multipolar shape. This is confirmed by simulations and seems to be caused by the first and last half turn of the toroid. This emission can be completely removed by wrapping the converter in a 30 μm thick aluminium foil. The contribution of this foil to the material budget is minor. For the time being this shielding option is not used but rather kept as a last resort if other optimisations finally should not lead to a sufficiently low noise design.

4. System Tests

Since read-out ASICs and module prototypes for the CMS tracker upgrade for SLHC are not yet available, the DC-DC converters have so far been tested with current CMS tracker hardware. This has proven to be a very fruitful system test-bed. Nevertheless, one always has to keep in mind that the response of the final system to the DC-DC converters might be different. The test system consists of a super-module (*petal*) of the current CMS tracker end-cap design, equipped (for these tests) with up to 4 silicon strip modules with a strip length of about 18 cm. The APV25 front-end ASICs have a shaping time of 50 ns and analogue read-out. They require two input voltages of 1.25 V and 2.5 V and correspondingly the modules are powered by two DC-DC converters. These converters are inserted between the module pig-tail cable and the *petal* mother-board and are therefore a few centimetres away from the module.

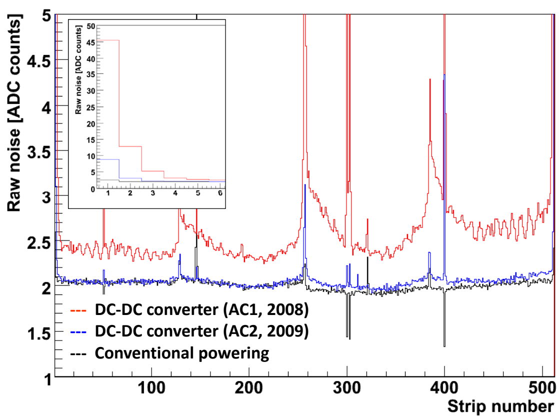

Figure 4: Noise vs. channel number for a strip module, powered either conventionally (lowest, black histogram) or by two different types of converters (upper, blue and red histograms). The inset shows a zoom onto the module edge channels.

Figure 4 shows the raw noise measurements for the 512 strips of a module. Raw noise is defined as the rms fluctuations of the measurements around the pedestal value for each channel. The black (lowest) histogram shows the noise when the module is powered conventionally, i.e. without converters. A few anomalous channels are visible which are due to wire bonding defects on this particular module. When the same module is powered with an early version of DC-DC converters (*AC1*), the red (upper) histogram is obtained. A significant noise increase is visible. Further measurements have shown that the "wing type" noise, increasing towards the APV25 edges, is caused by radiative noise while the "ripple" structure across each chip is caused by conducted noise. As can be seen in the inset in Fig. 4, the module edge channels no. 1 (and 512) are most sensitive to the converter noise. This is understood to be due to the on-chip common mode subtraction of the APV25, which is much less efficient for the module edge strips due to their capacitive coupling to the sensor bias ring. Therefore, the quadratic sum of the noise on the module edge channels is taken as a measure for the true noise in the system in order not to be fooled by the beneficial effect of the on-chip common mode subtraction.

The blue (middle) histogram in Fig. 4 shows the result with the more recent *AC2* converter. The noise increase is much reduced compared to *AC1*, but still visible.

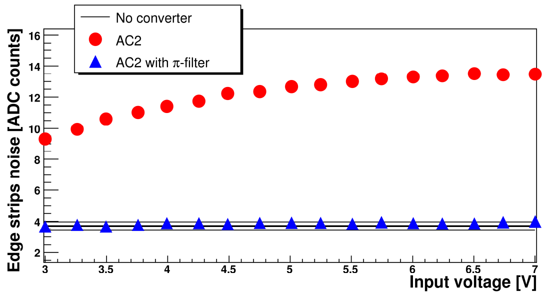

Figure 5: Module edge strip noise vs. DC-DC converter input voltage for *AC2* DC-DC converters without (red circles) and with (blue triangles) π-filter. Black lines indicate the noise level without converters.

The module edge strip noise with *AC2* is shown in Fig. 5 as a function of the input voltage as red circles. The noise increases with input voltage, as expected from Eq. 1. For comparison, the middle black line shows the noise level without converters, while the outer black lines indicate the spread of this noise in repeated measurements. The spectrum measurements shown in Fig. 3 demonstrated the benefit of a π-filter at the converter output. While the red circles in Fig. 5 correspond to the converter with the spectrum shown in Fig. 3 (a), the blue triangles are the result of a measurement with *AC2* converters with π-filter at the output, corresponding to the spectrum in Fig. 3 (b). The reduction of the spectral noise density by the π-filter has removed the excess noise in the detector system. This demonstrates that DC-DC powering of a tracking system is feasible without introducing additional noise. No shielding has been used in these measurements.

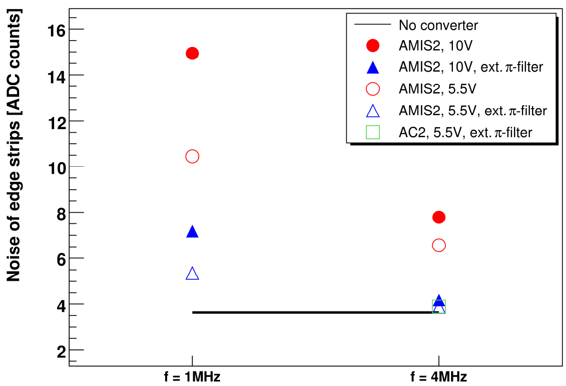

Figure 6: Module edge strip noise of the *AMIS2* converter at two different switching frequencies, for input voltages of 5.5 V and 10 V, with and without external π-filter.

Figure 6 shows the module edge strip noise for the radiation-tolerant *AMIS2* converter, at switching frequencies of 1 MHz and 4 MHz. When operated at the same switching frequency as *AC2* (4 MHz), very similar results are obtained. Without the external π-filter (red circles), a noise increase is visible which is more pronounced for the higher input voltage of 10 V. With this π-filter (blue triangles), the noise is down to the level obtained with conventional powering (black line) and *AC2* operated under the same conditions (green square). As mentioned above, the efficiency of *AMIS2* at 4 MHz is significantly lower than at the foreseen working point at 1 MHz. On the other hand, at 1 MHz the current ripple will be higher (see Eq. 1). This is in fact observed in the measurements shown in Fig. 6. At 1 MHz, even with the additional π-filters the noise is still higher than with conventional powering. Noise injection measurements on our test system have demonstrated that the increased noise at 1 MHz is not due to an increased susceptibility of the system at this frequency. Actually this system is more sensitive at 4 MHz. Therefore, the measurements of Fig. 6 show that increasing the switching frequency will decrease the system noise due to the decreased current ripple, at the price of increased switching losses, and vice versa. The additional noise observed with *AMIS2* at 1 MHz can be eliminated by increasing the distance between the converter and the module by a few centimetres. Also, no shielding has yet been applied in all these measurements. Further R&D has to determine the optimal implementation into the (future) detector system and the corresponding optimal choice of switching frequency.

5. Implementation into Detector Systems

The implementation of DC-DC converters into the detector systems will be quite different for the envisaged pixel upgrade and the possible later upgrade of the outer tracker. In the pixel system the converters will be placed onto the supply cylinder more than a metre away from the pixel modules and at a pseudorapidity of about ±4. Therefore, material budget, size and radiated noise are much less critical and from the results obtained so far this application of DC-DC converters looks well feasible. In the outer tracker, DC-DC converters will need to be installed near the detector modules and fully inside the acceptance of the detector. More R&D is needed on this part, as explained above. A case study for the (current) CMS tracker end-caps has shown in a full Geant4 simulation that the overall saving on material budget due to the use of DC-DC converters can be of the order of 8% [3].

6. Summary

DC-DC powering can supply the large currents at low voltage which are needed for pixel and strip tracker upgrades. Non-radiation-tolerant converter prototypes have been developed which can be integrated into a strip tracker system without introducing additional noise. First results with radiation-tolerant converters are promising.

References

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