DC-DC Converters

We explore the feasibility of powering the HEP detectors with 48 Volts DC and using local 48 V to 1.3 V (depending upon on the lithography of the front end electronics) local regulators located very close to the silicon chips. These devices are exposed to nuclear radiation and high magnetic fields. The numbers for the LHC are 10 – 100 Mega rads and 2 - 4 Tesla , while for ILC, they are 20 K rads and 6T.

Background

We have been involved with the ATLAS and CMS detector construction at CERN. Yale designed and constructed the low voltage regulator cards for the ECAL of CMS (see fig. CMS). The total numbers of cards is about 3.1K, each delivering 16 amps at 2.5 volts to -the front end 0.25 micron CMOS chips. The total current is 50 Kamps. The power supplies are located 30 meters away on the magnet yoke and supply 6.3 volts, with a loss of 1 Volt in each leg of the power cable. The regulator card input is 4.3 volts. The voltage across the regulators (LHC4913 made by S.T. Microelectronics) is 1. 8 volts for the minimum dropout voltage needed after 10 years of exposure to the radiation. These are linear voltage regulators in which all the input power is dissipated in the regulator package expect that which is delivered to the output. Linear regulators have low power efficiency but have low output noise and low EMI. Figure 1 is a layout of the DC powering system to make the point of the efficiency of delivering the power to the detector (in this case, only 40%).

After constructing the CMS ECAL power delivery system, we have been exploring alternate methods of delivering the power to the front end chips. For the ILC, the SiD detector will require 50 Kamps while the CALLICE detector will need 300 Kamps. The feature size of the front end silicon chip is migrating towards 65 nano meters, operating at ever lower voltages and higher currents. It is not clear yet if the power consumption of the system will decrease with the feature size.

To us the only feasible alternate power delivery system is the DC-DC switching converters that have very high power efficiencies, up to 95%. If we could supply 48 Volts and the local regulators convert it to say 2 volts for the chips, the result is a x24 reduction in the supply current and an x24 reduction in current conductors (copper or Aluminum) cross section. Less conductor cross section / volume may mean that more detector elements can be packed. The power dissipation will be lower due to the high conversion efficiency of the DC-DC switching regulators and the lower currents in the supply cables.

The main challenges are the radiation hardening of the elements of the semiconductors in the DC-DC regulator , the controller ASIC and the MOSFET switches. There are many groups who are experts in this field and we need to utilize their expertise. The other challenge is the operation in the high magnetic field which we shall address in this paper.

In 2005, we became aware of the work of Intel Corporation in integrating air core coils on their 90 nano meter CPU chips (ref. Intel 1-3). By using higher switching frequency air core coils can replace the ferrite coils used in the DC – DC converters. Their exploratory work tested operation at up to 480 MHz. There was an attempt made at NIKEF for the Atlas detector but it was not successful (ref nikef). Regulators with Air coils may have a few percent lower efficiency than coils with ferrite cores.

Introduction

Let us look at some DC-DC converter topologies

Charge pump: This utilizes charging a gang of capacitors in series to the input supply voltage and then connecting the capacitors in parallel across the load. The input to output voltage ratio is given by the number of Capacitors. It is limited to sub ampere currents but can output negative voltages.

Switch Mode: Synchronous Rectification. This is the most common technique being used for single chip implementation with internal or external MOSFET switches. PWD (pulse width modulation) is used to translate high input voltage to low output voltage by pumping charge into an inductor.

Resonant Switch Converters. Circuits with inductors and capacitors are used at or near resonance for transforming power to high voltages or higher currents. for higher voltages. Class-E RF amplifiers convert DC to RF at very high efficiencies.(Ref Sokal)

Other schemes: there are many variations based on the above to optimize zero voltage, zero current switching and topologies for high efficiencies. Our objective here is to focus on high supply voltage (48 V) with outputs in the range of 2 – 50 amps. This work is limited to using only air core coils.

Switch Mode: Synchronous Rectification.

A switched-mode power supply(SMPS), is an electronic power supply unit (PSU) that incorporates a switching regulator, an internal control circuit that switches the load current rapidly on and off in order to stabilize the output voltage. Switching regulators are used as replacements for the linear regulators when higher efficiency, smaller size or lighter weight is required. They are, however, more complicated and more expensive, and their switching currents can cause noise problems if not carefully suppressed..

Power converters are becoming increasingly commonplace in the electrical industry. Product manufacturers and suppliers of electrical equipment are demanding ever-increasing performance (i.e., higher efficiencies, lower output voltages, higher currents, faster transient response) from their power supply systems.

To meet these demands, switching power supply designers in the late l990s began adopting Synchronous Rectification (SR), the use of MOSFETs to achieve the rectification function previously performed by diodes. SR improves efficiency, thermal performance, power density, manufacturability, and reliability, and decreases the overall system cost of power supply systems.

In DC-DC Converters, the average DC output voltage must be controlled to be equal a desired level though the input voltage and output current may fluctuate. Switch mode DC-DC converters utilize one or more switches and an inductor to transform DC from one level to another. Generally the controllers work at a fixed frequency to make it easier to filter the output ripple. In Fig. SR, the Q1 and Q2 are turned on in a sequence to connect the inductor input to the Vinput or ground. The duty cycle is determined by the ratio of the output / Input voltages. A feed back from the output adjusts the duty cycle to keep the output voltage at the specified level. DC current always flows through the inductor.

When only Q1 switch is used and Q2 is replaced by a Schottky diode it is called a non-Synchronous Rectification. The diode keeps the current in the inductor flowing. There is more power loss in the diode due to the forward voltage than in the MOSFET

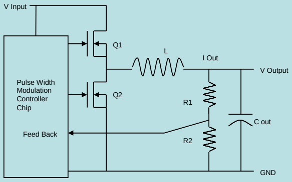
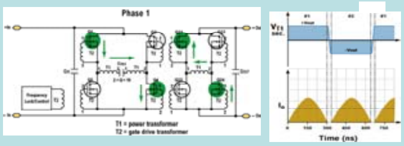


Fig SR **Synchronous Rectification**



RESONANT-SWITCH CONVERTERS (ref Mohan)

In certain switch-mode converter topologies, an *LC* resonant circuit can be used to shape the switch voltage and current to provide zero-voltage and/or zero-current switchings. In such resonant-switch converters, during one switching-frequency time period, there are resonant as well as nonresonant operating intervals. Therefore, these converters in the literature have also been termed quasi-resonant converters. They can be subclassified as follows:

(a)Zero-current-switching (ZCS) converters

(b) Zero-voltage-switching (ZVS) converters

Vicor Corporation is the leader in making Quasi resonant high density DC-DC converter modules. This is shown in Fig. Vicor. Their VTM /BCM power train has dual H bridges and extensive use of transformers. The input voltage range is 38-54 volts. Modules are available in various output voltages from 0.8 to 54 V. The match box size hybrid module delivers 200 watts with current limited to 100 amps maximum. The efficiency is above 94%.

Vicor has one ASIC controller ship, one power transformer T1 and gate driver transformer T2. The circuit Q is about 10 and they use proprietary techniques to use both ZCS and ZVS. The output noise and ripple is a few milli volts.

The VTM has no regulation circuitry in it. A 1% change in input appears at 1% change in the output voltage. This may be adequate for HEP applications if the 48 V power supply has remote sense capability. For other applications a pre regulator called PRM containing a buck boost regulator delivers 48 volts to the VTM from a 36-75 volt unregulated source.

Figure Vicor 2 is some oscilloscope pictures with PRM / VTM combination switching 30 amps at 4 volt output module ▪

Powering of Silicon Trackers

We look at the problem of powering the Silicon trackers in LHC and ILC detectors. Fig Stave shows a prototype mounted with 6 silicon Strips wafers each 4x6 cms sensor with readout chips. Each module is readout by 4 ASIC chips drawing about 1 amp @ 1.3 volts. The Stave may have 10 -30 modules depending upon its location in the detector. The Stave will draw 40 amps with 10 modules per Stave. All the control signals and power are routed via Kapton printed circuit board (PCB) lines.

There are two possible schemes;

4 Ampere Converters on each module. Mount converter modules on the readout printed circuit board. 48 volt is supplied via the PCB traces.

40 Ampere Converters on each stave. Here the PCB traces carry increasing more current towards the end.

For this exercise we assume that the LHC and ILC requirements are somewhat similar but with the following differences.

4 Amp units located near the front end and may be exposed to > 30 megarads of radiation in LHC while it is 20 kilorads for ILC. The unit should be made of low density materials. It may be possible to integrate the FETs on the ASIC.

40 Amp units can be located in a service area with lower radiation exposure.

LHC needs the power to be on continuously and the adequate cooling be provided. In ILC, the power can be switched on for the brief time when the beams are colliding. Here the duty cycle is 0.5% and the cooling solutions are simpler then for LHC. We ignore the Lorentz forces problem in switching current in the ILC. It may be necessary to provide slow current turn on/off.

LHC detectors use lower magnetic field while the ILC detector is being designed for 6 Tesla. The Converters have to be deigned to run in 1- 6 Tesla field without any magnetic materials.

Power Converter Design Issues

These are some of the issues that need to be explored.

The critical components are the ASIC controller chip, MOS FETs and the air coils.

Radiation hardness for 48 Volt silicon process may be difficult (or impossible) for LHC but doable for ILC.

Explore using air core transformers to reduce the voltages to be handled by the ASIC and the FETs. There is a tradeoff between voltage and current handled by the FETs for the same output power level.

CMS ECAL 50 Kamps.
Power Supply output = 315 KW
Power loss in Leads to SM = 100 KW
Power loss in Regulator Card = 90 KW
Power Delivered @ 2.5 V = 125 KW

ILC SiD Calorimeter = 100 K amps
ILC Callice Calorimeter = 300 K amps
Atlas SiTracker Upgrade = ?

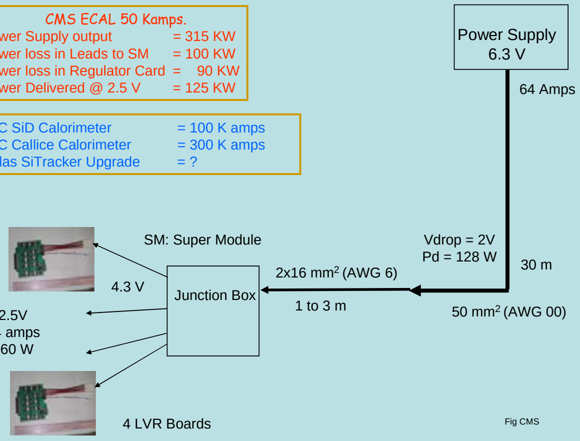


Fig CMS

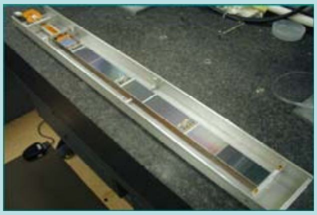


Fig Stave Silicon Tracker Stave (Super module) : Containing 6 modules:

Test Results with Air Coil

We are now concentrating on the air coils. Most of the available controllers operate at less then 500 KHz; there are a few operating at a few MHz with an inductor of 18 µH. We tested the following controller chips with the company supplied evaluation boards of following chips.

Texas Instruments TI 5430. Operating frequency is 500 KHz. Input range 5.5 to 36V. Minimum output is1.22, the evaluation board is set for 5 V. output rated at 3 amps. We tested by switching 2 amp loads.

Micrel Inc MIC2285 runs at 8 MHz switch using a 0.47 µH inductor.

Linear Technology LTC3418 runs at 4 MHz. 0.2 µH inductor Input range 2.25 to 5.5V. Output 0.8 – 5V @ 8 amps, the evaluation board is set for 5 V and we tested by switching 5 amp loads.

Ferrite Coil Inductor 25 uH

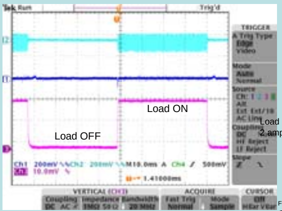


Fig TI 1

Air Coil Inductor 20 Turns

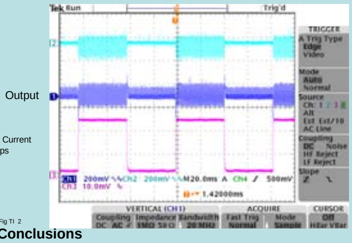


Fig TI 2

Conclusions

We are very encouraged by the tests with the air coils using standard switch mode controller chips. The efficiency with air coils is about 5 % lower.

For better operations (noise, efficiency, EMI shielding etc.) in the magnetic field the switching frequency should be an ordof magnitude higher. We would like to get other well funded groups work with us on pursuing this developments.

Acknowledgements

We thank the following companies for supplying us their evaluations boards and samples at no charge.
Vicor Corporation
Micrel Inc
Linear Technology Corporation

References:

Intel 1: Peter Hazucha et al: pages 838-845 IEEE Journal of Solid State Circuits, Vol. 40. NO. 4. April 2005.
Intel 2: Gerhard Schrom et al: pages 4702-4707 2004 35th Annual IEEE Power Electronics Specialists Conference.
Intel 3: Gerhard Schrom et al: pages 263-268 Proceedings of the 2004 International Symposium on Low Power Electronics and Design (ISLPED '04)
Nikhef: Sander Mos [sander.mos@nikhef.nl] Zero Iron Power Supply http://www.nikhef.nl/~sanderm/zips/index.html
Mohan: Power Electronics 3rd edition authors Mohan,Underland, Robbins. John Wiley & Sons Inc. ISBN 0-471-22693-9
Sokal Private Communication Nathan O. Sokal, Design Automation Inc, 4 Tyler Road, Lexington, MA, 02420, USA
Vicor: Vicor Corporation, Andover,MA, USA.