ARE SWITCHING POWER SUPPLIES ACCEPTABLE FOR THE LIQUID ARGON CALORIMETER FRONT-END ELECTRONICS?*

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Abstract

Using high power density DC-DC converters followed by linear ripple attenuators could satisfy the power requirements of the Liquid Argon (LAr) calorimeter front-end electronics. A solution based on resonant charging DC-DC converters is discussed in term of noise characteristics, radiation and magnetic field tolerance, power efficiency and reliability.

1. INTRODUCTION

The Liquid Argon (LAr) calorimeter system to be used in the ATLAS experiment has complex readout architecture composed of almost 190,000 high precision, high dynamic and low noise electronic channels. The global layout of the detector is shown in Figure 1. The central cryostat contains the barrel electromagnetic calorimeter (EM Accordion). Each end-cap cryostat houses an electromagnetic calorimeter (EM Accordion), two hadronic end-cap calorimeters and one forward calorimeter.

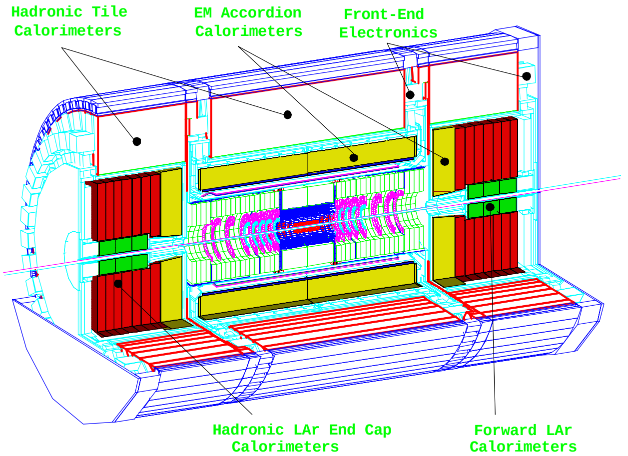

Figure 1. Three dimensional view of the LAr calorimeter system and the location of the front-end electronics

Figure 1 shows that the front-end electronics of the LAr calorimeter system is housed on the detector cryostats, in 64 “crates” attached to the cold to warm feedthroughs, in the crack between the barrel and end-cap calorimeters and at the rear of the end-caps. The front-end electronics, which process and prepare the detector signal for the “off detector” data acquisition system, is basically composed of preamplifiers, shapers, pipeline memory, digitisation and digital filtering. Different front-end crates are used for the three-calorimeter types. The majority of the crates serve the EM calorimeters. A typical crate contains 3584 readout channels densely packed in various boards. The power supply requirements for an EM crate are summarised in Table 1.

The large power consumption per crate, about 2.8 kW, combined with the limited space available in the detector area for the distribution of multiple low voltage power lines, jeopardise the use of linear power supplies located in the control rooms, i.e. far away from the detector, in favour of a solution which employs compact switching power supplies located in proximity of the front-end crate.

Table 1: EM crate power requirements

Pin	Voltage [V]	Current [A]
1,6,10	ground	
2	+ 6	180
3	+ 11	9
4	+ 6	24
5	+ 6	90
7	+ 4	105
8	- 4	150
9	- 6	12

2. “ON-DETECTOR” POWER SUPPLIES

Linear power supplies, which have been the traditional power sources in high energy physics experiments due to their stability and low output noise characteristics, have been generally mounted remotely from the detector location, in areas with no physical space and radiation environment constraints. This solution is based on the assumption that low or medium power must be distributed and/or that enough space is available for the power cables in the experimental area. Both assumptions are false for the Atlas LAr calorimeter system. With remote power supplies, the high power and the low voltages needed by the LAr read-out electronics, will require the use of massive water-cooled power cables which will not fit in the service area available for the detector. A different power supply system must be envisioned for the detector.

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The diameter of the power lines could be substantially reduced if high voltage lines are run from the control rooms down to the detector region, where the conversion from high to low voltage lines could take place. The power supply system could be indeed composed of two parts: a source of high voltage power to be located remotely and a source of low voltage power mounted “on-detector”, i.e. as close as possible to the front-end crates. In this solution each electronic crate will have a dedicated low voltage power supply properly dimensioned to fit into the space available.

The high voltage supply can be implemented by using standard commercial supplies, while the low voltage power source needs to be specifically designed for the Atlas LAr requirements. The “on-detector” supply will not be easily accessible during the experiment and consequently must be extremely reliable with built-in redundancy and provision for external monitor and controls. Moreover the supply should have low output noise, operate in magnetic field and be radiation tolerant. High power density and efficiency are also important. Table 2 summarises the power supply specification.

Commercially available low noise DC-DC converters can in principle satisfy most of the above requirements. Few converters are able to operate in magnetic and radiation environments.

DC-DC converter modules made by VICOR Corporation, Andover, MA 01810, USA, have been measured against specification and the results are summarised in the following section.

Table 1: Power supply specification

Input Voltage	300 VDC, with ripple +/- 10%
Output V/I	See Table 1
Output ripple	< 5 mV p-p @ 80% load
Environment	20 Gy/year and 10^{12} n/cm^{2}year B < 200 gauss
Redundancy	On each Voltage output
Efficiency	> 75% at 80% load
Cooling	Liquid – T operation ~ 25°C
Dimensions	350 x 360 x 130 mm^3

3. CONVERTER CHARACTERISTICS

3.1 Zero-Current-Switching

VICOR switching power supply modules make use of a patented resonant charging mechanism, called zero-current-switching (ZCS)[1]. Current flows through the MOSFET switch as half sine wave loops. The current is virtually zero both when the switch is closed and when it is opened. This result in a much less high frequency electromagnetic interference (EMI) than with conventional, fixed frequency switching power supplies. Any residual differential high frequency interference is easily removed by passive filtering.

VICOR converters can operate at frequencies in excess of 1MHz, with efficiencies greater than 80% and power densities of up to 7.3 W/cm^3. Two different series of VICOR DC-DC converter modules, with nominal input voltage of 300V, have been tested: the VI-200 series, or 1st generation modules, and the VI-300 series also called “2nd generation”. Both converter families share some common features such as availability of various standard programmable output voltages, stable regulation, current limit, internal overvoltage and overtemperature protection. All modules are parallelable with N+M fault tolerance and current sharing, and are phased-array-control compatible.

The second-generation modules contain a complete redesign of the control, magnetic, switching and packaging elements. The modules have also one-third the number of parts of the previous series [2].

The tested modules have output voltages from 5 to 12 VDC, similar to the ones of interest for the LAr power supply. For the VI-200 series the maxi size modules were tested, for the VI-300 series the maxi and mini size modules were tested.

3.2 Noise Characteristics

The virtually loss-less energy transfer from input to output achieved with the zero-current-switching technology greatly reduces the conducted and the radiated noise. The typical peak-to-peak (p-p) ripple noise of the VICOR converters for the output voltages of interest is ~ 100 mV on a 20 MHz bandwidth.

A large fraction of this noise concentrates above 10 MHz [3]. If a filter, the RAM module made by VICOR or an equivalent one, is added to the output of the converter, the noise reduces to less than 3 mV p-p. However questions remain to be solved in term of coherent noise contribution to the front-end electronics (FEB) noise due to the power supply. The issues to be proved are:

- Can the common mode high frequency switching signal be diverted from the input cables and preamplifiers on the FEB?
- Can the differential modulation at the switching frequency be reduced to a level where its noise contribution is negligible?

Measurements made using a VI-200 switching power supply on the most sensitive FEB supply, have shown that the coherent noise is ~ 56 µV rms compared to a random noise of 2.1 mV. The dominant coherent noise is a low frequency, almost sinusoidal ripple.

The additional low-voltage dropout regulators, foreseen for the FEB on-board filters, will virtually eliminate the already small residual ripple. No increase in coherent noise was measured by replacing linear power supplies with VICOR VI-200 DC-DC converters mounted in a MEGAPAC unit and followed by output ripple attenuators. A 0.5% noise degradation was measured with the ripple attenuators filter bypassed.

Similar results should be expected for the VI-300 converter family.

3.3 Magnetic Field Sensitivity

Units from the VI-200 and VI-300 series were operated at Brookhaven National Laboratory in a uniform magnetic field adjustable from zero to 10^3 gauss.

The parameters under measurements were the output voltage and the switching frequency of the device under test. The temperature of operation of the module was kept constant at ~ 50°C during the test through proper air-cooling. The results were identical for both families of converters and are illustrated in Figure 2 and 3 for a VI-300 module with 5V output.

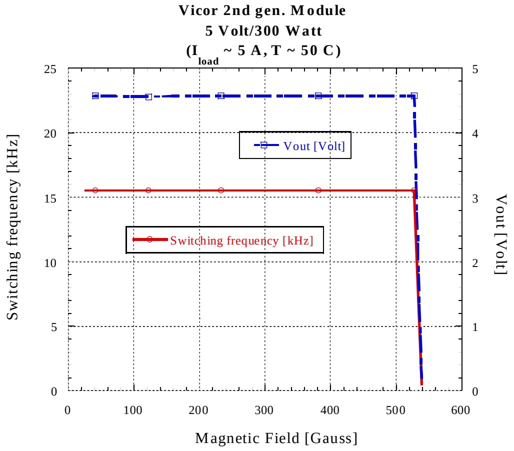

Figure 2. Magnetic field sensitivity with a field perpendicolar to the converter module width.

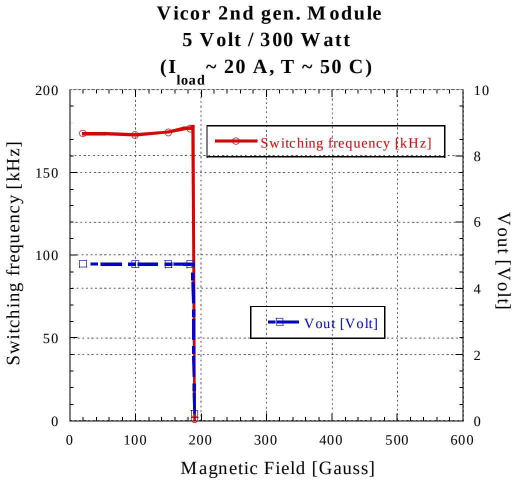

Figure 3. Magnetic field sensitivity with a field parallel to the converter module width.

The performance of the converter depends from the relative orientation between the magnetic field and the module under test. Figure 2 illustrates that, when the magnetic field is orthogonal to the width of the module, the converter operates with minor variation in output voltage and switching frequency, up to 520 gauss. At higher field the unit shuts off and does not restart until the magnetic field is decreased below the critical intensity. However the worst condition happens when the applied field is parallel to the width of the module. As shown in Figure 3, the converter operates correctly up to approximately 180 gauss, when it suddenly stops functioning. The failure is irreversible. A failure analysis performed by VICOR engineers found that one of the reset transistors of the unit was damaged by an excessive current flowing in the transistor during the main switch's off time, the increase in current was very likely caused by the saturation of the main transformer core. The relative orientation between the magnetic flux confined in the transformer core and the external magnetic field could also explain the observed not-isotrope behaviour of the converter. The magnetic field lines interfere with the operation of the transformers inside the VICOR module mostly when they are parallel to the transformer cores and if all cores are oriented in the same direction, such as in this case.

3.4 Radiation Tolerance to Neutrons

Converters from both VICOR families have been irradiated with 1 MeV neutrons at the University of Massachusetts, Lowell, USA. The parameters measured during the test were again the output voltage and the switching frequency of the converter. Through proper air-cooling, the module temperature was kept constant at ~ 50°C during the test. The results were very different for the two families of converters.

The VI-200 devices showed degradation almost immediately and failed in approximately 3 hours, at a total fluence of ~ 3×10^{11} n/cm^2. A second unit was subsequently irradiated at ten time lower fluence to exclude a fluence-dependent behaviour. This second unit also failed at the same total fluence. The damage was in both cases irreversible.

Failure analysis made by VICOR on the irradiated unit found that only the opto-coupler circuit in the converters had failed. Replacing the damaged opto-coupler with a new one successfully repaired both units. The standard otpo-couplers used in the VI-200 units are commercial circuits, with no special precautions taken to make them rad-tolerant.

Neutron irradiation results were very different for the "2nd generation" VI-300 converters. As illustrated in Figure 4, for a VI-300 module with 5V output, this family of devices were able to withstand up to ~ 1.3×10^{13} n/cm^2 without noticeable degradations. The control units in these "new" modules are made of bipolar integrated circuits without an opto-coupler circuit [4].

The measurements also indicate the presence of annealing effects related to the fluence. The irradiated converters showed a partial recovery after few days from the end of the test. However, no load current effects were measured.

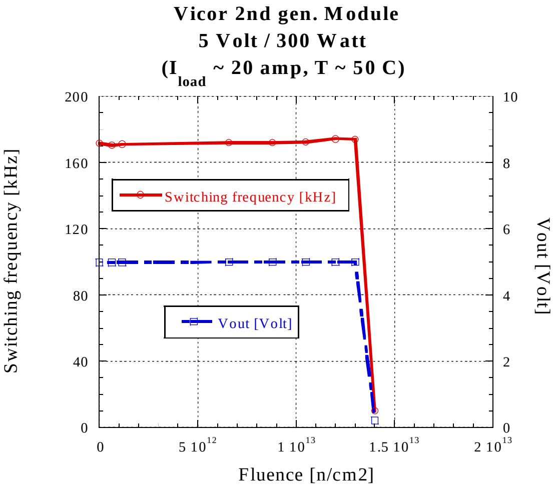

Figure 4. Radiation tolerance to neutrons, for a VI-300 converter with 5 V output voltage.

3.5 Radiation Tolerance to Ionising Radiation

Units from the VI-200 and VI-300 series were irradiated at Brookhaven National Laboratory with a ^{60}Co source. Figure 5 illustrates the typical response of the two families of DC-DC converters as a function of dose.

VICOR 1st gen. units can withstand 10^3 Gy (100 krad) with only a small decrease in output voltage (~ 1.5 %). Switching frequency and efficiency remain constant.

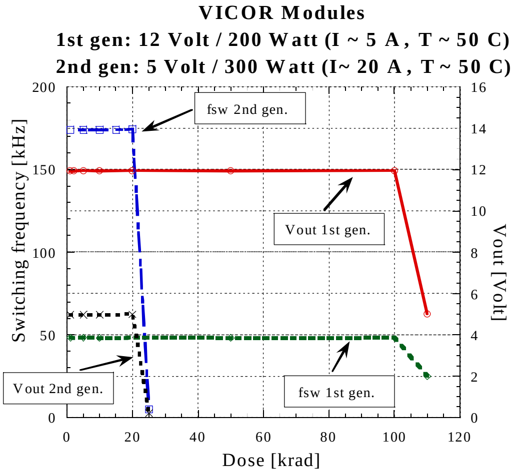

Figure 5. Radiation tolerance to ionizing radiation for a VI-200 and a VI-300 converter as a function of dose.

At higher doses the units are less efficient, the switching frequency and the output voltage decrease more and more. At $1.1\text{x}10^3$ Gy (110 krad) both characteristics reduce to ~ 50 % of their original value. No recovery was observed after the conclusion of the test.

Second generation converters stop functioning at ~ 200-250 Gy (20-25 krad). The failure happens rapidly with no annealing.

The different behaviour of the two families is still unexplained. VICOR has indicated that the 2nd gen units use a "proprietary" integrated power MOSFET (IPD), which differ from the one used in the 1st gen converters [4]. This MOSFET is an unpacked device bonded directly to the converter substrate. The VI-200 family uses a MOSFET device packaged in a TO-220 case. No layout compatibility exists between the two converter families. The different layout prevents from swapping the MOSFET transistors between families.

4. CHOICE OF THE CONVERTER

4.1 Second generation unit advantages

The VI-300 converter family has some advantages respect to the VI-200 family.

The 2nd-gen converters have higher power per unitary volume, have an improved transformer design which should reduce common mode noise [2], have on-third the number of part of their predecessors and meet the experimental magnetic field and radiation environment constraints. However some of the specification is barely met. The extremely high power-density of these units leaves some space to introduce some "shielding" in the full size power supply.

4.2 Reliability Issues

The main argument in term of reliability is the drastic reduction in number of components used in the VI-300 family (from ~ 200 components to ~ 35 components).

The improved quality screening of the components, the improved thermal management between the transformer and the baseplate, the reduced thermal impedance from the IPD junction to the baseplate have improved the unit mean-time-between-failure (MTBF) up to 2.5 million hours at 25°C.

Moreover the built-in protection and the current sharing capability allow N+M fault tolerance architecture.

The units will be anyway "components out of the shelf", a quality assurance procedure need to be defined to avoid properties variation from batch to batch. The quality assurance should be mostly performed at full size prototype instead that at single element level.

More measurements are needed to study single event effects (SEE).

4.3 Toward a prototype

A “six-voltages six-currents” power supply for a full front-end crate could be made by using 24 VICOR 2nd-gen modules in a configuration which will guarantee 100 % redundancy. Twelve converters will be active all the time while 12 units will be on stand-by and ready to start in case of a failure. The maximum deliverable current will exceed by 10 % the maximum nominal crate current.

Each voltage will have an input section to regulate the 300V DC input and an output section to achieve the output ripple specification. All the components used in this IN/OUT circuit will be evaluated for radiation tolerance. The converters will be mounted on three cooling plates and each cooling plate will dissipate the same power.

The limited magnetic field and ionising radiation tolerances of the tested modules will require additional “shielding” in the full size prototype.

The location of these “on-detector” power units must be carefully estimated to minimise environmental specification.

The supply control and monitoring electronics will be compatible with the slow-monitor system accepted by the LAr collaboration.

5. CONCLUSIONS

The commercial VICOR 2nd gen DC-DC converters, family VI-300, meet all the power supply specification for the LAr calorimeter system. However VICOR provides only the bare DC-DC converters. The modules need to be properly “packaged”; IN/OUT and control circuits must still be designed. An industrial counterpart interested in this application has been identified and a full size supply has been proposed.

Preliminary coherent noise measurements indicate that a power supply based on these DC-DC converters should be indistinguishable form a linear power supply, provided proper output filtering.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. VICOR, Application Manual 5th edition.
2. P. Mannion, “Second-Generation DC-DC Converters, Up Power Density And Lower Cost”, Electronic Design, September 2, 1997, p. 40.
3. R. L. Chase and others, “Can Vicor switching power supplies be used with the ATLAS EMCal front-end boards?”, BNL internal report, 1996.
4. K. Nardone, private communication.