Re-designing a radiation-tolerant low voltage power supply for the ATLAS Tile Calorimeter Phase-II Upgrade

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Abstract. Power Electronics used in high-energy physics experiments at the Large Hadron Collider more specifically the ATLAS detector, are custom built and have to work reliably in the presence of ionizing radiation and an ever present magnetic field. In many such applications, owing to cost constraints, components that are radiation-hard by design are often used for such systems. Moreover, design complexity, verification effort, and scalability issues in centralized structures can impede performance improvement in monolithic designs. We demonstrate the steps followed for upgrading and re-designing a radiation tolerant low voltage power supply for a large scale operation and the considerations made for such a design. This includes measurements taken at component level, system level, and radiation tests done using the newly upgraded low voltage power supply. The upgraded low voltage power supplies will power the next generation of Front-End electronics of the Tile calormeter in HL-LHC era.

1. Introduction

The Large Hadron Collider accelerator at CERN [1], will be upgraded to deliver an instantaneous luminosity up to 7.5 x 10^{34} cm^{-2} s^{1}. The increase in integrated luminosity will correspond to an average of 200 simultaneous proton-proton interactions per bunch crossing. The ATLAS TileCal which covers the central region of the ATLAS experiment is a sampling calorimeter using iron as the absorber and plastic scintillator as the active material and divided longitudinally into three cylindrical barrels. The partition scheme of the barrels consists of two central long barrel segments and shorter extended barrel segments at each end [1, 2]. Each partition is comprised of 64 wedge-shaped segment modules. The Phase-II upgrade program of the TileCal system aims to satisfy the HL-LHC requirements and will be compatible with the new Trigger Data AQuisition (TDAQ) architecture, able to transfer full data to the off-detector electronics optically at 40 MHz [1]. The Tile Calorimeter front-end electronics (drawers) are powered by 256 LVBOXes. Each LVBOX contains eight 200W DC/DC single-output modules transforming 200 VDC input into +10V low voltage output. Each LVBOX is water cooled, contains the so called ELMB Motherboard, ELMB module, the 200 VDC distribution Fuse-Board, intergrated cable set for connections, and chassis. The ELMB incorporates CAN Bus protocol for

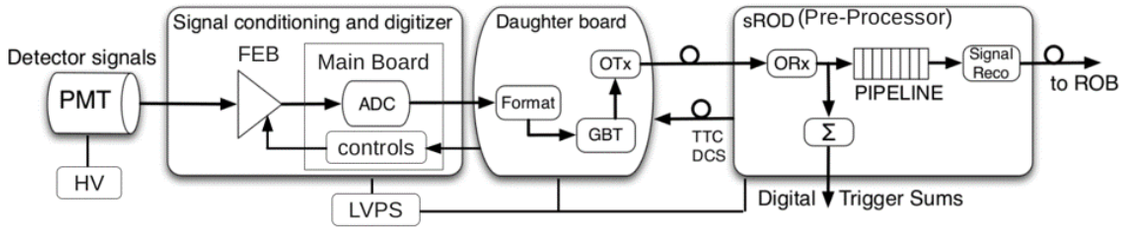

Figure 1: Upgraded TileCal readout architecture [2].

communication. It enables to monitor behavioural parameters of each DC/DC buck convertor, such as Iin, Iout, Vin, Vout, two on board temperatures. In order to evaluate the new readout architecture and the technology choices of the implementation, completely new on-detector and off-detector electronics are being developed, aiming to compensate for increased trigger rates and high-performance data acquisition.

2. Power and readout architecture

The low voltage power distribution system for TileCal provides power to the front-end electronics that reside on-detector as seen in figure 1. It is a three-stage power system. The bulk +200 VDC power supplies will be sourced in USA15, and distributed to the low voltage power supplies (LVPS) that reside inside "finger" of each module, just outside of each electronics drawer. These low voltage power supplies are also called "finger low voltage power supplies," (fLVPS). The fLVPS uses switching "Buck Converter" technology to convert the high voltage, low current power provided from the bulk source, into the low voltages required by the various sub circuits in the upgraded front-end electronics. The use of switching technology improves the efficiency of the power conversion, as opposed to the use of linear supplies. Upgraded fLVPS units will utilize identical LVPS bricks. Each of the new bricks produces +10 VDC as output. This is distributed to the front-end circuits, and the power is converted again using point-of-load (POL) regulators to the voltage levels needed by the local circuits. The interface in the fLVPS utilizes the ELMB, which is a standard for slow controls in ATLAS. The second part of the control system is based on the sub-system of small power supplies, called the AUXBoard which are placed in USA15 as bulk 200V DC power supplies. There is one AUXBoard for four fLVPS. New aspects of the upgrade design is to improve the performance, and adapt to the new requirements and interfaces of the upgrade. In the present system, the eight bricks that reside in the fLVPS supplies each provide power for specific circuitry in the drawer. They all use the same basic design, but are configured for the circuitry that they service, resulting in eight different types. In the new design, all eight bricks have the same specifications and performance requirements.

3. Functional description and specification of power supply

The basic topology of the brick is a transformer-coupled buck converter as used in the previous designs. The LVPS is centered around the LT1681 [4] controller chip with its dual transistor forward convertor (see figure 2) able to produce the drive pulse at the frequency of 300 KHz with an output duty factor that can vary from a few percent up to a maximum of 45%. The pulse width is controlled by a feedback circuit based on the values of the output voltage of the brick. This input permits us to ensure continuous-mode operation at the nominal voltages and currents. The signal from the LT1681 is sent to the Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) drivers [2,3,5]. These are transistor drivers that have sufficient current and voltage drive, to drive the high-side and low-side power.

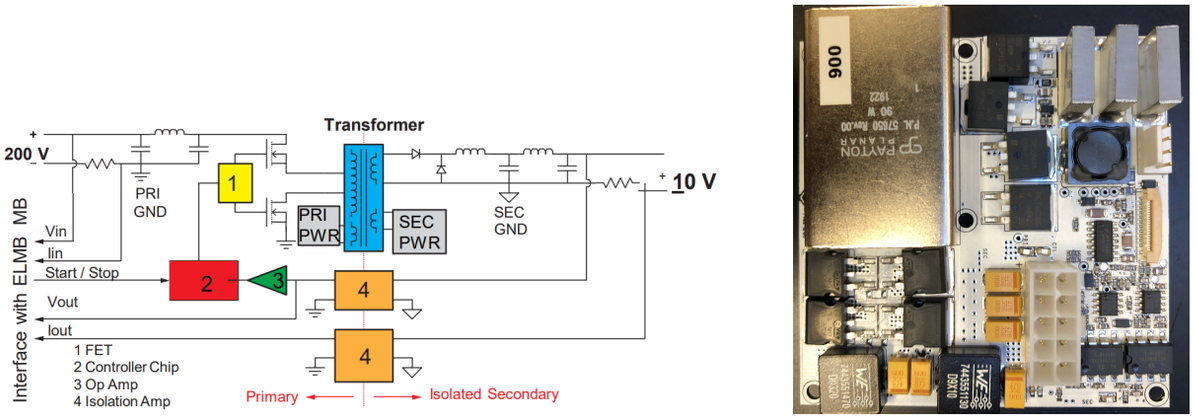

Figure 2: LVPS block diagram control system illustrating the LT1681 forward controller operating at 300 kHz [2] (Left) and University of the Witwatersrand low voltage power supply brick (right).

Both the high-side and low-side transistors turn on for the duration that the output clock is in the high state, and both are in the off state when the clock is low. When the MOSFETs conduct, current flows through the primary windings of the transformer, which transfers energy to the secondary windings. A buck converter [2,3] is implemented on the secondary side of the transformer and converts the signal to a constant voltage for the output. The output side also contains an additional LC (Inductor and Capacitor) stage for noise filtering. Voltage feedback, for controlling the output voltage, is provided by the opto-isolators [5]. This component processes the electrical signal converting it into digital signal at the input stage and transmitting it through pulsed light signal to the output, where it is converted back to an electrical analog signal. The signal is transmitted maintaining the input and output electrically insulated from each other. The design also incorporates two shunt resistors for measuring the output current, the voltage for which is also fed back using an opto-isolator.

The brick has three types of built-in protection circuitry as part of the design, namely the over voltage protection (OVP), over current protection (OCP) which are on the primary side. The third protection circuitry is the over temperature protection (OTP), which monitors the temperatures of the low-side transistor on the primary side. This circuit is integrated in the LT1681 design. When one protection circuit is triggered an 'off' signal is sent to the LT1681 which stops the brick immediately. The ELMB inside the LVBOX is used for digitization of monitored values from the bricks and ELMB send them via CANBUS to DCS. In particular, the ELMB monitors two temperatures on the primary side of the brick both close to the input of over temperature protection of the LT1681 and the output values.

The Printed Circuit Board (PCB) layout is a 6 layer board with dimensions of 80.26 mm by 80.26 mm and has mounting holes for attachment to the cooling plate inside the LVPS box. A shielded transformer following our custom specifications is used to step down an alternating high voltage produced from the forward controller to a lower an alternating voltage for DC-DC regulation. Ceramic cylinders made from Aluminium Oxide, called thermal posts, are used to transfer heat from brick components to the cooling plate. The metallized cylinders have one metallized face, which will be in contact with the pad of the switches and diodes on the PCB.

Parameter	Value
Threshold for Stable Load	2.3 A
Over Voltage Protection	12.5 V
Over current Protection	7 A
Duty Cycle at Nominal Load	> 45 %
Frequency at Nominal Load	300 kHz
Efficiency at Nominal Load	75 %
Input Current at Nominal Load	0.2 A
Over Temperature Protection	72 °C

Table 1: Specification parameters used to ensure uniformity of individual bricks in the test station software.

4. Improvements on the latest LVPS brick

The primary goals are to improve noise performance, reliability, and tolerance to Total Ionizing Dose (TID), Neutron Ionizing Event Loss (NIELs), single-event upset (SEU), while retaining the physical layout, interface to the detector control system, and other infrastructure.

4.1. Real-time monitoring of Low Voltage Power Supply

The brick measures six analog signals and sends them to the ELMB motherboard, which includes input voltage and current, output voltage and current, and the temperature readings from two points on the brick (primary and secondary side switches), measured using thermistors. Custom PC based software was synthesized to perform and monitor the LVPS brick and the tests are graphically displayed and recorded onto file these [4]. Testing ensures that LVPS bricks meet the criteria listed in Table 1. The feasibility of the design regarding the electrical parameters of specification was verified using a test-station [5] that was assembled at the University of the Witwatersrand. Various tests determine whether the protection circuitry of the LVPS is functioning correctly. Built-in protection circuitry are assessed for over current protection (at 10.5 A) and over temperature protection (at 70°C), in addition over voltage protection (at 12 V).

4.2. Thermal Management

In the upgraded design the ceramic posts utilize the same material which is the Aluminum Oxide (Al_2O_3) material to provide thermal coupling. The ceramic posts provide sufficient heat dissipation and can be seen from the two dimensional temperature maps of a +10 V brick operating at 2.3A which are shown in Figure 3, the old version of the power supply which had significantly lower efficiency MOSFET (left) and new upgraded version with high efficiency MOSFETs (right). Even if the obtained improvement are clear, there are two zones, where the location of the converter LT1681 and the location of the FET driver, that still show a very high temperature during operation. For this reason, these chips at the bottom side are coupled to the plate with the application of the Bergquist gap-pad for further reduction of the temperature to the two critical components responsible for heat generation of the power supply.

4.3. Radiation test results

Extensive radiation test campaigns have been on going for close to 5 years. We mostly attempt in finding candidates with acceptable degradation with Total Ionizing Dose (TID) and Neutron Ionizing event loss (NIELs). The Cobalt-60 gamma tests were performed at the CC60 facility

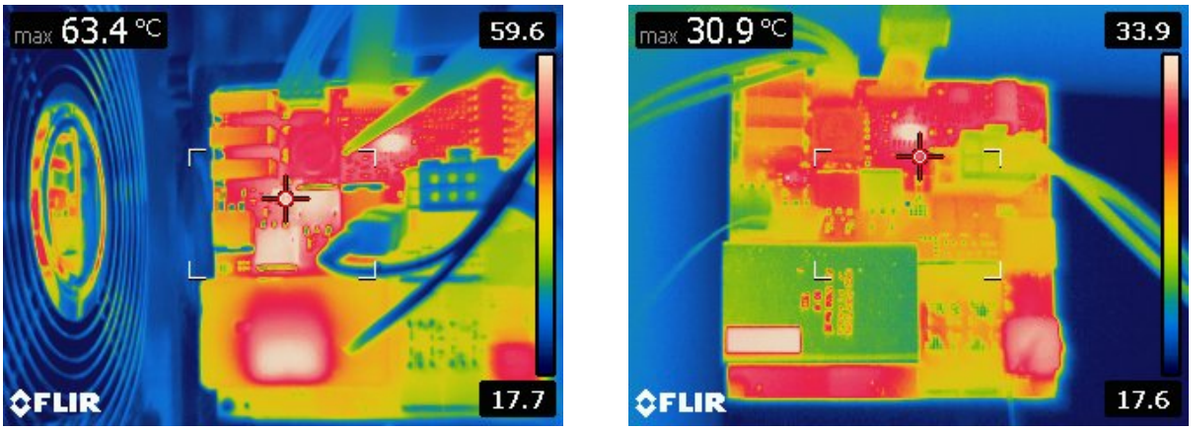

Figure 3: Two dimensional temperature maps of a + 10 V brick operating at 2.3 A with thermal coupling with Aluminum Oxide thermal coupling. These maps have been obtained with the application of a Bergquist gap-pad on the LT1681 and FET drivers. Thermal reading of the previous 8.1.0 version of the power supply (left) and the Thermal reading of current 8.4.2 version of the power supply (right).

at CERN. All irradiation sessions were performed with a dose rate of 3.75 Gy/hr. We placed the test set up (the power supplies and interface PCBs) at about approximately 75 cm from the CC60 source to ensure we receive a maximum dose close to 500 Gy at the center.There were no hard failures of bricks during the TID irradiation study. No transient event phenomena occurred during gamma irradiation, in the power supplies. All the bricks were running and monitored during up to end of the tests with only an output voltage drop of 1 mV/Gy. Since the accepted range of output voltage is 8 to 12 V from the point of load regulators, this drop is completely acceptable due to wide range of input voltage for our front end electronics. Parameters showed expected behaviour as a function of time for output voltage as shown in (Figure 4) and the output current in (Figure 4) both over a 12 hour duration.

5. Overall performance and reliability analysis

The overall performance of the tested low voltage power supplies must meet the stringent specifications of the ATLAS Phase-II LVPS project. Testing is based on two testing stations, both followed by debug and repair sessions. The sessions address protection and monitor circuits and are separated by the burn-in which aims at having the bricks working under stress conditions. At the end of the checkout procedure all the bricks must match the design parameters within the allowed ranges before checkout. Quality control testing at Wits University is ongoing and test benches are operable. The LVPS prototype guarantees over 80.5% efficiency at 2.3 A nominal load and +10V input and able to withstand harsh environments from the overall design.

6. Summary and Outlook

We have built and tested the LVPS bricks which are manufactured in South Africa and tested at Wits University. The reliability and stability of the system has been visibly improved with respect to the previous prototype produced at Wits University with key improvements being the thermal management and slow deviations of the monitored voltages. The project is well on track. More improvements are expected with the final design to include a decrease in clock jitter and stability in output noise and in the clock frequency. Expectedly, no gamma radiation related malfunctioning was detected. The LVPS progress of the ATLAS TileCal have been presented in several meetings and reviews. Further analysis of the LVPS bricks can be used to

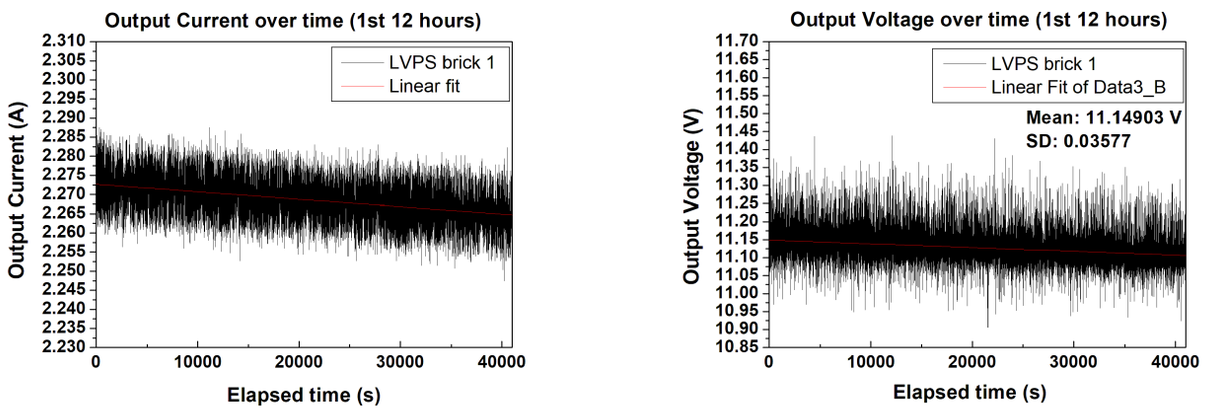

Figure 4: Output Current (A) and output voltage (V) of the LVPS monitored during irradiation testing at the CC60 facility.

gain detailed insight in what causes variations in detector response. Once a brick passes the Quality Assurance tests it will be sent to CERN for installation inside an LVBOX.

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