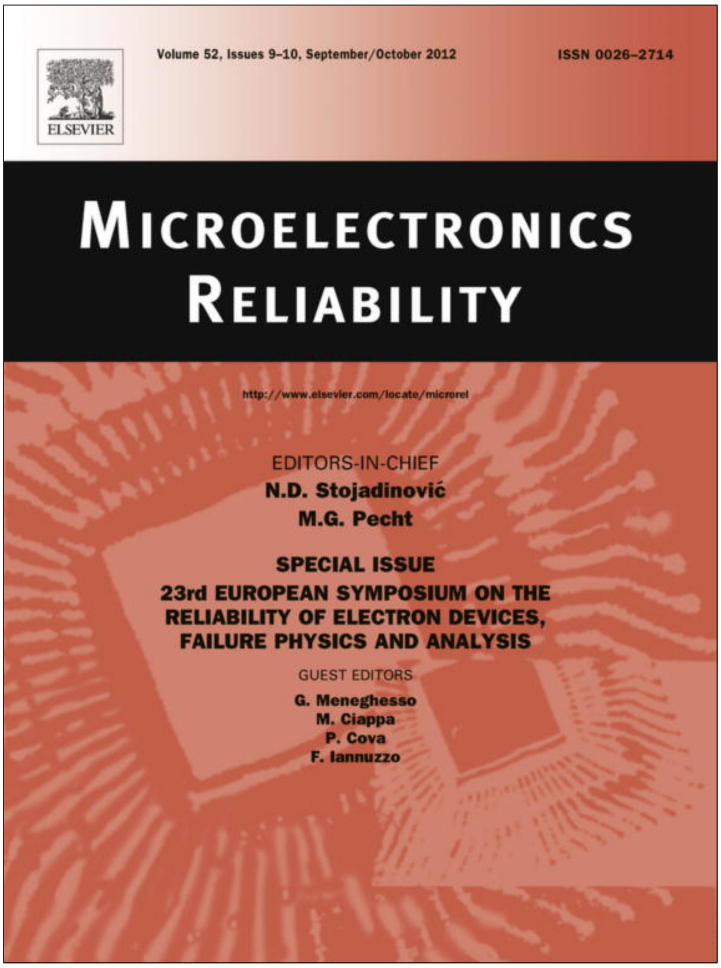
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Reliability oriented design of power supplies for high energy physics applications

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ABSTRACT

The paper describes the design of switching converters suitable for power supply application in the LHC proton accelerator, in operation since 2010 at the European Organization for Nuclear Research (CERN) in Geneva (Switzerland). Experiments running at LHC must reliably operate in a harsh environment, due to radiation, high magnetic fields, and stringent thermal constraints. The followed approach takes into account the very tight reliability requirements during all the design stages, from the choice of circuit topologies and radiation hard power components, to the thermal layout and material optimization. Results carried out on prototypes are reported.

1. Introduction

The upgrades of the Large Hadron Collider (LHC) experiments at CERN planned for the beginning of the next decade, and in particular the ATLAS experiment [1], requires a thorough re-design of the power distribution system's architecture. The requirements of new front-end electronics and the increase of the radiation background, about a factor of 10 above the present nominal values, are indeed unsuited with the capability of the present power distribution systems. A possible solution involves the development of a distributed power supply network, with point of load converters deployed at the very heart of the detectors where electronic devices must face a highly hostile environment, in terms of very high background of both charged and neutral particles [2,3] and for the presence of a non negligible magnetic field up to 100 mT, thus opening a severe tolerance issue for component selection and system design. This investigation proposes a new power supply distribution network, taking the ATLAS electromagnetic Liquid Argon (LAr) calorimeters [4] as the case study. Fig. 1 gives an idea of the complexity of the environment in which the power supply must operate.

The LAr Low Voltage Power Supplies (LVPSs) are constrained within the iron structures of the hadronic calorimeter and cannot be moved or oriented differently. Their dimensions cannot be enlarged in order to improve the thermal performance. They are immersed in a moderate magnetic field, up to 30 mT [5], so they can be cooled only by using a coolant under stringent requirements, as reported in [5]. The background radiation is quite high, corresponding to 450 Gy of gammas, $7.7 \times 10^{12}/\text{cm}^2$ of 1 MeV equivalent neutrons and $2 \times 10^{12}/\text{cm}^2$ of 20 MeV hadrons. In this environment, the delivered power of the single power supply box, measuring $15 \times 40 \times 30\ \text{cm}^3$, must be 3.3 kW under the worst conditions with efficiency of 78% at least, without significantly increasing the external environmental temperature.

The LVPS boxes are not accessible during the data taking periods, while their accessibility during the shutdown periods is very difficult and requires a long time, and a fault in one box has the consequence of making unavailable a non-negligible part of the detector. For these reasons, the single box will be composed of three power units with the requirement of redundancy, so that two units must be able to supply the full power in case of a faulty unit, and its required MTBF must be of 5×10^5 h at least.

The presently installed LVPS showed critical issues on many aspects: mechanical, workmanship, thermal, component stress, tolerances and flaws of design. Some of them are related to the assembly process and to the quality inspection and control, while others are related to the design and component choice. In particular, the thermal dimensioning was poorly considered and simulated, leading to the formation of internal hot spots. The adopted topology was relatively simple, but there was a lack of failure and worst case analyses, and many components were not specified with the proper tolerance, generating instabilities in the final

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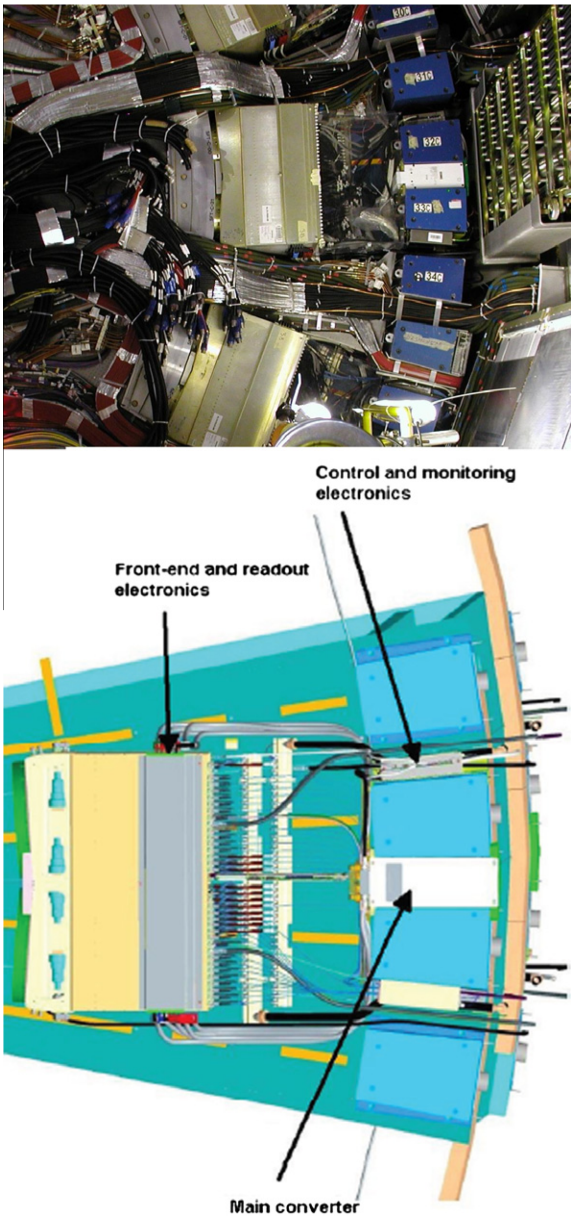

Fig. 1. Layout of electronics and power supply in the ATLAS LAr calorimeter.

performance. About 60% of the delivered LVPS failed the acceptance tests, and many of them who passed the tests showed some kind of fault after few months, or even few weeks, of operation under full load.

In this new design we concentrated mainly on the design issues, from a better topology in terms of efficiency and performance in a radiation environment, to detailed thermal analysis and simulations, in order to minimize the high temperature spots.

To this purpose, a single 12 VDC bus is considered, fed by an isolated DC–DC resonant Main Converter (MC) with redundancy characteristics. The DC bus is distributed to the electronic front-end and read-out boards, where non-isolated Point of Load (POL) converters are implemented for voltage adaptation and regulation. It is important to emphasize that the choice of the 12 VDC bus voltage is just an example, other values could be selected as well.

In Section 2 the MC structure, its realization and its thermal management are discussed, showing the possibility of achieving high reliability with low overall losses and generated switching noise. Preliminary experimental results are also reported. Possible realizations of POL converters are investigated in Section 3. The fundamental issues related to the radiation hardness tests made on commercial components are reported in Section 4.

1.1. Power distribution network

In the present realization, Fig. 2, the power supply system consists of a main isolated DC–DC converter with multiple outputs (ranging from − 7 V to + 11 V) followed by many distributed low-voltage drop-out (LDO) regulators supplying different analogue and digital loads.

The presented Intermediate Bus Architecture (IBA) adopts a unique voltage bus with high voltage level in order to reduce the power losses during the distribution of the electrical energy, as shown in Fig. 3.

The power supply in the area of the experiment, a cavern sited 100 m underground, is provided through cables fed from AC/DC power converters with 280 VDC outputs. The conversion from the high voltage DC bus to the intermediate voltage DC bus is delegated to the power converters sited close to the Front End Boards (FEBs, the loads) in a hostile environment. Furthermore, the proximity of the main DC–DC conversion units to the electronic circuits of the LAr calorimeters makes the size and the temperature variation of the power converter enclosure as mandatory requirements for the design. A modular approach has been proposed for the main converter in order to meet the $(n + 1)$ redundancy requirement and improve the overall reliability, the robustness, and the thermal efficiency. Three identical 1.5 kW modules connected in parallel provide the 3 kW required in operation, guaranteeing power continuity even in the case of failure of one module and limiting in this way the partial out-of-service of the detectors.

The aim of this paper consists in showing the reliability-aware design of a modern power converter purposely developed for applications in a field (high energy physics experiments), were the reliability constraints are very tight and force to explore all the possible solutions at different level: topologies, components, materials, layout. The motivation for this effort comes from the numerous failures evidenced by the previous generations of power supplies adopted in these conditions, which forced frequent maintenance, incompatible with the system specifications. We addressed the reliability improvement of such a heterogeneous system at the design stage, by accounting for the degradation mechanisms evidenced in previous power supply generations adopted for the same application.

2. Main converter

The Switch in Line Converter (SILC) topology [6] has been implemented for each module. A list of advantages has driven the choice: the reduced voltage stress across MOSFETs reduces the sensitivity of power devices to ionizing radiation; the zero-voltage commutation at switch turn on allows high switching frequencies with reduced commutation losses and high efficiency; the first order dynamics makes the power cell an excellent candidate to supply other converters as in the cascade configuration of the distribution buses. The single module includes several sub-blocks: a main 1.5 kW SILC converter, a 20 W auxiliary converter to supply controllers and drivers, a current sharing control circuit, a smart main switch that manages the operation of the modules and enables the parallel connection and a master external control unit that supervises the synchronization of the clocks and manages the monitor and the enable/disable signals.

A full set of test has been performed in order to characterize the converter. Depending from load conditions the efficiency ranges

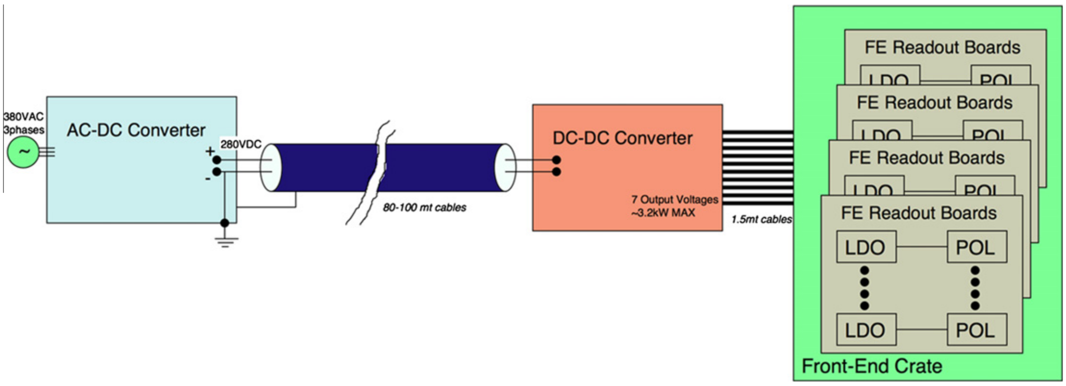

Fig. 2. Power supply distribution of the ATLAS LAr calorimeter: present situation.

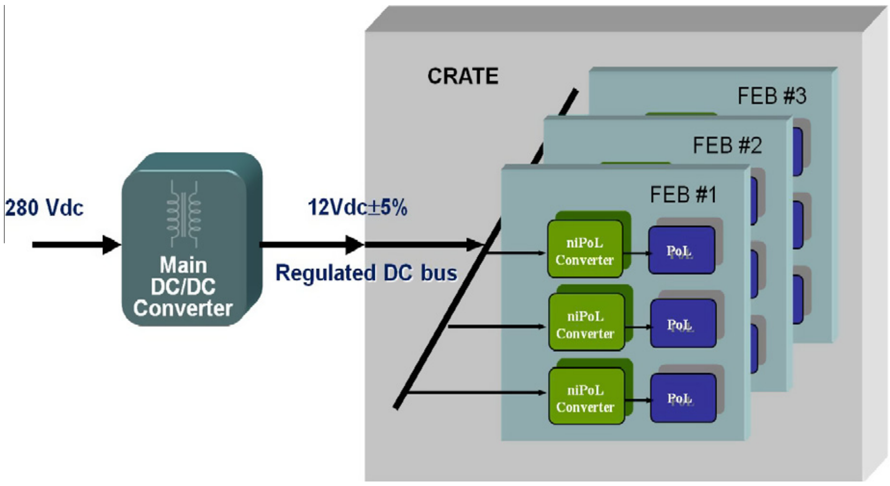

Fig. 3. Power supply distribution, based on an IBA architecture, proposed for the upgrade of the ATLAS LAr calorimeter.

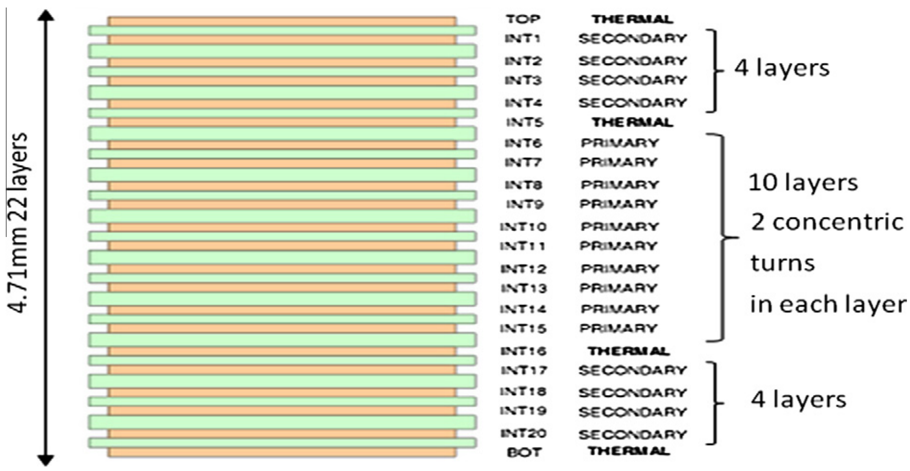

Fig. 4. Schematic view of one transformer PCB with 22 layers (four of which, indicated by "THERMAL" are intended to extract the heat generated in the windings).

80–90% and frequency response of the control to output transfer function confirms a first order dynamics. The converter was also tested for load current transients. Since loop gain is stable with wide margins, no ringing of output voltage is expected in response to current variations.

2.1. The planar transformer

The presence of a stationary magnetic field up to 30 mT made critical the design of the magnetic components. The need of using low permeability core (KoolMu 60 um) and, at the same time, the exigency to limit the size and the heat dissipation, led to the design of a dedicated 1.5 kW planar power transformer specifically devoted to this application. The two primary (T1, T2) and secondary windings (T3, T4) of the transformer were realized by a suitable connection of four PCBs of 22 layers (Fig. 4).

The use of low permeability core increases the iron losses and produces an overheating of the transformer. In order to improve the dissipation and fully exploit the cooling system, four thermal layers connected to the heat sink were inserted between the windings.

The PCBs developed for the planar transformer are based on FR4 substrate. Copper layers have been used for windings and heat dissipation. The possibility to use Insulated Metal Substrate (IMS) in order to optimize the heat dissipation has been investigated but not implemented in this demonstrator. The thermal conduction through the inner thermal layers is guaranteed by a number of copper plated vias. A detailed description of the thermal design of the planar transformer can be found in [7].

A prototype (Fig. 5) was fabricated and tested in stationary field. Good performances up to 2.5 kG are reported in Fig. 6, which shows the transformer behavior in a stationary magnetic field of 2591 G.

2.2. Main converter thermal management

The MC design had to comply with very tight thermal constraints: due to the proximity of highly susceptible electronic systems for detector's signals conditioning (see Fig. 1), the metallic box containing the converter should be ideally adiabatic and all the generated heat be collected by the water cooling system through dedicated cool plates for every module. At the same time the converter component temperatures must be kept as lower as possible, to increase the system reliability. To reach these two targets accurate Finite Element (FE) thermal analysis was conducted, at components, power module, and system level. Board layout and materials were also optimized, as reported in [8]. Fig. 7 shows a photograph of one module of the MC mounted on the water heat-sink.

The single MC module was tested, at nominal load (1 kW output power) and in the case of extra-load due to a possible module failure (1.5 kW), in operating water cooling condition. The whole thermal map of the upper surface was acquired by an infrared thermocamera and the temperatures of the more critical components were measured by thermocouples. In both cases the maximum temperatures are limited in a range which ensures sufficient reliability of the components.

Table 1 summarizes the maximum temperatures of the main heating components in a module measured during the tests described above.

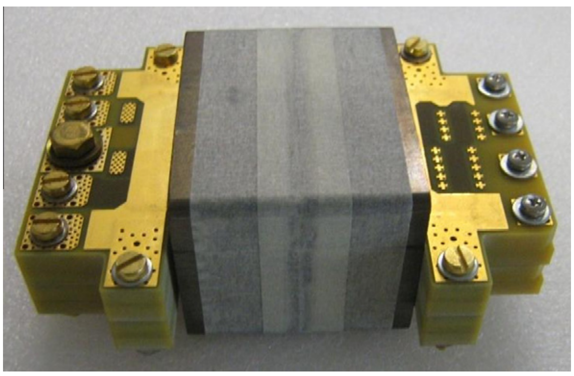

Fig. 5. Prototype of the planar power transformer.

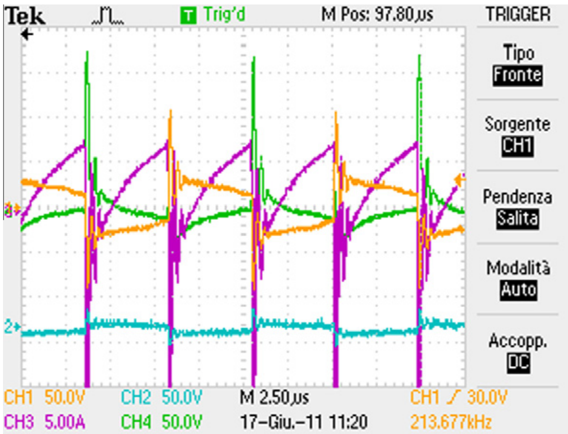

Fig. 6. Transformer behavior in stationary magnetic field (B_{DC} = 2591 G). Orange = V_1; blue = V_2, magenta = I_1; green = $I_{snubber}$ (proportional to switching losses). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The layout of the whole MC, consisting of three modules in a sealed box (see Fig. 8), was designed with attention to obtain the maximum insulation towards the external walls.

Unlike from previously used power supplies, the modules are cooled by separate water heat-sinks, powered in parallel by the same external hydraulic circuit. Moreover, FE analysis demonstrated that improving the thermal insulation of the upper surface of the modules will increases the amount of heat extracted by the water cooled heat-sinks, then reducing the box walls heating, as requested by specifications, still maintaining the components maximum temperatures acceptable [8]. The fabrication of a prototype of the whole boxed MC, is in progress.

3. Point of load

The proposed solution makes use of a high step-down ratio topology operating at high frequency (Fig. 9). A detailed description of the operation of this topology can be found in [9,10].

The high step-down ratio is motivated by the need of pushing the DC bus voltage to the highest possible value to increase the power capability of the distribution system, the current being lim-

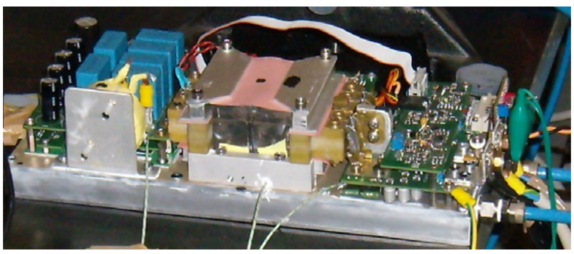

Fig. 7. Photograph of the MC mounted on the water heat-sink during the tests.

Table 1
Measured maximum temperatures (°C) of some components in a water cooled MC module supplying 1 or 1.5 kW. T_{H2O} = 18 °C, T_{amb} = 25 °C.

Component	T_{max} (1 kW)	T_{max} (1.5 kW)
Input MOSFETs	44	70
Output diodes	50	84
Transformer core	67	95
Transformer windings	56	107

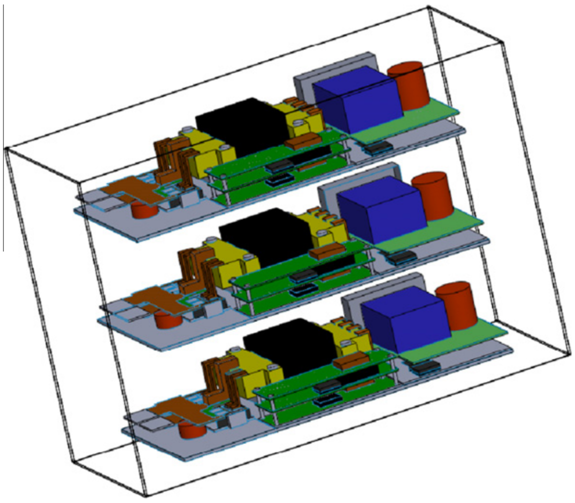

Fig. 8. FE model of the whole boxed MC.

ited by DC bus cabling. The selected topology features: high step-down ratio with reasonable duty-cycle values, reduced switch voltage stress, interleaved operation with automatic current sharing and output current ripple cancellation. Differently from conventional interleaved Buck converters, the switch voltage stress reduction by a factor of two ($V_{DS} = U_{in}/2$) not only decreases the commutation losses but, at the same time, increases the MOSFET reliability when operating in an environment with high radiation levels.

A 12 V-2 V (I_{out} = 20 A, f_{sw} = 280 kHz) DC/DC converter prototype has been built using standard components so as to validate the selected topology (Fig. 10).

The efficiency measured as a function of output current ranges between 80% and 86% in the absence of any external magnetic field.

3.1. Developing proper magnetic material for inductors

The POL converters directly installed on detectors are required to work in a very high magnetic field environment. To avoid the saturation of the inductor, it could be replaced with a coreless one, but this choice has two drawbacks: the inductor dimension, which limits the output current to a few A, and the increased radiated noise. An alternative is to replace the core, normally composed of ferrite, with some other material, able to work in that particular environment without saturating. In collaboration with the FN S.p.A. Company, we are developing this alternative, by characterizing special materials for inductor cores. Apart for the tolerance to magnetic fields of the order of 1 T, these materials must show low coercive force, high immunity to radiation, and good performance at high switching frequencies.

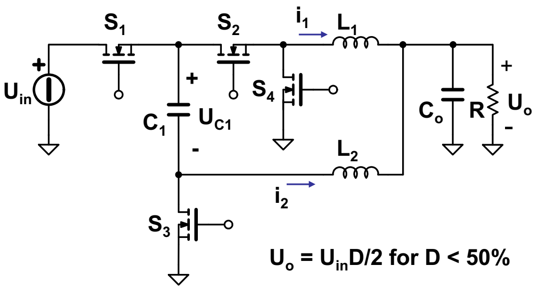

Fig. 9. POL converter electrical scheme.

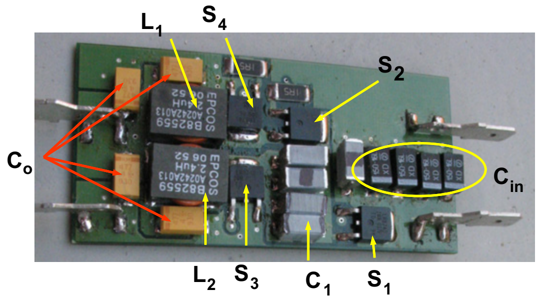

Fig. 10. POL prototype (L = 7 cm, W = 3.5 cm).

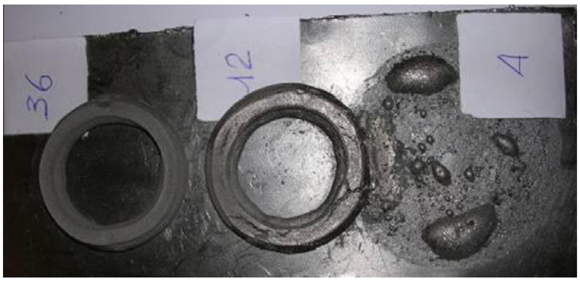

Fig. 11. Toroid samples after the sintering process.

The first chosen material is a Fe soft magnetic powder with 6.5–6.9% Si content, produced by Hoganas. Due to the cold ductility of such a material, the metal injection moulding process is difficult, and its optimization and tuning of parameters required a long time. Other necessary fabrication steps, like de-binding and sintering at high temperature in H_2 atmosphere, are still under development. Some good and bad samples after the sintering process are shown in Fig. 11. Some sample cores were produced and successfully tested under gamma radiation up to 5 kGy [11].

4. Radiation tests on power MOSFETs

Power MOSFETs to be used in power converters for high energy physics applications must be able to sustain high fluencies of γ-rays, protons and neutrons, so that they must be tolerant to both total ionizing dose and Single Event Effects (SEE), induced by energetic protons and neutrons. The devices were chosen among the new generation of power MOSFETs having thin gate oxide, in order to reduce the threshold voltage shift while keeping sufficiently high the tolerance to SEE. Two families of state-of-the-art commercially-available devices were chosen rated at 30 V and 200 V for POL and MC, respectively. Fig. 12, which reports the reduction of the threshold voltage at increasing γ-rays fluence for the 200 V MOSFETs, indicates that most of the devices can be used since we are thinking of reverse biasing the gate at -10 V in the off state.

The results of Fig. 13, obtained on 200 V samples, indicate that the specified fluence in ATLAS experiment can be achieved by reducing the device operating voltage.

5. Conclusions

We presented a reliability oriented approach for designing the power supplies for the future upgrades of the LHC experiments.

The distributed power architecture, with topologies implemented for main converter and point of load have been described and experimentally characterized. Thermal analysis of power

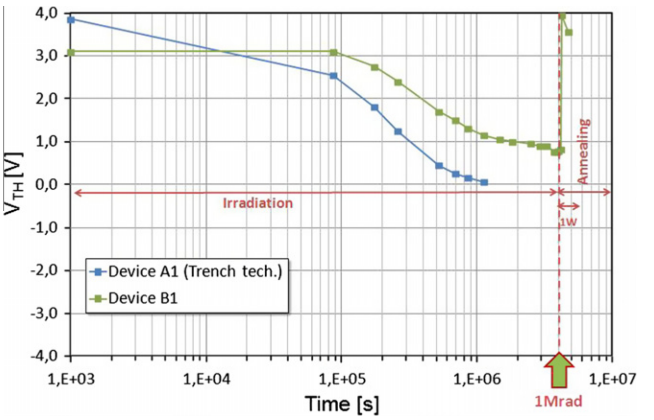

Fig. 12. Threshold voltages vs. γ-rays doses for the 200 V commercial devices tested.

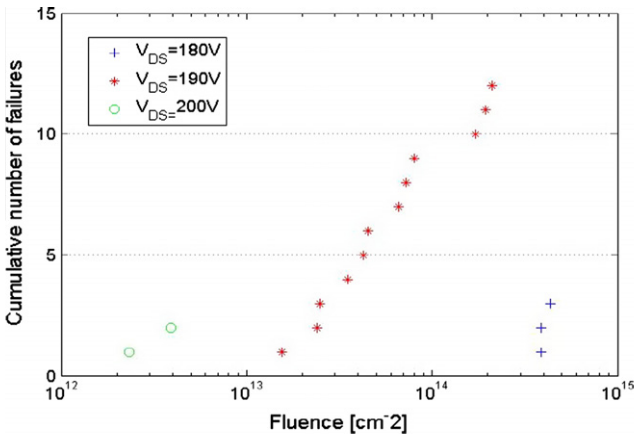

Fig. 13. Cumulative number of failures during protons irradiation vs. fluence.

devices has been taken into consideration for proper engineering of the prototypes.

Components and material were selected to cope with the standing magnetic field, radiation dose and thermal constraints. A novel high saturation magnetic material is under evaluation. Various power MOSFETs have been successfully tested for total ionizing dose and single event effect tolerance. Experimental results on prototypes were shown, which indicate good performances. Reliability tests on single components and the whole module have been performed and passed.

This is, in the opinion of authors, a good example of reliability-aware power system design, obtained by the collaboration of research groups skilled in different aspects, which enabled to join the experience on the degradation mechanisms from the field with the application of modern technological solutions.

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